AUSTRALASIAN GROUNDWATER CONFERENCE

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BRISBANE CONVENTION & EXHIBITION CENTRE
QUEENSLAND

GROUNDWATER IN A CHANGING WORLD

Book of Abstracts

NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

AGC2019

The Australasian Groundwater Conference (AGC) was held in Brisbane Queensland, 24-27 November 2019. This conference was an epic event filled with informative presentations, entertaining networking events and stunning field trips exploring the sights and sounds that this subtropical dynamic region has to offer. The AGC 2019 featured a stimulating technical program around the theme of "Groundwater in a Changing World" that covered a broad range of applications to resources, infrastructure and environment. The program included stimulating plenary speakers, engaging panel discussions and enticing social events. Over 600 groundwater researchers, industry professionals and policy development specialists from around the region attended this unique event. There were many opportunities on offer for delegates to share their experiences, inform best practice, and identify the steps they can take to bring about lasting improvements to the management of our vital groundwater resources. Our hard-working volunteer organisational team wishes to thank sponsors, speakers, delegates, exhibitors and volunteers for making the conference such a huge success!

Professor Jim Underschultz

Australasian Groundwater Conference Chairperson 2019

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Abstracts presented on Monday 25 November 2019

Plenary Presentations

Integrated management of groundwater-energy-food nexus for sustainability

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Groundwater management is important for global and local sustainability, because of not only connectivity of large groundwater footprints through the global trade and local groundwater depletion, but also climate change impacts on groundwater resources directly and indirectly, and carbon emissions through human activities using groundwater. Groundwater, energy and food are interlinked each other beyond the boundaries of each shed as well as trans-spatially through the food and energy trades. Interactions between groundwater-food-energy nexus and environmental/ economical/social impacts, are analyzed in terms of multi-scale integrated management and governance of the nexus by increasing synergies and reducing trade-offs in Belmont Forum project on Urban water-energy-food (WEF) nexus. A decision support integrated model is developed to analyze the WEF nexus and assess environmental and economic impacts, with three databases of resources, interlinkage, and scenario in multi-spatial scale. Trade-offs are analyzed between economy and environment as well as local and national scale.

Planning for a water secure world – a global miner's perspective

Laura Tyler [1]

1. BHP, Adelaide, SA, Australia

Water is a shared resource, with high economic, environmental and social value. Access to it is a basic human right. Water is also an essential enabler in modern mining. The sustainability of mining operations around the world relies on the ability to obtain the appropriate quality and quantity of water. Water management is different for different regions and geographies but, in many of cases, relies significantly on sustainable groundwater usage and management – a hotbed of conversation in the resources industry.

BHP uses around 300,000 megalitres of water (120,000 Olympic sized swimming pools) annually to run its global assets and produce commodities, of which more than 50 per cent comes from groundwater resources. In this talk, Laura Tyler shares the different practices in place at BHP to manage water responsibly, with water

stewardship at the heart of the Company's vision to have a water secure world by 2030. Laura will explore the different groundwater challenges and risks facing BHP and the resources industry today, and the importance of planning, and investing in the technical basis and technology which underpins sustainable water management decisions, now and into the future.

Hydrogeology – the role, integration of the profession, and the need for common technical language

Chris Langton [1]

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Abstract not supplied.

Special Session: Great Artesian Basin - Hydrogeology Journal Special Issue

The Great Artesian Basin, Australia – from discovery to current hydrogeological, hydrochemical and isotope hydrology interpretations

M. A. Habermehl [1]

1. Dr M.A. Habermehl, Kaleen, Canberra, ACT, Australia

The Great Artesian Basin (GAB) in Australia underlies semi-arid and arid regions across 1.7 million km^2 or one-fifth of Australia. The Basin's groundwater resources were discovered around 1880 and the development of flowing and pumped artesian water bores provide water for the sheep and cattle of the grazing industry, homestead and towns, and for oil, gas and mineral mining ventures to exist in and near the Basin. The GAB is a multi-layered confined aquifer system, with aquifers in Jurassic and Cretaceous continental sandstones and intervening confining beds of siltstone and mudstone of the constituent Eromanga, Surat and Carpentaria sedimentary basins. The Basin is up to 3000 m thick and forms a large synclinal structure, uplifted and exposed along its eastern margin and tilted southwest.

Recharge to the exposed aquifers occurs mainly in the eastern margin, an area of relative high rainfall. The western margin in Australia's arid centre receives minor recharge. Regional groundwater flow is towards the southern, south-western, western and northern margins, and based on isotope hydrology studies, at 1 m/year to 2.5 m/year. Age dating by isotope hydrology studies of the artesian groundwater in the Basin determined ages of up to 1 to 2 million years. Groundwater quality is good, at 500 to 1500 mg/L total dissolved solids and is predominantly Na-HCO_3-Cl type water, with in the southwestern part Na-Cl-SO_4 type water. Groundwater temperatures in bores are 30^0 to 100^0 C, and in artesian springs 20^0 to 45^0 C. Most flowing artesian springs discharge in the southwest margin and produced carbonate mounds and contain unique flora and fauna. Spring carbonate deposits have been dated by thermoluminescence and uranium series dating and result in ages between 465 000 ± 43 000 years and 740 000 ± 120 000 years. Lateral groundwater

movement in the aquifers dominates, though vertical upwards leakage is considered important. Potentiometric surfaces of the Jurassic and Lower Cretaceous aquifers are still above ground-level throughout most of the Basin, though pressure drawdowns of up to 100 m have been recorded in recent decades in highly developed areas, and consequently some artesian water bores and springs ceased flowing. Governments supported bore rehabilitation and management programs have led to groundwater pressure recovery in some areas. Computer modelling of the Basin's hydrodynamics assisted these programs.

Aspects of the hydrogeology, hydrochemistry and isotope hydrology studies of the Great Artesian Basin will be discussed, summarising the recent knowledge on the Basin.

1. M.A. Habermehl - The Great Artesian Basin, Australia – from discovery to current hydrogeological, hydrochemical and isotope hydrology interpretations (in prep./press/2019 - Hydrogeology Journal) M.A. Habermehl - Artesian Springs of the Great Artesian Basin – Hydrogeology, hydrochemistry and age dating of artesian groundwater and spring deposits (in prep./in press/2019) - Proceedings Royal Society of Queensland- Springs Special Issue

Estimation methodology and improved characterisation of unmetered stock and domestic groundwater use in the Surat and southern Bowen basins of the Great Artesian Basin (Australia)

Steve Flook [1] , Dhananjay Singh [1] , Sanjeev Pandey [1] , Linda Foster [1] , Sean Lowry [1] , Keith Phillipson [1] , Jit Khor [1] , Joanna Smallacombe [1]

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A key challenge for managing the aquifers of the Great Artesian Basin (GAB) is the limited available data for private groundwater use. Estimates of unmetered private groundwater use are critical for conceptualisation of groundwater systems and for understanding the system response to the current and future stresses. In the absence of an existing methodology, the Queensland Government's Office of Groundwater Impact Assessment (OGIA) developed a demand-based method to estimate unmetered stock and domestic (S&D) groundwater use.

The method integrates publicly available datasets including property grazing potential and availability of other water supplies to derive a range of groundwater use estimates. The methodology also distributes the demand for groundwater use across existing bores and across screened geological formations based on bore construction and OGIA's formation attribution assessment. The method has been applied to the Surat and southern Bowen basins.

This presentation will provide an overview of the demand-based method, highlighting new understanding of the temporal and spatial distribution of groundwater use in Surat and southern Bowen Basins. Results were validated at the bore level with limited metered bore data, and at the sub-regional level from census data and landholder survey information. Across the Surat Basin, comparisons with previous estimates indicate a reduction in S&D water extraction from approximately 80,000 to 25,000 ML/yr.

OGIA's 2016 methodology was applied to the Eromanga and Carpentaria basins of GAB to support the review of the Queensland *Water Resource (Great Artesian Basin) Plan 2006*. Over the past two decades, resource development activities including coal seam gas (CSG) extraction have rapidly expanded in the Surat and southern Bowen Basins, sub basins of the GAB. It is important for resource managers to be able to

differentiate between the impacts of groundwater extraction during resource development activities and the impacts of groundwater extraction for consumptive uses. The method and underlying principles of the estimation methodology are broadly applicable to unmetered S&D extraction from other regional groundwater flow systems.

Estimating current and historical water extraction from the Great Artesian Basin and other regional scale aquifers in Queensland, Australia

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Understanding groundwater use, both current and historical, is important for understanding the hydrogeology of groundwater systems, and for water planning. The Queensland portion of Australia's Great Artesian Basin (GAB) is managed under the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017. Methods were developed to estimate current and historical abstractions from the different hydrostratigraphic units of the basin. In the first stage, source aquifers were assigned to ~96,000 bores within the Queensland GAB footprint. Of these, 19,753 bores were assigned directly to the GAB, with other bores sourcing groundwater from units above or below the GAB. In the second stage, current groundwater use for all bores and historic groundwater-use trends were estimated, covering the 115-year period between 1900 and 2015. These estimates took account of periods of inactivity at the bore, the aquifer condition (sub-artesian, artesian), and the nature of discharge (controlled or uncontrolled). The process used publicly available datasets. This paper presents an overview of the methodology and how the estimates were used to support water planning. The current groundwater use from the GAB in Queensland was estimated to be 322 GL/year, which is lower than previous estimates, partly because of improved estimation techniques, the bore capping and piping programs that have been in progress since 1989, and the naturally reducing discharge rates from uncontrolled artesian bores.

Field investigations of potential terrestrial groundwater dependent ecosystems and comparison to popular conceptual models within the Surat Basin

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Arrow Energy has undertaken field investigations at four locations in the Surat Basin to understand if terrestrial ecosystems, identified through a desktop risk assessment, are dependent on the presence of groundwater.

The field investigations encompassed numerous complementary methods to derive multiple lines of evidence as to whether the ecosystems are groundwater dependent.

The methods included coring to observe tree rooting depth, and assess hydrogeological conditions, assessment of soil moisture and leaf water potential, and stable isotope analysis of soil moisture, groundwater and xylem water.

Consequently, it was possible to identify, with a strong degree of confidence, the source zone of predominant moisture uptake and therefore hypothesise whether vegetation at each site was likely to fit the definition of a GDE.

This study provided multiple lines of evidence that up to three of the four locations are unlikely to fit the classical definition of a GDE and be reliant on groundwater from the regional water table aquifer, but rather are utilising shallow sources of soil moisture located above the regional water table aquifer, and that rooting depths of targeted tree species in the study areas are shallower than commonly thought.

The study's outcomes have resulted in a more robust understanding of vegetation moisture uptake sources which in turn provides the basis for the revision of historical simplistic conceptual models of terrestrial GDEs in the Surat Basin and to provide direct evidence of the ability of targeted tree species to source water from the most accessible point within the ecosystem which is not always the regional water table aquifer.

Groundwater recharge at the eastern intake beds of the Great Artesian Basin using multi-isotope studies

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Objectives: Large sedimentary basins with multiple aquifer systems, such as the Great Artesian Basin (GAB) in Australia, are difficult to study because of the very large time scales associated with groundwater flow. The GAB is the world's largest and deepest artesian groundwater basin and has become increasingly stressed due to demand from multiple competing industries (agriculture, oil, coal and gas). Quantifying groundwater recharge is crucial for understanding the water balance for this economically and culturally important multi-aquifer system. The complexity of the GAB can only be dealt with by applying multiple lines of evidence including environmental isotopes, supported by hydrochemical, sedimentological, and geophysical observations.

Design and Methodology: Three studies on the recharge areas of the GAB investigated recharge to the Hutton Sandstone and the Precipice Sandstone (QLD) and the Pilliga Sandstone (NSW). Multiple environmental tracers (major ion chemistry, ^{18}O, ^{2}H, ^{3}H, ^{13}C, ^{14}C, ^{36}Cl, $^{87}Sr/^{86}Sr$, ^{85}Kr, ^{81}Kr, noble gases) were measured. Recharge rates were derived from tracer concentration profiles and aquifer cross-sections with porosity derived from previous studies.

Conclusions: Tracer results in the Precipice Sandstone are consistent with pumping test data and re-injection of coal seam gas produced water, suggesting high hydraulic conductivities. They provided the first estimate of average long-term annual recharge to this deep confined aquifer, which is of a similar order of magnitude as today's industrial re-injection of CSG water.

A consistent interpretation of tracers within the Hutton Sandstone was only possible assuming dual porosity involving diffusive tracer exchange between flowing and stagnant pore spaces. The new results highlight that the Hutton Sandstone receives only ~ 3% of the recharge previously estimated using Chloride Mass Balance (CMB) at the intake beds.

Results for the Pilliga Sandstone provide evidence for two distinct flow paths, with the southern path providing a much higher flow velocity than the northern path. ^{85}Kr and ^{81}Kr measurements also validated the initial findings derived from using ^{14}C and ^{36}Cl, but are much more robust.

Hydrogeological implications of active tectonics in the Great Artesian Basin

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The surface drainage systems across central and eastern Australia testify to a diverse range of tectonic processes that continue to modify the landscape in subtle ways. The distribution of channel forms and offsets in the drainage catchments in the Lake Eyre Basin points to the existence of a tectonically active north to northwest-trending fault system that correlates with a distinct potentiometric anomaly in deep aquifers in the central part of the Great Artesian Basin (GAB). Correlations in the distribution of seismic activity and drainage form with changes in lithospheric thickness suggest faulting reflects in part stress sourced from sub-lithospheric mantle flow beneath the GAB, while geometry implies fault activity dates to the late Miocene. These observations have implications for hydrogeological interpretations and groundwater process understanding, while also providing constraints on water balance studies. Recognition of tectonic control on pressures within key aquifers also has groundwater management and monitoring implications, and more general utility for unconventional energy development and monitoring.

Sequence stratigraphy, palaeo-depositional environments, and aquifer geometries and connectivity of the Hutton Sandstone to Springbok Sandstone interval of the Surat Basin, Queensland

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Objectives: The ~650 m thick interval from the Hutton Sandstone up to the Springbok Sandstone in the Surat Basin (Queensland, Australia) are aquifers of the Great Artesian Basin. Hydrological modelling of groundwater flow and pressure evolution is an important tool for management of this resource. Stratigraphy and depositional environment are essential to model conception and build as they provide estimates of aquifer geometry and heterogeneity. This study investigates the stratigraphy of the interval of interest with well log data integrated with generally underutilised seismic data.

Design and Methodology: A sequence stratigraphic methodology has integrated seismic, wireline, core and outcrop data regionally at select areas. A 3rd and 4th

order sedimentary depositional cycle framework pinned to two regional datums is developed. This framework allows sedimentary packages of same age to be correlated laterally highlighting heterogeneity and connectivity of aquifers. In contrast, most current models use a lithostratigraphic approach to correlate packages of similar lithology which may overestimate the lateral extent and connectivity of aquifers. Environments of deposition are interpreted from lithofacies and lithofacies associations based on core descriptions integrated with well log motifs.

Original Data and Results: An example section of 7 wells tied to 17 seismic sections was extracted out of a larger regional study encompassing more than 600km of seismic lines. The resulting Surat Basin sequence stratigraphy results in a different interpretation of the character of both the Hutton Sandstone and the Springbok Sandstone than previously published (i.e. fluvial–lacustrine). This section is interpreted to be from lower delta plain (distributive channel belts and floodplain), delta front, and tidal depositional settings. Furthermore, the sandstone and coal forming facies aren't necessarily extensive lithologic units, as depicted in existing correlations.

Conclusions: The evolving Surat Basin sequence stratigraphy framework results in a new geological concept of genesis for these aquifers that may change the fundamental understanding of the connected extent of aquifers in the Hutton-Walloon-Springbok interval. This may significantly affect how fluid flow modelling is used to manage those resources because less continuous, more heterogeneous aquifers transmit pressure and respond to well operations differently depending on the correlation method used to define the modelling domain.

Hydrochemical variations of groundwater and spring discharge of the western Great Artesian Basin

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Objectives: The chemical variations of groundwater provide important clues to the geochemical processes responsible for water quality and evolution across the western GAB. The objective of this study was to examine the hydrochemical variations of groundwater and spring discharge along the entire western GAB expanding on several key results from a 4-year project studying the hydrochemistry of the western GAB presented in Love et al. (2013) and Love et al. (2013).

Design and Methodology: The dataset comprises data collected during the Allocating Water and Maintaining Springs in the Great Artesian Basin project funded by the National Water Commission (Love, et al., 2013, Love, et al., 2013), with additional data from a government database, as well as, a number of published government reports and journal articles. Electrical balances and comparison of monitoring and duplicate data was undertaken to ensure the collated data were representative and accurate.

Original data and results: The regional hydrochemical trends generally support the modern interpreted flow paths, indicating that these generally represent the long-term flow paths. However, the chemical variations along the flow paths in the western GAB are complex with their composition being a function of several controlling processes, including recharge location, evapotranspiration and water-rock interactions. These processes being spatially variable cause groundwaters to be generally of Na-HCO_3 type east of Lake Eyre and Na-Cl-(-SO_4) type when originating from the western margin. Springs within the western GAB springs appear to be discharging water predominantly from the main GAB aquifer. However, springs on the Peake and Denison Inlier are either completely or partially fractured rock source and there are several springs discharging water with a component from a source other than the main GAB aquifer.

Conclusion: The source, evolution and several key geochemical processes responsible for water quality were identified through this study. However, work is still needed to fully characterise all water-rock interactions and geochemical processes occurring within the main GAB aquifer.

Coupled Modelling (Reactive Chemistry & Transport, Geomechanics & Transport)

Development of upscaling laws for geochemical reactions and their integration in reservoir-scale models

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Sub-meter scale lithological heterogeneity in the form of intraformational baffles is known to play an important role in fluid flow and geochemical reactions. The processes governing fluid flow at these scales, the development of fluid flow upscaling laws and their integration in reservoir-scale models are well established. However, there exists a knowledge gap in the development of upscaling laws for geochemical reactions arising from the presence of sub-meter scale lithological heterogeneity. This study explores geochemical reaction rates in intraformational baffles and the development of respective upscaling laws for integration in reservoir models in order to better understand carbon mineralisation in geological CO_2 storage reservoirs. Ten 2-D model realizations at sub-meter scale resolution are set-up to capture the lithological heterogeneity of the Paaratte Formation, Otway Basin. Reactive transport simulations are run on different realizations to develop an understanding of the processes controlling CO_2-rock reactions. Three different approaches are developed to upscale the impact of baffles on reaction rates from cm-scale to reservoir scale based on the process understanding. The development of geochemical upscaling laws alone is not useful unless the laws are integrated in reservoir scale simulations. For this purpose, a workflow is developed where the upscaled properties are classified for composite rock types and their depth logs are derived. The composite rock type logs are subsequently populated in the reservoir scale model. Reactive transport simulations are then run for two reservoir scale models, one comprising the upscaled properties while the other without the upscaled properties. The results from two simulations are then compared to establish the

importance of incorporating upscaled properties in reservoir scale geochemical simulations. The workflow for the development of upscaled rate laws and their implementation in reactive-transport models is presented in the context of CO_2 storage reservoirs but it is applicable to any groundwater system as well.

Understanding flow and chemical reactions at the pore scale

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Large-scale observations are governed and controlled by small scale heterogeneity, for example in terms of local flow velocities and reaction rates. Continuum scale modelling traditionally assigns intrinsic properties to composite rock types as a practical way to account for small-scale heterogeneity, yet, many studies have shown discrepancies between modelled and observed results. In this study, reactive transport models at the pore scale are used to understand the heterogeneity in the flow and variations in the local reaction rates due to the interactions between the mineral and the fluid. For this purpose, a bioclastic limestone sample with calcite as the major mineral is used as a pore domain. A multi-component reactive transport model at pore-scale was developed using a Java interface which combines COMSOL® and PhreeqC. A particular feature of the model is the implementation of the mineral-fluid boundaries where kinetically controlled mineral dissolution or precipitation can occur. The reaction rate is governed by the local flow velocity and the local ion activity product coupled to the pH and the concentration of the calcium ions. Different flow rates were simulated to study the transition from transport to kinetically controlled reaction rates by calculating the local Damköhler (*Da*) number. At slower inflow rates, diffusion dominated the concentration gradients and the reaction rates were transport limited. At higher inflow rates, concentration gradients became steeper and dissolution was kinetically controlled with $Da < 1$. The mass transfer due to dissolution is also implemented and the changing pore geometry of the porous media is simulated. The model offers an alternative approach to existing models at the pore scale with aqueous speciation of the components at every time step in the fluid phase leading to a better and more accurate representation of the chemical system.

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Scenario modelling of reactive transport processes governing fluoride release and attenuation during managed aquifer recharge

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Pulses of elevated fluoride (up to 58 µM) and filterable reactive phosphorus (FRP) (up to 55 µM) were observed were observed during a large scale groundwater replenishment trial where 3.9GL of highly treated, deionised wastewater (average TDS 33 mg/L) was injected into siliciclastic Leederville aquifer of the Perth Basin. Previous experimental work identified that the elevated fluoride and phosphate concentrations are due primarily to the dissolution of the carbonate-rich fluorapatite (CFA: $Ca_{10}(PO_4)_5(CO_3F)F_2$) which was found to occur in the Leederville aquifer sediments. A reactive transport model has been developed using MODFLOW (Harbaugh, 2005) and PHT3D (Prommer et al. 2003) for groundwater flow and reactive transport processes respectively. It was calibrated to geochemical analysis collected approximately monthly from 20 monitoring bores over the four-year period of the field trial. The model incorporates the incongruent dissolution CFA as the primary source of fluoride and includes all geochemical processes identified during previous experimental study and modelling work. The primary motivation for the current modelling study is to assess whether fluoride concentrations may eventually exceed drinking water limits (1.5 mg/L = ~79 µM) with continued large-scale injection.

The model simulations identified that fluoride is initially mobilized due to acidity generation near the injection well where the low ionic strength but oxic deionized wastewater is triggering pyrite oxidation. Further dissolution of CFA is triggered by the very low calcium concentrations of the deionized wastewater injectate. Under the low ionic strength conditions calcium initially preferentially partitions on aquifer exchanger sites and elevated pulses of fluoride concentration occur when calcium concentrations in solution remain low. Sorption of fluoride under the moderately alkaline conditions (pH 7.6-7.9) to the aluminium-rich Leederville aquifer sediments was found to be limited. Maximum fluoride concentrations were inferred to be controlled by equilibrium with CFA occurring in the aquifer and are not expected to exceed the elevated concentrations that were observed under post breakthrough low calcium conditions. However, a long tapering pulse of moderately elevated fluoride is expected to remain in the aquifer. Scenario modelling of mitigation strategies involving the amendment of $CaCl_2$ and CaO (quicklime) in the injectate to further reduce fluoride and phosphate mobilization during managed aquifer recharge were also assessed. Insights from this study may be broadly applicable to understanding fluoride release and mobilization from CFA and similar fluoride-bearing calcium phosphate minerals both during managed aquifer recharge (MAR) operations as well as due to natural processes.

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Metal mobilisation and re-precipitation with CO_2 stream injection in the Precipice Sandstone: Experimental data input for a reactive transport model

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A demonstration scale CO_2 injection trial has been proposed in the Glenhaven area of the Surat Basin for investigating the feasibility of CO_2 geological storage. The Precipice Sandstone is the targeted reservoir, with the Evergreen Formation the cap-rock. During CO_2 storage, injected CO_2 will dissolve into formation water and the resulting acidification induces water-rock reactions. These reactions have the potential for mobilisation of metals associated with the mineral phases. Subsequent water-rock interactions have the potential to limit that mobility. This presentation will describe the data that was used to build a reactive transport model to predict potential impacts to water quality. Drill core from the site was characterised including mineralogy, total metals and extractable metals; in addition, trace metal content in specific minerals was determined by synchrotron X-ray fluorescence microscopy. Based on porosity, permeability and mineralogy, several hydrostratigraphic units were identified in the Precipice Sandstone. The lower Precipice Sandstone is quartz-rich while the upper Precipice Sandstone and Evergreen Formation are more mineralogically diverse with increasing feldspar and clay content, as well as some heavily carbonate cemented sections. All of the hydrostratigraphic units contain traces of sulphides and carbonate cements containing iron, arsenic, lead and a number of additional transition metals. Experiments were performed at reservoir pressure and temperature conditions to react pure CO_2 and impure CO_2-SO_2-NO-O_2 with low salinity formation water and the different drill core lithologies. Metals such as lead and iron were released during siderite, calcite, chlorite and sulphide dissolution, while arsenic increased to lower concentrations. In the upper Precipice Sandstone, pH buffering and elevated O_2 content resulted in Fe-oxyhydroxide precipitation and incorporation or adsorption of metals and arsenic in secondary precipitates. Geochemical modelling of the experiments accurately reproduced the dissolution, precipitation and adsorption reactions for the different hydrostratigraphic units. Reactive transport modelling showed mobilisation of metals, and if sinks for the released metals were not present, lead and arsenic would have exceeded water quality guidelines within the plume. Accounting for the precipitation of carbonate minerals and Fe-oxyhydroxides plus the associated adsorption resulted in significant attenuation of predicted dissolved concentrations of lead and arsenic.

Denitrification parameter uncertainty under uncertain redox conditions

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Excess nitrate leaching from agricultural areas, resulting in contamination of groundwater resources, is a global phenomenon. This is also the case in New Zealand, where recent increases in land use intensity associated with farming, have resulted in a substantial increase of nitrate levels in groundwater and freshwater systems. A key removal process for nitrate in the subsurface is denitrification, which is a microbial process, occurring under low oxygen conditions in the presence of a suitable electron donor.

Due to physical and chemical heterogeneity nitrate reduction may vary significantly, even within small catchments. In this work we integrate a machine learning approach within a physically based groundwater flow and nitrate transport model to incorporate geochemical uncertainty in the form of uncertain and spatially variable redox conditions. The aim of this work is to understand and quantify the uncertainty of model parameters used to numerically parameterize nitrate reduction in geochemically heterogeneous aquifers, and in particular to i) quantify the uncertainty related to the spatial delineation of uncertain and spatially variable groundwater redox status in an alluvial aquifer, ii) assess the uncertainty on the estimated nitrate reduction potential due to uncertainty in redox conditions, iii) assess the uncertainty of denitrification model parameters and how the uncertainty changes with increasing scale, and iv) analyze how parameter uncertainties affect model prediction uncertainties at various scales.

Horizontal dewatering well construction – a combination of technologies and practices delivering the next generation mine dewatering solution

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1. Dunstans Construction Group, Wangaratta, VIC, Australia
2. Fortescue Metals Group, Perth, WA, Australia

Conventional mine dewatering practices previously considered robust are increasing being exposed as sub-optimal, especially as mining increasingly occurs below the water table in permeable deposits. Furthermore, an industry-wide push to increase mining efficiency and productivity is often hindered by physical conflict with conventional (vertical in & ex-pit) dewatering wells. Construction of the first horizontal dewatering well (a/k/a Dewatering Well Placement [DWP]) for a hardrock mine in Australia is presented. DWP offers a step-change improvement in mine dewatering with the wellhead outside the pit and the production section directionally drilled to purposely target hydraulic zones beneath the pit floor. Fortescue Metals Group commissioned the construction of the first horizontal dewatering well in a Channel Iron Deposit (CID) at their Solomon Mine in the Pilbara Region of Western Australia.

The design followed an established workflow that considered ore deposit geology, mine hydrogeology and geomechanics; target pump rate and electronic submersible

pump (ESP) selection; directional tooling, downhole surveying and drilling fluids; and well architecture, completion technologies, development and drilling equipment requirements. Drilling and completion combined technology from the oil and gas industry (*e.g.,* directional drilling, steering, ESP and packers [slipover & riserless pump]) along with traditional well construction practices and civil construction. The well was constructed as a blind (single entry) completion, with an entry angle of 25 degrees from horizontal, to 930 m Measured Depth (MD). An optical gyroscopic steering tool was used to avoid magnetic interference of the iron ore body and accurately steer the drillhead to the target zone. A slotted liner was anchored in place using an inflatable slipover packer, which also provided an annular seal. A four stage ESP with an operating range up to 300 L/s, along with a riserless pump packer to reduce friction losses, was housed inside a horizontal section of the surface casing at a Total Vertical Depth of 92 m. Further optimisation of DWP is currently underway with the construction of a second well, which will be presented. DWP requires technologies and practices from different industries that when combined result in a step-change improvement and the next generation mine dewatering solution.

Longitudinal dispersivity increases with distance. should we allow for this in our analyses?

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A contaminant (or tracer) plume spreads by both molecular and mechanical processes. Variations in groundwater velocity (i.e. mechanical spreading) caused by aquifer heterogeneities can be represented with the parameter longitudinal dispersivity (a_L) which is known to increase with distance. The rule of thumb that a_L is approximately 10% of the length scale (L) is often used, seemingly based on the work by Gelhar et al. (1992). Zech et al. (2015) revisited the Gelhar et al. (1992) study, demonstrating that not only the spatial distance but also the degree of heterogeneity influences a_L.

However, the issue remains that a_L determined at one distance from a source will not always be a good predictor of transport behaviour at another. This talk explores the use of spatially variable a_L in order to improve the predictive ability of tracer/contaminant behaviour.

Over 79,000 solute breakthrough curves were generated using various synthetic heterogeneous aquifers using the numerical simulator HydroGeoSphere. a_L values were determined for breakthrough curves (at various distances from the tracer source) using two approaches: (1) fitting the Ogata and Banks (1961) solution, and (2) fitting a 1D numerical model where a_L increases linearly with L. The fitted a_L or a_L-L relationships were then used to predict the shape of breakthrough curves at both upstream and downstream locations.

The a_L-L approach in was generally better able to predict the shape of breakthrough curves at other distances compared to the use of a $a_L$value fitted using the Ogata and Banks (1961) solution. However, it should be noted that a_L does not always increase linearly, with $a_L$reaching a maximum value after some distance. Nonetheless, the improved predictive ability from the use of spatially variable dispersivities is an approach that warrants further investigation.

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Geomechanical considerations for hydraulic conductivity estimation of the jointed rocks

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Hydraulic conductivity of the jointed rocks is one of the main input parameters for an all groundwater modelling and assessment. Based on the Darcy's law for porous media, this parameter relates the flow rate to the pressure gradient. Rock discontinuities play important role in water circulation within the jointed rocks. They occur at various forms and scale and provide pathways for water flow. Water flows inside discontinuities and the magnitude and the orientation of the hydraulic conductivity is a function of the geometrical properties of discontinuities. Based on the cubic law, the hydraulic aperture of rock discontinuities has the most significant effect on the hydraulic conductivity of jointed rocks. The hydraulic aperture of rock discontinuities is a stress-dependent parameter and reduces with increasing applied stress. Furthermore, the horizontal stress magnitude is typically proportional to the stiffness of the material in which the measurement was taken. The horizontal stress in softer strata is lower than the stress in the stiffer units. Therefore, the geomechanical considerations are very important for hydraulic conductivity estimation of the jointed rocks. This paper presents the analytical and semi-analytical methods which developed by the authors to incorporate the geomechanical characteristics of the jointed rocks to estimate the hydraulic conductivity. The application of these methods for several real cases shows that the anisotropic conductivity of the jointed rocks can be estimated by using its geomechanical characteristics. The estimated hydraulic conductivity components have been compared with the measured values which confirmed the reliability of the proposed formulations.

Cumulative Groundwater Impacts - Assessment & Management

Stream depletion calculations for resource consenting – reality and uncertainties

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Groundwater take applicants must provide an assessment of environmental effects which includes an estimate of likely stream depletion caused by the proposed groundwater abstraction. The consideration of stream depletion and subsequent surface water allocation varies across regional councils; however, most applications use standard spreadsheet models to calculate stream depletion with the

Theis/Jenkins equation or the Hunt (1999), Hunt (2003) equations. These methods are quick and easily repeatable and so have value in providing consistent assessments. However, a desktop review of stream depletion calculations for groundwater takes in the Mataura River above Gore in Southland found that the applications had been inconsistently reviewed in the past; in many cases stream depletion had been underestimated and values entered into the models were poorly justified. For this review, documentation surrounding 85 groundwater bores was assessed to determine whether stream depletion calculations were robust, considered impacts on all nearby streams, were based on reasonable storage and transmissivity values and were transparent in their application. This work provides a critical desktop assessment of the uncertainties surrounding values in some of the larger groundwater takes, the impact of pumping test quality and streambed conductance assumptions. Results are compared to streambed conductance fieldwork completed in the Otago region. Field investigations demonstrated the demonstrated how stream appearance can be highly misleading. The findings from this work emphasise the need to incorporate uncertainty analysis into resource consenting and improve the transparency and consistency of assessments, and also the value of field investigations in sensitive catchments.

Communicating groundwater science: reporting to reduce cognitive strain and reach a broader audience

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Community and government interest in understanding groundwater related risks and impacts from land use activities continues to rise. With this growing interest there is a greater need for clear communication about what is often referred to as the 'Dark Arts' of science.

Hydrogeology is inherently 'mysterious' as it relies on understanding the complex movement and behaviour of water we can't see. To understand the groundwater regime and predict responses to land use change we use a range of techniques to collect, analyse and interpret the 'clues'. With greater government and public interest in groundwater matters there is a greater need to explain the 'clues' and effectively and consistently communicate how the story was pieced together.

This presentation pulls together over a decade of experience in groundwater impact assessments for major projects across Australia, capturing feedback from government agencies, peer reviewers and the broader community. The presentation outlines a framework to help hydrogeologists structure and focus their reports, as well as useful tips on how to best reach the target audience. All projects are unique due to variables such as location, regulatory setting and the type of land use activity. Therefore, the purpose of the presentation is to provide high level guidance on ways to communicate the groundwater assessment process, risks and potential impacts from land use activities to a broader audience, and hopefully gain more trust in good science.

Application of uncertainty analysis to salinity modelling

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A series of three numerical groundwater models that cover the irrigated area in the Victorian Mallee were refined to improve the confidence in estimates of the salinity impact of irrigation in the region. Groundwater recharge from irrigation causes mounding on the regional aquifer(s) which, in turn, drives increased groundwater discharge to the Murray River. This region of Victoria has experienced orders of magnitude increase in irrigated area and consequential recharge over the past 15 years. Increased groundwater flow delivers increased salt to the Murray River which contributes to economic and environmental damage. The refined numerical models included a quantitative uncertainty analysis which defined parameter uncertainty of groundwater flow to the river for the first time in a model for salinity impact.

The approach adopted involved a preliminary qualitative uncertainty analysis that defined the key parameters of the numerical model and how they were defined and constrained. This was followed by quantitative uncertainty analysis using deterministic modelling with linear uncertainty analysis. The predictive uncertainty is calculated from the sensitivities of each model outcome to each parameter, the pre-calibration uncertainty of the parameters, the observation uncertainty and the mismatch between observation and simulated values. Linear uncertainty analysis starts with calculating the Jacobian matrix, the matrix containing the sensitivities of each model outcome to each parameter. In this study, this is achieved by running the model at least twice for each parameter included in the uncertainty analysis.

The assessment found that the river conductance term was a key contributor to model uncertainty. Groundwater flux estimates were found to vary by up to +/- 15% with 95% confidence based on the acceptable calibration. This for the first time puts the degree of uncertainty in salt load estimates and hence on river salinity impacts in context and is an important indication of the way that uncertainty can be used in salinity assessment in the Murray Basin.

Estimating sources of inflow on mining complexes

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Mining projects in Australia are required to estimate the volume of groundwater extracted from the ground via mine inflow and dewatering operations. They are also required to estimate the source of those inflows, for extraction licencing and to detect potential environmental impacts. The licensed groundwater sources can be generally classified as either alluvial or hard rock.

Estimating the source of inflow for a single open cut mine is a relatively simple numerical modelling exercise. However, when multiple mining operations and multiple sources interact, the estimation of inflow sources can be complex.

A simple 'sandbox' numerical groundwater model was used to explore different methods to estimate the source of inflows in a case with multiple mines and groundwater sources. Results of this simple model unveil possible pitfalls if the calculation is not made correctly and suggests a "best approach" for the calculation.

Dealing in groundwater, New South Wales

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One of the most significant changes in groundwater regulation introduced by the *Water Management Act 2000* is the separation of the water licence from land ownership. This has facilitated the development of the groundwater market within New South Wales. Groundwater entitlement can be traded or leased without the need to purchase any associated land and licensees can also hold entitlements with zero shares and purchase account water as required on a seasonal basis.

The significant movement of pumping stresses associated with trading has resulted in regulation challenges. Impacts associated with these changes need to be managed within acceptable levels on existing groundwater supply bores as well as environmental assets.

The areas of greatest trading activity are the highly productive inland alluvial groundwater systems within the Murray Darling Basin. The volume of account water annually traded in these groundwater systems typically ranges from 15 to 30 per cent of all water debited from accounts. This has risen to as much as 50 per cent in some years. These systems are all fully committed, and the market is the only avenue for new groundwater-based industry to acquire access to groundwater which has in turn has seen an increase in applications for new water supply bores.

The increasing volume of groundwater trade and need for state-wide consistency have been primary drivers for recent changes in the groundwater trade assessment process in NSW. Groundwater trade applications are triaged based on preliminary criteria to determine the impact risk and then assessed on defined impact criteria. These criteria refer to environmental assets, culturally significant sites, existing groundwater supply works and the local sustainability of the groundwater system. Cumulative impacts of the change in pumping stresses associated with the trade are included in the assessment.

Flowing wells on the Adelaide Plains – implications for ASR Management

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The Adelaide Plains contain productive limestone aquifers that are well suited to Aquifer Storage and Recovery (ASR). During winter storm water is harvested and injected underground, while in summer water is recovered for recreational and commercial uses. ASR is a useful tool for freshening brackish aquifers and provides an alternative water source to expensive mains water.

Expansion of ASR in the Adelaide Metropolitan Area has progressively increased from the early 2000's and consequently winter injection has resulted in Artesian pressure conditions at some locations. Artesian conditions can persist for weeks to months.

Over the past 10 years a number of 3rd party wells have become artesian and flowed in winter. In most cases wells are completed in open spaces with little implication. Injection can continue while head-works are fabricated and wells are 'shut in'.

However, in 2018 a flowing well occurred within a factory floor. This has raised queries as to how many 'hidden wells' are buried in proximity to infrastructure. Numerous production wells are completed on the Adelaide Plains whilst historically suburban areas contained market gardens. There may be a number of buried wells unaccounted that emerge as winter injection increases.

This talk discusses current aquifer behaviour on the Adelaide Plains, recent upward trends in confined aquifer pressures and current response strategies to flowing wells. The talk focus on the south-western suburbs of the Adelaide Metropolitan Area.

Tip toe through the tulips - the role of the OWS in EPBC assessments

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The Office of Water Science (OWS) provides scientific advice to the Commonwealth regulator on potential direct impacts to water resources, and indirect impacts to Matters of National Environmental Significance (MNES) that arise through impacts to the water resources on which they rely. Advice is provided on a wide range of projects across many industry sectors including the resources sector. This advice allows regulators to incorporate leading-practice science into their decision-making processes.

The OWS has undertaken a review of recent scientific advice that they have provided to the Commonwealth regulator, with a focus on resource sector projects. The review aimed to highlight, in relation to potential groundwater impact assessments, areas where the information and data provided by proponents was limited. When knowledge gaps are identified in impact assessments this often results in the proponent being asked to provide further information and data or undertake additional studies. Fulfilment of these requirements can be required either prior to an assessment decision or as part of management plans which commonly require approval at an early project stage. This may cause project timeframes to increase and can affect the proponents operational planning.

This review has resulted in a better understanding of the key areas (relating to groundwater) where further data and information on potential impacts is often requested from proponents and issues that many be conditioned by the regulator with requirements for further studies. The presentation discusses the results of this review and provides examples of the variability in data and information received from proponents.

The findings of this study identify areas for improvement in both impacts' assessment and communication of impact assessment outcomes. This may assist proponents to meet their forecast project timeframes and aid in operational planning.

Groundwater level trend analysis to inform likelihood of cumulative coal seam gas impacts in the Surat CMA

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The Queensland Office of Groundwater Impact Assessment (OGIA) is responsible for assessing cumulative groundwater impacts arising from coal seam gas (CSG) extraction in the Surat Cumulative Management Area (CMA) and preparing an Underground Water Impact Report (UWIR) every three years.

The main objectives of this groundwater level trend analysis project were:

- To analyse regional groundwater level trends in the main aquifers of interest directly above (Springbok Sandstone and Condamine Alluvium) and below (Hutton Sandstone) the coal seam gas reservoir (Walloon Coal Measures) in the Surat Basin.
- To analyse the potential causes of these groundwater level trends, with a primary aim of identifying CSG versus non-CSG water extraction impacts.

This project adopted a multiple lines of evidence approach using both qualitative and quantitative techniques. Specific statistical methods used include Mann-Kendall analysis of groundwater level trends, and Spearman correlation analysis of groundwater levels with major water balance factors such as rainfall, and local CSG and non-CSG water extraction. In addition, traditional conceptual hydrogeological analyses were used to assess if connectivity pathways are present between the reservoir and the individual aquifers. Hypothesis testing was undertaken using a simple sub-regional groundwater flow model. Finally, a new classification criterion was introduced and employed to assess the likelihood of CSG impacts at individual monitoring points within OGIA's groundwater monitoring network.

CSG associated water extraction is a more recent stress and presents as an additional influence on an already impacted aquifer system. Long-term declining groundwater level trends are observed in all three aquifers of interest. These declining trends tend to be highly correlated with local-scale, non-CSG water use estimates and rainfall, and occur both before and after the commencement of CSG extraction, and inside and outside of CSG production areas. The key challenge of this study was to separate these more recent CSG influences on groundwater level trends, from long-term non-CSG water use impacts and climate influences.

Recharge & Groundwater - Surface Water Interaction

Influence of new constructed wetlands on groundwater recharge in a rapidly urbanising catchment

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Objectives: This study used multiple lines of evidence, gathered during and after the commissioning of a newly constructed wetland in an urbanising catchment (Western Port Basin) to examine its effect on recharge and interaction with the underlying aquifer system. Understanding how such wetlands interact with groundwater is critical to effective water-cycle management in areas experiencing rapid urbanisation.

Design and methodology: Nested monitoring bores were installed adjacent to the wetland during early construction, and time series water level, electrical conductivity (EC) and soil moisture data collected. Surface and groundwater major ions, stable and radiogenic isotopes ($\delta^{2}H$, $\delta^{18}O$, ^{3}H and ^{14}C) were analysed before and after the wetland began regularly filling with stormwater runoff from new surrounding suburbs.

Original data and results: Prior to the wetland regularly filling with water, the shallow aquifer contained groundwater with EC >3,000 µS/cm, with fresher groundwater (EC ~1,000 µS/cm) occurring in the underlying deep aquifer. Groundwater in both aquifers contained no detectable tritium, and radiocarbon activities between 72.8 and 75.5 percent Modern Carbon. Following regular filling of the wetland with stormwater runoff, shallow groundwater EC began to fluctuate, periodically dropping below 1,000 µS/cm following rainfall events, before returning to pre-event values. The data from this early period (including hydraulic gradients) indicate dynamic ground- surface water interaction, with two-way exchange of water between the wetland and shallow groundwater. Following more than two years of runoff regularly filling the wetland, shallow groundwater EC stabilised at below 800 µS/cm, with tritium values of 2.29 TU and radiocarbon activity of 98.3 pMC. These data indicate that the original groundwater had been displaced by recharge from the wetland, creating an expanding plume of fresh recharge within the more saline regional groundwater. This plume has yet to affect the deeper groundwater, which experienced water level fluctuations in response to filling of the wetland (likely due to pressure loading) but showed no change in hydrochemical or isotopic composition.

Conclusions: The findings represent the first study to use environmental isotopes to demonstrate leakage from a constructed wetland as a significant new recharge mechanism in a catchment experiencing rapid urbanisation. Overall our data indicate that recent land-use change has modified recharge processes from low rates of diffuse rainfall recharge under pre-urban conditions to focussed recharge via leakage from constructed wetlands. This has significant implications for locations and rates of groundwater recharge, and for water quality protection (particularly if stormwater contains pollutants).

The development of recharge models under irrigation districts with perched water tables

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The assessment of the impact of Mallee irrigation on River Murray salinity is a management priority for the MDBA Salinity Strategy. A 2017 review identified two different modelling approaches for the treatment of irrigation recharge, both of which could introduce consistent biases and hence affect salinity management. This issue could be addressed by (1) developing unsaturated zone models (UZMs) that can represent perching; and (2) incorporating and calibrating such models within an accredited groundwater model. This talk addresses the first step.

Previously, simple UZMs were used to estimate time lags between irrigation changes and recharge changes. These models are not appropriate for low conductivity soil layers that cause perching. Perching leads to lateral movement away from the irrigation field and possibly water returning to the land surface, affecting both timing and magnitude of recharge. The complexity of historical irrigation developments and soil properties challenge the development of UZMs that are simple enough for groundwater modelling. This talk describes the development, testing and application of appropriate UZMs. The outputs from these models for a range of 'benchmarking' studies have been successfully compared with those from FEFLOW.

Several steps are required to apply UZMs: (1) districts are disaggregated into recharge zones based on soil properties and date of initial irrigation; (2) an agronomic water balance is developed to represent irrigation history; (3) run the models for each zone using agronomic water balance as input; (4) use drainage output to partially calibrate soil properties; and (5) calibrate irrigation efficiency parameters alongside hydrogeological parameters to best match groundwater data.

The applicability of these models has been trialled for the Loxton-Bookpurnong irrigation districts. Modelled recharge and drainage volumes were found to be sensitive to perching, emphasizing the importance of perching for salinity assessment modelling. As well, the approach provides for a holistic calibration process to constrain salt load estimates.

Locating groundwater discharge into a large coastal lagoon

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Objectives: The objective of this study was to identify the spatial distribution of groundwater seepage into Te Waihora/Lake Ellesmere, a large (200 km^2), shallow coastal lagoon in Canterbury, New Zealand. This lagoon holds important ecological, cultural and recreational values, yet has suffered from significant water quality decline in recent decades.

Design and methodology: This study used broad-scale methods to identify the spatial distribution of groundwater inflow into the lagoon during the summer. An airborne thermal infrared imaging survey was flown over the lagoon to detect relative cool patches indicating possible groundwater inflow. This dataset was compared with physical and chemical parameters (radon-222, conductivity, temperature, dissolved oxygen) measured in the lagoon by boat.

Original data and results: Data analysis revealed areas of groundwater seepage into Te Waihora at locations previously identified, as well as areas not known before this study. The data identified both point-source springs and diffuse seepage. This study conducted the first broad-scale survey of seepage into the lagoon and found groundwater inflow in locations previously thought to be unlikely. This dataset will allow for follow-up work to improve the estimate of the groundwater proportion of the lagoon's water budget in light of identifying these new seepage locations.

Conclusions: This study demonstrates the successful use of broad-scale methods for identifying the spatial distribution of groundwater discharge into a large coastal waterbody.

Understanding recharge process on North Stradbroke Island

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This presentation describes the possible recharge process on North Stradbroke Island (NSI) and a possible explanation of why groundwater levels are receding. Groundwater levels on NSI have been monitored since the 1960s. Groundwater levels were at their highest in 1974 and for most bores, levels are now approaching their history low. There has been public concern over why groundwater levels and some perched lakes, are falling.

Recharge is derived mostly from infiltration of rainfall. In a few locations perched lakes and stream bed loss also contributes to recharge, and there is some localised anthropogenic recharge associated with sand mining. One of challenges in understanding recharge is the scant rainfall (spatial and temporal) data for the island. Long term rainfall data is restricted to Dunwich and Point Lookout. In recent years, daily rainfall is observed at a further six locations. While there is reasonable correlation at the annual scale, at the day scale it is poor.

An examination of bore hydrographs reveals the depth to regional water table varies for near ground level beneath the coast fringe, to over 100 metres below the highest dunes. Moreover, there is an increasing delay in the water level response in the regional aquifer, with increasing depth. Delays of up to at least 130 days were identified, where the depth to the water table was nearly 100 m below ground level.

Daily estimates of recharge were derived from the SPLASH_Mult software which is a one-dimensional model for simulating the temporal behaviour of soil moisture in the plant root zone and in the unsaturated zone below the root zone to the water table. Modelling has shown evapotranspiration from the root zone has a major influence on recharge, as well as antecedent condition and the magnitude of daily rainfall. About 80 percent of the island has an assigned root depth of 6m and 18 percent has a root depth of 1m

The average rainfall for Dunwich since 2011 is about 88% of the long-term average rainfall of 1568mm. The model results how the corresponding average annual recharge for a root depth of six metres is 71% of the long-term average annual recharge of 410mm. Modelling of recharge shows the low groundwater levels may be related to the below average recharge. A further consideration is the possible impact of fires and higher evapotranspiration due to regeneration.

Assessment of spatial distribution of river recharge through hyporheic zone

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In lowland landscapes rivers remain the most important refuges for biodiversity. Among the other aspects shaping functional diversity of riverine ecosystems, especially the ones that remain of low dynamic the processes of water exchange in the hyporheic zone are reported as critically important.

The 3D groundwater flow model based on FEFLOW (DHI) is focused on water flow calculations in hyporheic zone. The model covers the 4 km stretch of the Upper Biebrza River (Poland, Europe). This area remains one of the biggest consistent wetland areas of the European Union. This section of the river is characterized by its undisturbed riverbed due to the ban on mowing and dredging since 1992 (part of Biebrza National Park). Automatic measurements of groundwater head in piezometers located in five transects (40 piezometers, time series covering 1 year with 3-hours frequency) combined with hydrological and meteorological data, were conducted to calibrate the model.

The new equipment, designed by authors for rivers with a thick peat sediment, was used to support the model verification process.

The model enables estimation of the velocity field and the water exchange flux between the river and aquifer in the hyporheic zone. Obtained results indicate the sections of the river which are characterized with a higher or lower intensity of water exchange between the river and the aquifer. Ecohydrological research of the riverine and riparian habitats conducted simultaneously to hydrogeological survey create the starting point for quantitative analysis of the relationship between changing status of these habitats and the dynamics of groundwater-surface water interaction.

Research was carried as a part of project OPUS No.2016/21/B/ST10/03042, funded by National Science Centre, Poland.

Using multiple lines of evidence to characterise groundwater recharge in a rapidly urbanising catchment: implications for future land and water management

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Objectives: Understanding how land-use change influences the water cycle is of critical importance to land and water management. Several physical and hydrochemical/isotope techniques were used to estimate groundwater recharge rates and identify key controlling factors in a rapidly urbanising catchment in southeast Australia (Western Port catchment).

Design and methodology: Multiple lines of qualitative and quantitative evidence regarding groundwater recharge were collected: environmental tracers (radiocarbon, tritium, chloride), time-series soil moisture profiles, high frequency water level and electrical conductivity measurements and lithological mapping.

Original data and results: The presence of significant tritium (>1.0 TU), along with radiocarbon activities >85 pMC and low chloride concentrations (<150 mg/L), allowed identification of areas with significant recent recharge. These were strongly associated with elevated topography and the absence of volcanic clay (the dominant near surface lithology) along the catchment margin. This finding was supported by time-series analysis of soil moisture profiles, indicating minimal vertical propagation of precipitation below 1.5 m depth in volcanic soils. Chloride mass balance and water table fluctuation-based recharge rates mostly ranged between 1.5 and 50 mm/yr; however, rates exceeding 100 mm/year were identified in a spatially restricted zone. In this area, the volcanics are absent and Quaternary sand directly overlies the lower Cainozoic aquifer. This zone comprises a small percentage of the study area (approximately 15%) but is estimated to contribute approximately half of the recharge. This new understanding of the recharge resulted in a significant revision of the conceptual hydrogeological model for the region.

Conclusions: The findings underscore the importance of characterising recharge locations and processes based on field data, to support protection of groundwater quality and quantity. For example, careful land-use planning could be carried, to strategically protect areas of high recharge rates and quality within catchments experiencing rapid urban growth.

Strontium isotopes as tracers to assess inter-aquifer and groundwater-surface water exchanges in sedimentary basins: an example from the Surat and Clarence-Moreton basins in Australia

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Understanding connectivity between aquifers, aquitards and groundwater dependant ecosystems (e.g. streams or springs) remains a challenge and a key component of conceptual hydrogeological model development, particularly in large sedimentary basins potentially affected by coal or gas resource developments.

This presentation will demonstrate how Sr isotope ($^{87}Sr/^{86}Sr$) analysis can help to identify and characterise interactions between different aquifer systems and overlying surface water features within the geologically linked Surat and Clarence-Moreton basins.

For this, samples (>200) were collected from the major aquifers (e.g. Gubberamunda, Hutton, Precipice and Springbok sandstones), from the coal seam gas target formation (Walloon Coal Measures) as well as rainfall, shallow alluvium, streams and springs. In addition, sub-samples of core from exploration and stratigraphic wells within these two sedimentary basins were analysed to provide end-member strontium compositions from host rocks.

The analysis of cores demonstrated that there is a distinct and regular vertical contrast in $^{87}Sr/^{86}Sr$ ratios between different hydrogeological units. The analysis of groundwater from sedimentary and volcanic bedrock showed that all major hydrogeological units have a distinct and relatively narrow range of Sr isotope ratios, confirming the benefit of this tracer as a fingerprinting tool to characterise connectivity between aquifers in these basins. This was further confirmed by Sr isotope analyses in shallow groundwater and surface water. A synoptic stream sampling campaign under baseflow conditions confirmed that Sr isotope signatures in creek water are similar to those of the underlying bedrock formations, allowing to identify the regions where aquifers and surface water systems may interact.

Although each study requires screening of the regional geology and mineralogy to determine whether Sr isotopes are useful as an isotopic fingerprinting tool, the results of this study suggest that a similar approach is likely to be useful for refining the conceptualisation of hydrogeological systems in other sedimentary basins in Australia (e.g. other sub-basins of the Great Artesian Basin) and globally.

Hydrogeological, climatic and anthropogenic drivers of acidification within an inland acid sulfate soil wetland – investigations to inform remediation

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The Barwon Downs borefield has been a crucial back-up source of water supply for the Geelong region during drought, and has been operated since the 1980's. This has caused drawdown throughout the Barwon Downs Graben and some impact to groundwater receptors. The most notable of these is Boundary Creek, a tributary to the Barwon River in its upper catchment, in which reaches have been converted from predominantly gaining reaches to predominantly losing reaches. As a result, the flow regime in the creek has changed from a perennial system to one that flows during winter months or following high rainfall events.

Furthermore, flows through Boundary Creek have historically supported a wetland known as the Yeodene or "Big" swamp, an inland peat swamp which contains acid sulfate soils. In response to reduced flows and drying throughout the Boundary Creek catchment, sulfidic soils within the swamp have oxidised. This has resulted in the release of acidic and metalliferous leachate to the creek when it flows. This has been realised in the form of fish kill events in the Barwon River.

While the cause-effect paradigm here would seem simple at first glance, it has been complicated by a number of additional factors. These include climate change, the construction of an on-stream dam, the development of agriculture and farming throughout the catchment and the occurrence of peat fires in the wetland. The study presented here assesses these potential drivers by considering the timing of such changes with shifts in flow and water quality in the creek.

The study builds on this understanding and presents the findings of subsequent investigations including soil sampling to ~6 m depth at 17 locations across the wetland for geochemical analysis, groundwater-surface water level and quality monitoring.

The findings of the above investigations have been compiled to build an understanding of the hydraulic and geochemical nature of the creek and wetland system. In doing so, the viability of remediation strategies such as the release of supplementary flows to the creak or the treatment of soils or water with neutralising agents are better interrogated.

Indigenous Groundwater Connections, Knowledge and Values

Indigenous Groundwater Values & Connections

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Abstract not supplied.

Partnering indigenous knowledge (Mātauranga Māori) and biophysical science: developing a planning framework for rock art and cultural landscape protection in relation to disturbance of freshwater environments

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3. Te Ana Ngāi Tahu Māori Rock Art Trust, Timaru, New Zealand
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The New Zealand government funded *Ngā Kete o Te Wānanga* ('the baskets of knowledge') project explores complementarities and synergies between science and mātauranga Māori (indigenous knowledge) to inform and enhance freshwater decision-making. A case study focussing on the protection of Māori rock art and wider cultural landscapes facilitated exploration and development a knowledge partnering (or convergence) frameworks in the context of freshwater management. Tāngata whenua[1] values, including land-based freshwater taonga[2] and wāhi tūpuna[3] can be significantly impacted by freshwater management decision making - but are rarely considered in current planning processes.

Preservation and management of rock art sites – including their freshwater taonga – requires a diverse knowledge of their history and archaeology, cultural values and biophysical characteristics to assess their vulnerability to resource management decisions. The cultural landscapes often contain important groundwater-dependent ecosystems (wetlands, spring and streams) and therefore an understanding their hydrogeological context is important. The partnering of knowledge was achieved using a collaborative process that involved local Maori knowledge-holders, an indigenous advocacy group (the Ngai Tahu Rock Art Trust) and a hydrogeologist (biophysical scientist).

A sensitivity mapping framework and guidelines were co-developed to help planning authorities identify potential risks to rock art panels and freshwater taonga from activities that have potential to modify the local groundwater and surface water environments. These are currently in the process of being refined and adopted by a local government planning authority. The guidelines and methodologies could be transferred to other land-based tāngata whenua freshwater values.

The outcomes of this research offer a practical gateway for partnering seemingly disparate knowledge systems - mātauranga Māori and biophysical science - to inform freshwater decision-making whilst also acknowledging the needs and aspirations of indigenous communities. Framing knowledge as 'process' (rather than 'the thing known') can allow new 'convergent' knowledge to emerge from sensitively designed and implemented transcultural and transdisciplinary partnerships. This work also helps to shift the predominant narrative of being 'managers of a resource' to being 'managers of our interaction' with ecosystems.

[1] tāngata whenua - Māori term that literally means "people of the land"

[2] taonga - a highly valued object or natural resource (including wetlands, springs and rivers)

[3] wāhi tūpuna - a place important to Māori for its ancestral significance and associated cultural and traditional values

Scientific benefits of partnering with Traditional Owners

Josephine A. Searle [1]

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Often Aboriginal engagement is seen as a legal obligation to fulfil in order to get land access approvals, however by building genuine relationships through partnerships, there can be so many more benefits realised, not the least of which, are amazing scientific insights.

Building trust and respect between Government scientists and Traditional Owners is not always easy. Engaging early, tailoring your approach, and being open and honest are keys to success. However, involving Traditional Owners in the research, working side by side, is where the best benefits come from.

Recent examples from the Kimberley Region of Western Australia demonstrate the impressive scientific contribution Traditional Owners have made in groundwater investigations, from identifying groundwater dependent ecosystems, defining gaining reaches of rivers, as well at siting bores to intersect paleochannels. The logistical support and local knowledge of tracks and conditions also significantly benefits our work. This input has saved time and money, and lead to much better outcomes overall. With the final result being a shared understanding of how the system functions, as well as greater uptake and acceptance of the management strategies.

A collaborative study combining contemporary hydrogeological methods with traditional knowledge to understand living water in the Great Sandy Desert

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The traditional water sources (Jila and Jumu) of the Great Sandy Desert are of significant cultural value to the traditional owners, the Ngurrara people. Prior to European settlement these were the only source of water for the people of the Great Sandy Desert and they are integral to Ngurrara culture. The Ngurrara people have

long-term observations of the surface waters' seasonally changing taste (salinity) and water levels. This collaborative research project was established to increase our understanding of these valuable water features and support the development and implementation of water resource monitoring and management.A hydrogeological review of aquifers and groundwater-surface water (GW-SW) interactions was conducted for five culturally-significant water bodies: Wili Jila, Kurnajarti Jila, Puluwala Jila Lumpu Lumpu Jila and Lake Pirnini Jumu. This assessment included monitoring bore installation and measurement of water levels and major ion composition over a 15-month period. The Jila and Jumu of the Great Sandy Desert are diverse in hydrogeological setting and water chemistry. Water balance data show rainfall is insufficient to maintain the water levels observed at permanent surface water expressions (Jila) throughout the year. Surface water assets that are disconnected from underling aquifers (Jumu) only provide temporary sources of water prior to evaporation. Characterisation of the groundwater shows both NaHCO3 are Na-Cl type waters occur in the project area. Regional groundwater levels suggest groundwater flows from the south and north of the project area toward a topographically low, terminal basin. However, hydrogeochemical data shows groundwater to be least saline at the lowest elevation of the project area, where it is expected to be the most saline. Bringing together traditional ecological knowledge and contemporary hydrogeological methods, this study has provided an updated understanding of the hydrogeological systems that have been relied upon by the Ngurrara people. This renewed understanding has been applied to the development of a monitoring and management system that seeks to preserve these important water bodies under the concept of Living Water.

Special Session: Springs of the Great Artesian Basin - The Royal Society of Queensland Special Issue

The evolution of knowledge and management of springs in the Great Artesian Basin

Steven Flook [1]

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The Great Artesian Basin (GAB) is a regional groundwater system recognised internationally for its significance both as a reliable water source and in facilitating development within Australia's semi-arid to arid interior. Notably, the GAB's unique hydrogeological features also result in natural discharge areas, including spring wetlands intrinsically linked to cultural values and endemic flora and fauna.

This presentation will provide an overview and context for this session of the conference. The content will include a brief synopsis of the values of spring wetlands, the evolution of spring knowledge, and the importance of multidisciplinary science to improve understanding of the ecohydrological processes at GAB springs. The overarching theme will be the challenge of balancing emerging water demands and threats, scientific uncertainty and conservation outcomes.

Springs of the Great Artesian Basin – an initiative of the Royal Society of Queensland

Angela Arthington [1]

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This presentation describes the background and impetus for this Special Session on *Springs of the Great Artesian Basin* sponsored by the Royal Society of Queensland. The Royal Society has a long and rich involvement in science dating back to 1859, the year Queensland was proclaimed a separate colony. Publication of the *Proceedings of the Royal Society of Queensland* is the foundational role of the Society and brings to international attention peer-reviewed research as well as commentary from researchers and practitioners on management applications of science.

From time to time, the Society publishes a Special Issue of its Proceedings devoted to a theme of particular interest. In 2018 the Council of the Society agreed to publish a Special Issue of its Proceedings devoted to *Springs of the Great Artesian Basin.* Australia's Great Artesian Basin springs provide a unique focal point for the intersection of many types of knowledge – First Nations' and colonial perspectives, discovery, science and management, governance and policy. Progress across these themes has been significant since the early descriptions of the Great Artesian Basin and the ecosystems dependent on groundwater resources, yielding many individual publications and technical reports. The Royal Society recognised the need for consolidated knowledge to support evidence-based management, and for a strategy for the future of these precious ecosystems. A funding drive has yielded generous contributions to cover publication costs, and to sponsor this Special Session of the *Australasian Groundwater Conference* – a very welcome opportunity to showcase some of the exciting papers about springs already in production.

The complete Special Issue will include 20 or so papers spanning Indigenous values and uses of springs, the history of springs research, their distribution, hydrogeology, biodiversity, threats, risks, management strategies and conservation issues and a perspective on the future, given present and future developments and threats. Digital and print copies of the Special Issue of the *Proceedings of the Royal Society of Queensland – Springs of the Great Artesian Basin* – can be ordered from the Society.

Artesian springs of the Great Artesian Basin – hydrogeology, hydrochemistry and age dating of artesian groundwater and spring deposits

M.A. Habermehl [1]

1. Dr M.A. Habermehl, Kaleen, Canberra, ACT, Australia

Artesian springs of the Great Artesian Basin, Australia, are the natural outlets of the artesian groundwater, and are predominantly found near the Basin's southern, south-western, western and northern marginal discharge areas. Artesian springs also occur near the eastern recharge areas. Artesian springs played an important role in the discovery of the Basin's artesian groundwater and the first flowing artesian waterbores were dug and drilled near springs. The largest concentration of springs and their sedimentary deposits, mainly tufa carbonates, forming conical mounds and

platforms, occur near the south-western margins. The Basin is a multi-layered confined aquifer system, with aquifers in Jurassic and Cretaceous continental sandstones and intervening confining beds of siltstone and mudstone of the constituent Eromanga, Surat and Carpentaria sedimentary basins.

The Basin underlies semi-arid and arid regions across 1.7 million km^2, or one-fifth of Australia. Hydrogeological and hydrochemistry studies show that most artesian springs and waterbores derive their water from the main (tapped) Jurassic-Lower Cretaceous Cadna-owie-Hooray Sandstone aquifer and its equivalents. Age dating by isotope hydrology studies of the artesian groundwater in the Basin determined ages of up to 1 to 2 million years. Drilling of the spring carbonate deposits revealed thicknesses of up to 30 m. Several age dating studies, including thermoluminescence and uranium series dating of the carbonate mound shaped spring deposits southwest of Lake Eyre, show ages up to 740 000 ± 120 000 years. Spring deposits appear to show a range of episodic ages and could indicate a relationship with wet periods in the recharge areas of the Basin.

1. Habermehl, M.A. (in prep/press/2019) Artesian Springs of the Great Artesian Basin – Hydrogeology, hydrochemistry and age dating of artesian groundwater and spring deposits. Proceedings Royal Society of Queensland - Springs Special Issue 2019 Habermehl, M.A. (in prep/press/2019) The Great Artesian Basin, Australia – from discovery to current hydrogeological, hydrochemical and isotope hydrology interpretations. Hydrogeology Journal (2019)

In search of lost springs in the eastern Great Artesian Basin

Jen Silcock [1]

1. The University of Queensland, St Lucia, QLD, Australia

Desert springs have captured the human imagination since time immemorial. They have underpinned survival, travel and culture across arid regions globally, as well as supporting unique biological communities, often including species that live nowhere else. However, since the industrial era many have become lost – either through extinction due to groundwater extraction and other human impacts, or simply by virtue of being bypassed with mechanised transport and the proliferation of alternative artificial water sources. Sometimes springs have become extinct both physically and in human geographical knowledge.

It is essential to understand the location, activity status, history and ecological values of springs at a landscape or aquifer scale, in order to effectively manage their values and protect them from current and emerging threats. Over the past three decades, researchers at the Queensland Herbarium and University of Queensland have compiled a comprehensive database of all known active and inactive springs in the eastern Great Artesian Basin (GAB) underlying Queensland and New South Wales, spanning 1.5 million square kilometres. We employed comprehensive field surveys, local knowledge, historical maps, and a review of historical and contemporary literature. The database includes information on location, activity status, hydrogeology, and cultural and ecological values of nearly 2882 known springs, including 2132 that remain active.

Springs are clustered in nine main groups, termed 'supergroups'. Cultural and ecological values vary markedly between and within groups, as do activity status and threats. This presentation will provide a summary of the approaches to building spring knowledge across the Great Artesian Basin and the role of the spring database

in ensuring long-term conservation outcomes for springs and the values they support.

Macro-invertebrates of GAB springs: how understanding their distributions can help us conserve them

Renee Rossini [1]

1. The University of Queensland, St Lucia, QLD, Australia

Springs are unique freshwater ecosystems that are often overlooked in discussions of global freshwater ecology and conservation. Springs that emerge from the Great Artesian Basin (GAB) in Australia support a high diversity of endemic aquatic species. Most of these species have a high risk of extinction due to their small geographic distributions and severe habitat loss. However, many are poorly understood and unprotected. They are mostly invertebrates for which basic taxonomic and ecological information is lacking and global impetus for conservation is weak.

Quantifying the hydro-ecological processes that shape and sustain the unique biotic assemblages of discharge spring wetlands of the GAB and predicting how endemic springs taxa will respond to threatening processes, will help us prioritise our conservation actions for this huge suite of species. In this talk I will give a crash course in the biodiversity of invertebrates in GAB springs, discuss our current understanding of threats to their persistence, and briefly propose a functional approach to predicting their risks of extinction.

Evolution in isolation: the endemic fishes of Australia's remote Great Artesian Basin springs

Adam Kerezsy [1]

1. Dr Fish Contracting, Lake Cargelligo, NSW, Australia

Patterns of fish distribution within Great Artesian Basin springs fall into two distinct categories: the opportunistic colonisation of springs by widespread riverine species following flooding, and long-term habitation – and speciation – within isolated spring complexes by fishes' endemic to certain spring groups.

The endemic fishes of Australia's Great Artesian Basin springs persist in the most unlikely fish habitats imaginable. Within predominantly hot and dry landscapes, they inhabit the only reliable wet areas, which are frequently the same temperature as the surrounding plains and as shallow as the body depth of some of the species.

There are seven fish species endemic to Great Artesian Basin springs; the Dalhousie catfish (*Neosiluris gloveri),* Dalhousie hardyhead (*Craterocephalus dalhousiensis*), red-finned blue-eye (*Scaturiginichthys vermeilipinnis*), three localised species of gobies (*Chlamydogobius gloveri*, *C. micropterus* and *C. squamigenus*) and the Dalhousie mogurnda (*Mogurnda thermophila*). These species occur at only three locations; Dalhousie in South Australia, and Edgbaston and Elizabeth Springs, which are both in Queensland.

All spring species are functionally endangered due to their small ranges and small populations; however their formal status varies widely between state, national and international legislation and/or lists. All fish endemic to GAB springs are threatened by a broad suite of factors that endanger inland aquatic ecosystems, such as water

extraction, pollution and the possibility that alien or unwanted species may become established.

Persisting as they do in such unique and specialised habitats, the study of these GAB fish – and all GAB springs endemics - can reveal much about evolution, speciation and resilience. It is therefore imperative that we respect and preserve them and their unusual habitats. Although there is a growing recognition that conservation of the fishes and their habitats is important, this is complicated by the confusing variability of their conservation status and a lack of basic knowledge regarding their ecology and precise distribution. This presentation will provide an overview of the unique fish species that rely on GAB springs and the challenge in conserving species where there is only limited knowledge.

Regulatory tools for managing resource development impacts on spring ecosystems

Revel Pointon [1]

1. EDO Queensland, West End, QLD, Australia

Springs of the Great Artesian Basin (GAB) and other similar regional aquifer systems provide essential water flow to support unique ecological communities, ecological processes and cultural values. There are a number of regulatory tools designed to facilitate the protection of these values.

This presentation will provide an overview of the legal framework that seeks to regulate impacts on groundwater and springs in Australia, particularly from a federal level under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). They will include a brief overview of the Australian regulatory framework, the known ecological values of spring ecosystems - listed and those that are not – and analysis of how the framework is operating in practice, with case study examples, and consideration of potential for improvements.

Twenty years on from the EPBC Act commencement, this presentation provides a reflection on the effectiveness and adequacy of the regulatory framework to manage impacts on these unique ecosystems. The two key challenges of focus will be the existing regulatory process, particularly focusing on its application where there is scientific uncertainty, and the framework for listing species and communities.

Recent examples of resource activities proposed in the vicinity of spring systems in Queensland, Australia, will be reviewed to better understand how the regulatory framework is operating in practice and to consider whether improvements may be implemented to more effectively manage the competing agendas of resource development and springs protection.

An adaptive management plan for GAB springs

Lynn Brake [1]

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The Great Artesian Basin (GAB) is one of Australia's most important natural assets. It is among the largest artesian aquifer system in the world, and Australia's largest freshwater resource. GAB springs, the natural surface expressions of the GAB aquifers, have iconic geological, cultural and ecological values that are widely recognised both nationally and internationally. They are one of the few major artesian spring systems in the world that have not been severely degraded by over-exploitation of the water-bearing aquifers and/or the impacts of land-use in and around spring vents

An adaptive Management Plan has been developed to protect active GAB Springs on land used for pastoral production, mining or other purposes. The Plan is designed to protect asset values of springs with as little disruption to productive land uses as practicable. It is built around an evidence-based template that facilitates cooperative spring management between landholders and management agencies. The template consists of practical, cost effective methodologies to:

- Classify springs and identify important values and threats to particular spring groups
- Identify risks that may arise from various types of land uses
- Develop intervention strategies to manage the risks with as little disruption to land uses as practicable
- Monitor changes that indicate how well risks are being managed
- Modify on-ground management in response to changing conditions

The Template called *Springs on Your Place* is designed to be easily understood by landholders and water managers as well as other government and industry decision makers. It is built around an attractive, easy to use graphic database that provides robust information on each of the spring groups within the 13 super groups across the GAB. *Springs on Your Place* uses best and most up-to-date local and scientific knowledge and has the capacity to be revised and updated as knowledge gaps are filled, decisions made, and spring conditions change. *Springs on Your Place* can be a key consultation tool between landholders and department staff to aid in decision making about the most appropriate management response for particular spring groups.

Emerging Analytical & Numerical Methods

The Ensemble Optimizer: making management optimization under uncertainty possible since 2019

Matthew J. Knowling [1] , Jeremy T. White [2]

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Publish consent withheld

Using an adjoint state approach to estimate cumulative streamflow depletion efficiently

Chris Turnadge [1] , Roseanna M. Neupauer [2] , Bob Anderssen [3] , Russell S. Crosbie [1] , Craig T. Simmons [4] , Okke Batelaan [4]

1. CSIRO, Glen Osmond, SA, Australia
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3. Data61, CSIRO, Canberra, ACT, Australia
4. National Centre for Groundwater Research and Training / Flinders University, SA, Australia

Streamflow depletion describes the reduction of baseflow to a stream resulting from groundwater extraction. Traditionally, this was conceptualised as the reduction of baseflow at a specified time following a finite period of continuous extraction. Here we termed this concept "instantaneous streamflow depletion" (ISD). Since the 1950s, a range of analytical solutions have been developed to predict ISD. The subsequent advent of numerical groundwater flow simulation enabled more detailed assessments, including the use of both forward and adjoint modelling approaches. However, traditional analytical and numerical approaches both require the evaluation of a large number of model runs, in order to assess a range of potential bore-stream separation distances (i.e. potential bore locations). In the present study, an alternative concept was considered: the total volumetric reduction in baseflow to a stream resulting from continuous groundwater extraction over a finite period. We termed this concept "cumulative streamflow depletion" (CSD), which is relevant to combined assessments of surface water and groundwater balances. We derived an adjoint state approach to provide efficient estimates of CSD. A single numerical adjoint model run provided estimates of CSD impacts at all potential locations of interest. The composition of the loading term that forms the basis of the adjoint state approach was derived analytically from first principles. The method was validated using multiple synthetic case studies representing variations in (a) streambed resistance and (b) stream and bore base elevations. The results of adjoint solutions compared almost exactly to those calculated using equivalent closed-form analytical solutions. The adjoint method was also used to estimate the potential for CSD in an alluvial groundwater flow system in the Gloucester Basin, based on an existing numerical forward model. In summary, the adjoint state method derived in this study was found to provide an efficient means of estimating cumulative streamflow depletion based on existing forward models.

Recent developments in speeding Up MODFLOW-USG simulations: the truncated Newton Method and GPU acceleration

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Long simulation run-times are the eternal nemesis of the numerical modeller: they impact schedules, prolongate sensitivity analyses, and place practical limits on model scale and the ability to perform comprehensive statistical uncertainty quantification. We present recent software developments in accelerating numerical simulations to combat this. These developments have so far been applied to MODFLOW-USG but may in future also be implemented in other software that uses Newton-Raphson linearisation. The first development is the truncated Newton method, which computes and applies a dynamic residual-based termination criterion to limit the number of linear solution iterations necessary to solve nonlinear problems. The second development is a new port of the entire MODFLOW outer iteration loop to run on NVIDIA GPU devices, including matrix formulation, nonlinear residual reduction and linear solver logic. The two developments may be used together or separately, and we demonstrate significant speedups in simulation run-time through their use – particularly on modern GPU devices.

Reconstruction of baseline groundwater levels using backwards Cumulative Rainfall Departure and highly-parameterised parameter inversion

Eduardo De Sousa [1]

1. DHI, Como, WA, Australia

Groundwater recharge estimates using the Cummulative Rainfal Deparure (CRD) method have been widely used in literature (Bredenkamp, 1995), in areas where groundwater levels and rainfall present a strong correlation. This study further explores the utilisation of this method for hindcasting and estimation of baseline groundwater levels in areas where monitoring data is scarce.

The proposed methodology has been applied in the Lake Muir-Unicup Natural Diversity Recovery Catchment (MUNDRC). The catchment consists of a complex system of lakes, swamps and flood plains, located in southwestern Australia. Long term rainfall time-series in the area have shown a systematic decline over the past decades, with an abrupt change since the 70's.

Conceptual and numerical groundwater-surface water models have been developed to assess the effects of rainfall decline in the lakes and surrounding environment. The lack of groundwater and lake level monitoring data prior to the rainfall decline makes the establishment of baseline levels and initial conditions difficult.

The CRD method has been utilised in a backward form to estimate groundwater levels prior to the decline of rainfall rates. The simplified nature this method has inherent non-uniqueness between rainfall ratios and evapotranspiration. To address that, multiple CRD models were carried at different locations within the catchment and calibrated simultaneously using regularized parameter inversion.

The calibration was undertaken with PEST-HP using 91 models, following by uncertainty analysis through the generation and sampling of the posterior covariance matrix, with a total of 500 realisations per model.

The results from the optimisation indicated a good agreement between CRD results and respective observations. Furthermore, the distribution of the calibrated parameters values is reasonable and in agreement with the conceptual model.

1. BREDENKAMP DB, BOTHA LJ, VAN TONDER GJ and VANRENSBURG HJ (1995) Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. WRC Report No TT73/95

Generating hydrogeological virtual realities for hypothesis testing in groundwater modelling

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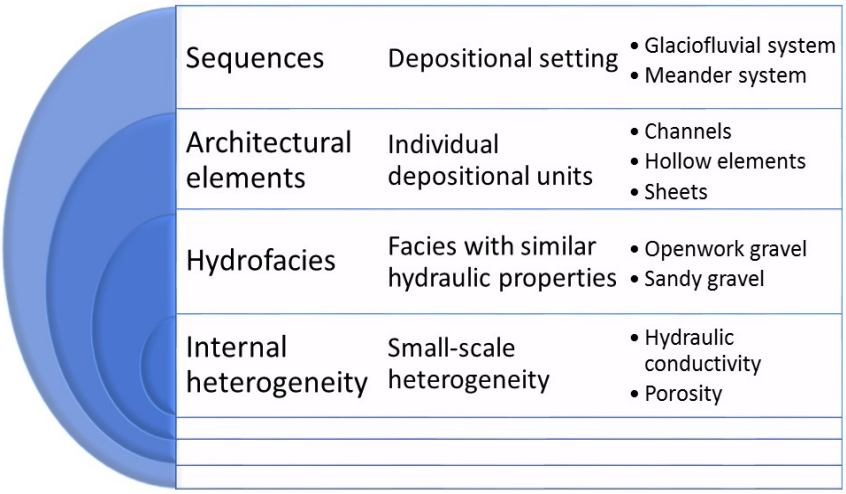
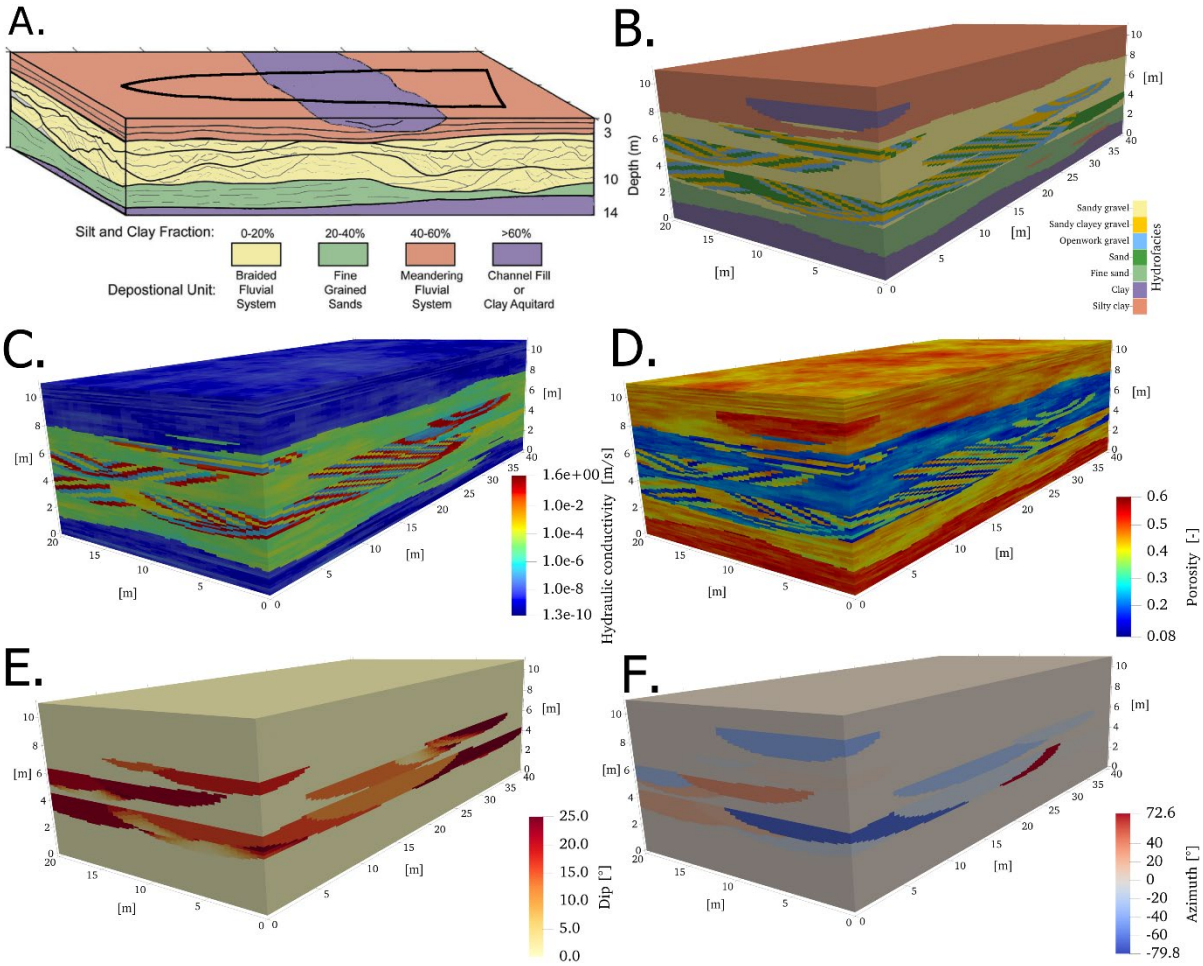
Objectives: Heterogeneity of subsurface hydraulic properties controls groundwater flow and contaminant transport. However, the depositional processes which account for the creation of clastic aquifers are often neglected in hydrogeological modelling. Many existing methods for simulating subsurface heterogeneity do not honour depositional concepts or cannot simulate heterogeneous bedding structures present in fluvial deposits.

Design and methodology: We have implemented a hierarchical modelling framework for simulating sedimentary deposits in the Hydrogeological Virtual Realities (HyVR) simulation package. The package uses an object-based modelling approach to model hydraulic parameter fields with multiple scales of heterogeneity.



Outputs: HyVR outputs are three-dimensional parameter fields that can include hydraulic conductivity, porosity, anisotropic ratios, and bedding parameters (dip and azimuth). The last three parameters can be used to simulate hydraulic anisotropy through rotation of full hydraulic conductivity tensors. HyVR has been designed with the groundwater modeller in mind, and as such, simulation outputs can be used in forward flow-and-transport numerical modelling tools (e.g., MODFLOW), allowing qualitative geological concepts to be tested in quantitative hydrogeological models.



Conclusion: HyVR (https://github.com/driftingtides/hyvr) is an openly available Python module that is comprehensively documented (https://driftingtides.github.io/hyvr/), for ease of use. It allows hydrogeological researchers to develop object-based models for use in standard groundwater modelling software. It forms an open codebase that can be further extended and developed by the hydrogeological community.

1. Bennett, J. P., Haslauer, C. P., Ross, M. and Cirpka, O. A. (2019), An Open, Object-Based Framework for Generating Anisotropy in Sedimentary Subsurface Models. Groundwater, 57: 420-429. doi:10.1111/gwat.12803

Comparing modelling approaches for salinity impact assessment of irrigation in SA Mallee

Juliette Woods [1] , Tariq Laatoe [2] , Dougal R. Currie [3] , Tony J. Smith [4] , Kittiya Bushaway [1] , Virginia Riches [1] , Glen R. Walker [5]

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5. Grounded in Water, Adelaide, SA, Australia

Impacts of past and present irrigation practices on River Murray salinity is a priority for river management in the Mallee region. A 2017 review examined modelling approaches to estimate salinity impacts from irrigation and found they could introduce biases. Additionally, there is no direct modelling of the unsaturated zone to account for perching on clays which has a significant influence on the magnitude and timing of salt loads to the river. These limitations create potential for bias when linking on-ground actions (such as irrigation efficiency improvements) to salt loads in the river but could be addressed by (1) developing unsaturated zone models to deal with perching; and (2) incorporating and calibrating such models within an accredited groundwater model. This talk addresses the latter step.

A pilot trial was conducted for the Loxton-Bookpurnong irrigation districts of South Australia, comparing two modelling approaches. The first was that of a 2011 groundwater model, where some assumptions were made about hydraulic conductivity, and then the recharge was inferred, via an inverse method. An agronomic water balance was used as a check but was not used to estimate the recharge.

The second approach was developed and calibrated during the pilot trial. An agronomic water balance was integrated with a semi-analytic unsaturated zone model and a numerical groundwater model. The integrated model used a recharge time series generated by the water balance and unsaturated zone model. This was applied to distinct recharge zones, based on lithology, date of irrigation development and drainage practices. The outputs, especially recharge and salt loads to river, were compared to those with the 2011 accredited model. , in which an integrated agronomic water balance-unsaturated zone-groundwater model was developed and calibrated; and the modelling outputs, especially salt loads to river, were compared to those with the 2011 accredited model.

The integrated model was fit-for-purpose in that it enabled estimation of salt loads for various scenarios. Irrigation actions were able to be more directly linked to groundwater responses and salt loads than with the inverse method. Drainage information was important to constrain soil properties and vertical fluxes.

The conclusions from the study are

1. Collating historical data on drainage and irrigation development helps constrain the degrees of freedom in calibration;
2. Salt loads varied in magnitude from original model, although timing was similar.

The results of the pilot trial are being used to develop recommendations for modelling salinity impacts for Mallee irrigation districts.

The early days of groundwater modelling in Australia, 25 years from 1970 to 1994

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This talk is a nostalgic journey through the first 25 years of groundwater modelling in Australia, roughly the years 1970 to 1994 (when PEST was born). The early years were before MODFLOW, before Excel, before SURFER, before Windows, and long before GIS. Back then, every modelling activity was an innovation. Our perspective is coloured by personal experience in New South Wales (Australia) when the authors were working together in the State Government Water Conservation and Irrigation Commission. The game-changer was acquisition of a Digital PDP8/e in 1972 with 8 kb of memory, which supported only Assembler and FOCAL programming languages, followed by BASIC and eventually FORTRAN. I/O was via hardware toggles, a teletypewriter keyboard (10 cps), and paper tape which doubled as the initial storage device, followed by serial cassette tape, 8-inch floppy discs and eventually large hard discs with 5 Mb capacity. The focus was on analytical models for the first decade until distribution of PLASM (from USA) in the mid-1970s, AQUIFEM in the early 1980s, and MODFLOW in the mid-1980s, supplemented by bespoke code. Our story ends with the creation of PEST, a great Australian invention. In keeping with the theme of this conference, we witnessed groundwater changing from obscurity to prominence over a quarter of a century, and analytical and numerical techniques developed by us and others in those early years were truly "emerging".

A novel approach to representing longwall induced fracturing in finite difference groundwater models

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Longwall mining induces a significant change to the overlying groundwater system by creating an interconnected fracture network above the collapsed longwall cavity. This change occurs in response to land subsidence and delamination of sedimentary beds. Representing the effects of mining induced subsidence in MODFLOW models has traditionally been simulated as an increase to permeability, loosely based on several subsidence studies (Tammetta 2017, Guo 2016, & Booth 2002). AGE has developed a method where the newly created fracture network above each longwall panel is implicitly coupled in the MODFLOW model. Using a derived equation to calculate the total sum of fractures above the spent coal seam, a modified version of the 'Connected Linear Network' package (CLN) flow equation was used in the Drain package (DRN). A Fortran executable was developed to calculate the rate of groundwater drawdown using the total aperture of the fracture network (A), the in-situ host vertical permeability (Kz), and the length the fracture network extends into each cell (l). The maximum height of connective fracturing is automatically calculated using an option of either the Ditton-Merrick (2014) and Tammetta (2016) equations. The DRN package attempts to lower the groundwater level down to the bottom of each fractured cell, i.e. toward zero pressure, at a calculated conductance rate. This method solves the common issue of model convergence when directly representing extremely high fracturing intensity (high permeability), adjacent to in-

situ cells with low permeability. Case studies presenting historic longwall mine dewatering of several major projects in New South Wales indicate excellent calibration to pressure and inflow using this technique. Future studies could utilize this method in combination with fracture enhancement predictions from COSFLOW (Adhikary 2007) modelling.

Groundwater Dependent Ecosystems

Where does submarine groundwater discharge occur?

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Submarine groundwater discharge (SGD) from unconfined coastal aquifers to the ocean is common within a few hundred metres of the coast. It has also been observed to occur further offshore, associated with semi confined paleochannels that formed during the last glacial maximum. Fresh groundwater discharges from such paleochannels to the ocean occur between the Queensland coast and the Great Barrier Reef (GBR) where seafloor depths are typically greater than 20 m below sea level. These SGD points are known locally as "wonky holes" and are sought after for recreational fishing. Groundwater development higher in the catchment can change the quantity and quality of SGD which may detrimentally impact the surrounding ecosystems.

The overarching aim of this work was to establish the types of ecosystems that exist in areas of SGD and how they might be vulnerable to groundwater management. The objective was to identify where SGDs are likely to occur, what the dominant flow processes are and to establish the types of marine ecological environments (coral and/or seagrass) they are associated with.

The approach was to gather and collate information about the occurrence of SGD and ecosystem type from the literature and local knowledge and compare these to existing spatial datasets to see if any correlations exist and whether these can be used to provide evidence of where SGD is likely to occur on a broader scale.

Preliminary analysis of high-resolution bathymetry datasets shows local depressions that coincide with known locations of wonky holes and indicate many other locations of potential SGD that have not yet been confirmed. Sea surface temperature anomalies also align with some suspected areas of SGD. RECOM (Relocatable Coastal Ocean Model) was used to establish under what conditions SGD would be likely to disperse rapidly or have a longer residence time, thus having a stronger influence on local ecological environments.

Preliminary outcomes show that several existing spatial datasets can provide multiple lines of evidence indicating where SGD is likely to occur.

Murray Darling Basin groundwater management under the Basin Plan

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Groundwater is a vital source of water throughout Australia and the world. Similar to many other places, groundwater is the only reliable source of water for many rural and remote communities, mining operations and agricultural industries in many parts of the Murray-Darling Basin (MDB). Groundwater also supports the MDB environment with some ecosystems and species completely dependent on groundwater to meet their needs and others using groundwater to supplement surface water flows. River red gums, for example, are an iconic species with deep roots that access groundwater. Many such groundwater dependent ecosystems are significant cultural places for Aboriginal nations.

In the past, the complexity and importance of groundwater has not been well recognised and the connection between groundwater and surface water has not been well understood. This had, at times, led to inadequate management of this precious and finite resource, resulting in issues associated with access and water quality. In response to such concerns, State water management arrangements for groundwater made many interventions to address issues and in 2007 the *Water Act* (2007) was passed by the Australian Parliament. A requirement of the Water Act was that the Murray-Darling Basin Authority be set up and develop the Basin Plan with the aim to bring the Basin back to a healthier and sustainable level of water use, while continuing to support farming and other industries.

The Basin Plan sets the amount of groundwater that can be taken from the Basin's groundwater resources each year and ensures groundwater is monitored and managed through local water plans and water resource plans (WRPS). WRPs outline the mechanisms for achieving community, environmental, economic and cultural outcomes in accordance with the Basin Plan requirements. The Authority is working with Basin state governments to ensure the management arrangements detailed in WRPs consider relevant risks to ensure sustainable management of groundwater resources across the Basin. This management regime ensures the risks to the Basin's groundwater resources are effectively managed and adaptively reviewed over time.

Mapping groundwater dependence in data poor areas: analysis of earth observation data in the Isa Geological and Bioregional Assessment region, north-west Queensland, Australia

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The Australian Government's Geological and Bioregional Assessment (GBA) Program is assessing potential impacts of shale and tight gas development on water resources and the environment in three onshore basins: Cooper, Isa and Beetaloo. The Isa GBA region is host to two major groundwater systems: a deeper Proterozoic system and a shallower system associated with sediments of the Carpentaria and Karumba basins, collectively part of the Great Artesian Basin. If shale gas were to be developed in the

future there could be potential to impact groundwater and surface water and the ecosystems that rely on these resources.

Surface water – groundwater interactions are a key component of the hydrological system, important for supporting a variety of environmental assets. Analysis of earth observation data in this remote region has helped assess the interactions between surface water and groundwater where the availability of other spatial and temporal datasets is limited. In particular, new remote sensing methods have enabled rapid and consistent mapping of parts of the landscape with potential dependence on groundwater.

Two remote sensing products (Water Observations from Space summary statistics and Tasselled Cap Index wetness exceedance) were used to investigate the persistence of surface water and soil moisture in the landscape. In this region, areas that retain water for at least 80% of the time or are wet during the dry season (May to October) are likely to have a reliable groundwater source or access to groundwater during periods of limited rainfall. These areas most likely support groundwater dependent ecosystems, including springs.

Preliminary analysis of earth observation data has enhanced understanding of surface water – groundwater interactions in the Isa GBA region, complementing analysis of sparse streamflow, groundwater and hydrochemistry data. Targeted field validation could improve understanding of groundwater dependence in the landscape and enhance confidence in the findings of this assessment.

A new approach to prioritising groundwater dependent vegetation communities in New South Wales, Australia

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Objectives: The NSW *Water Management Act 2000,* associated Water Sharing Plans, and the Basin Plan 2012, require NSW Department Industry, Water to identify groundwater dependent ecosystems (GDEs) and prioritise the most ecologically valuable within each plan area for protection. The High Ecological Value Aquatic Ecosystems (HEVAE) framework has already been adopted to prioritise riverine ecosystems for management in surface water sharing plans. Here, we provide a method developed using the HEVAE framework to prioritise terrestrial vegetation GDEs for management.

Design and Methodology: The GDE HEVAE method is developed as a spatial model, that uses recorded and predicted distribution data, and mapped vegetation data to provide weighted scores for each attribute associated with the four HEVAE criteria (distinctiveness, diversity, vital habitat and naturalness) and are combined into an overall score. The combined scores categorise the ecological value of each groundwater dependent vegetation community (depicted as GIS polygon features) from very high to very low.

Original data and results: This method determined outcomes to assist NSW water management activities for water sharing plans and water resource plans under the Basin Plan. The outcomes can be represented as maps to provide a visual representation of locations of vegetation communities of ecological value, and as an attributed dataset to allow the user to look at each individual attribute and the associated criteria to determine the key drivers contributing to the scores.

Conclusion: The methods developed have provided a systematic, repeatable and transparent approach to integrated related information. This to helps prioritise areas of importance for water management needs such as; scheduling of GDEs into water sharing plans, using consequence scores within risk assessments, allowing individuals to locate GDEs of varying ecological value to inform other assessments, and prioritisation of areas to undertake monitoring and evaluation. When coupled with the NSW Riverine HEVAE methods, ecological value of assigned groundwater and riverine GDEs are consistently assigned.

The Groundwater Dependent Ecosystems (GDE) Atlas' role in decision-making

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Objectives: Information identifying the location and characteristics of Groundwater Dependent Ecosystems (GDEs) is a key input for Environmental Impact Assessments (EIA) and water management plans (Nelson, 2019). The Bureau of Meteorology's GDE Atlas is Australia's comprehensive national inventory of GDEs (Hoyos *et al.*, 2016). The National Groundwater Strategic Framework identifies the Atlas as a key source of groundwater-surface water connectivity information. The Atlas is also an important tool identified in the Independent Expert Scientific Committees' Information Guidelines. It is used across multiple levels of government, industry, consulting, natural resource management and by the general public. To maximise the impact and value of the Atlas its future development will be based on clear strategic direction and understanding of user requirements. This presentation will show how recent developments have improved the Atlas for use in decision-making using a case study from the EIA process.

Design and methodology: Stakeholder engagement activities were undertaken in 2017 – 2019 including establishing a GDE Reference Group and conducting workshops and surveys. This established the needs of key stakeholders (GDE Atlas users, GDE data custodians and GDE experts) for future development of the Atlas.

Results: Stakeholder requirements included timely GDE data updates, infilling of missing GDE data coverage, additional datasets (e.g. groundwater levels), web services and supporting information (e.g. updated GDE Toolbox). These requirements informed the development the "*GDE Atlas Future Directions 2018 – 2024*", a 5-year strategy for updating the Atlas.

Conclusion: The Bureau, together with the GDE Reference Group, is delivering the *Future Directions* strategy through establishing regular, streamlined GDE data updates, updating the GDE data model, developing a business case for updating the GDE Toolbox and publishing GDE web services. These developments will provide a comprehensive and current suite of GDE information for use in decision-making including the EIA process.

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Root-zone "Periscope" and its applications for investigating plant-water relations and modelling transpiration

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Since the first stoma appeared about 400 million years ago, moisture exchange between lands and the atmosphere extends into the root zone. However, due to its invisibility from the surface, root distribution and its temporal variation are difficult to estimated, which greatly hinders investigation of soil-plant-water relations and transpiration modelling. Plant water potential reflects dynamic water condition in vegetation, which is determined by moisture supply in the root zone, atmospheric demand, and plant physiological control. Thus, dynamic water potential can provide a "periscope" to observe root zone hydraulic conditions. Based on this hydraulic connection in the soil-plant-atmosphere continuum (SPAC), plant individuals work very likely as "observation wells" to the whole root zone at predawn, and as "pumping test wells" in daytime. They provide information to estimate root-zone and plant hydraulic states, and hydraulic properties. In this presentation, we will show how this root-zone periscope concept, based on continuous monitoring of plant water potential, has been used in SPAC model development, root water uptake model improvement, transpiration model parameterisation, as well as investigation of plant drought responses.

Drought-Induced hydrogeological impact causing dieback in a grassy woodland threatened ecological community, Monaro, NSW, Australia.

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Widespread (~200,000 ha) drought-induced dieback of *Eucalyptus viminalis*, the dominant species in the Tablelands Snow Gum, Black Sallee, Candlebark and Ribbon Gum Grassy Woodland threatened ecological community, is severely impacting native vegetation health and causing habitat loss in the Monaro. Past debate about the causes of *E viminalis* mortality in this area (Ross and Brack, 2015; 2017; Jurskis, 2016) had equivocal findings. There is international consensus that greater understanding of the links between tree mortality and climate change, when trees are under chronic or acute water stress, is needed (Allen et al. 2010, Booth 2017, Correa et al. 2017, Prober et al. 2017a, 2017b, Curtis 2019). An understanding of hydrogeological landscape (HGL) processes (Moore et al. 2018) in this landscape, specifically access to groundwater, allowed causal factors for tree dieback to be evaluated. Extreme climate impacts since the early 2000s have influenced root access to groundwater in parts of the landscape (this study) in a manner that caused stress for an extended period afterward (see White 1969, Lynch and Cowood 2018) making trees susceptible to secondary impacts (e.g. insect strike with limited insect

predation due to land clearing/open landscapes and changes in fire cycles) resulting in localised tree mortality. This impact is apparent even when predisposing cohort factors (e.g. tree age, natural range) are considered. Clarification of the HGL processes operating in areas of tree dieback, explains why the pattern of impact differs in different parts of the landscape allowing strategic targeting of restoration actions. For the 2060-2079 NARCLIM (12 model) climate projection, *E viminalis* shows high (>80%) consensus for climate stress across the Monaro (MacKenzie, 2018; personal communication). Use of the HGL framework allows the evaluation of other potential stressors (e.g. land/water salinity, solute/toxin transport, soil sodicity/erosion susceptibility) and informs targeted natural resource management to accommodate future climate and land-use change.

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Multidisciplinary and adaptive approach to assessing groundwater dependence of River Oak community in NSW Hunter coalfields

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Changes in government policy and legislation in recent years has led to increased focus on understanding the groundwater dependence of ecosystems potentially impacted by coal and csg activities. This presentation outlines a study conducted at an operational underground coal mine in the NSW Hunter Coalfields that employed adaptive management techniques to characterise the local groundwater regime and provide advice on the likely level of groundwater dependence of vegetation within an approved area of future mining. The study focusses on vegetation and an aquifer associated with an ephemeral creek that discharges from steep headwaters on to a low-gradient alluvial plain overlying coal measures that will be mined in future using longwall methods.

The study was conducted in an iterative, staged approach that involved collaboration between the client, consultants from multiple disciplines and a government agency. The study included an ecological assessment that identified a River Oak vegetation community, localised along the creek, as the only community likely to be groundwater dependant. While previous surface water assessments provided information on the flow regime. The groundwater component involved field investigations to understand the local geology and groundwater conditions. Findings from the fieldwork, and the ecological assessment were used to locally update an existing regional scale numerical groundwater model. The purpose of the modelling was to establish whether evapotranspiration was simulated across the study area, indicating likely interaction between vegetation and groundwater. Predictive scenarios identified changes in groundwater levels due to mining that may adversely impact vegetation interacting with the groundwater system.

Based on these findings and collaboration between the various technical disciplines, the level of reliance of River Oak community on alluvial groundwater was assessed. The study also looked into where uncertainty may remain in understanding groundwater reliance over time, and from this a targeted monitoring program was developed to enable ongoing adaptive management.

This presentation will outline the methodology, findings and key learnings from the process. This includes discussion on the value and challenges with communication between different technical disciplines and stakeholders.

Recharge & Groundwater-Surface Water Interaction/Novel Investigation Techniques

Infiltration, recharge and plant water availability in a tropical environment – Ranger Uranium Mine, Northern Territory

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The Ranger Uranium Mine is surrounded by Kakadu National Park in the Northern Territory, Australia. Mining commenced in 1980 and the mine area is due for the release back into Kakadu National Park in 2026 once restoration of the mine is completed.

As part of the restoration program a Trial Landform was constructed in 2009. The primary purpose of the Trial Landform was to assess rates of erosion and the likelihood of successful revegetation rates. As part of the assessment, the Trial Landform is monitored with its own rainfall gauge and collection points which record surface runoff volumes and sediment load. On average, for the period 2009-2018, surface runoff is 20% of rainfall.

In order to better understand water infiltration into the Trial Landform and provide a baseline for future investigations direct infiltration measurements, using a disc permeameter, were undertaken. This information can be used to better understand how infiltration rates vary across the Trial Landform and hence provide a further input to inform understanding of plant water availability on the final landform. This data could also be used to help refine recharge estimates for the groundwater model.

The results from these trials indicated that infiltration rates range between 9 and 99mm/hr indicating highly variable infiltration rates which are likely to be replicated on the final landform and so inform planning to achieve the best environmental outcomes.

Modelling shallow groundwater recharge and ET processes using FloPy

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In groundwater models of regions with shallow groundwater, piezometric surfaces and fluxes to groundwater dependent ecosystems (GDEs) can be highly sensitive to the parameterisation of recharge and evapotranspiration (ET) processes. For most regional scale models however, recharge has typically been conceptualised based on a percentage of rainfall, while ET is often defined by an arbitrarily defined maximum ET rate, declining to zero with increasing depth to water table. While shallow groundwater processes require an improved conceptualisation, over-parameterisation and increased computational time are challenges for unsaturated zone – groundwater model coupling.

A regional scale groundwater model was developed for part of the South East of South Australia using FloPy, a Python based interface for MODFLOW 2005. The FloPy interface allowed for transparency and reproducibility in the modelling and facilitated rapid and flexible model development that could easily couple with other models or site-specific processes. A lookup table approach for modelling net recharge (gross recharge minus ET from groundwater) was established from previous research and incorporated into the transient FloPy groundwater model. The lookup table was developed from unsaturated zone modelling using WAVES and was based on climate data, soil clay content mapping and the time-varying South Australian Land Cover Layers. This allowed the complex unsaturated zone behaviour to be captured, without significantly increasing the number of model parameters.

The modelling resulted in similar calibration performance for groundwater heads as the regional model, but with a water table that better followed the land surface between the observation bores. Sensitivity of modelled groundwater heads to recharge and evapotranspiration parameters varied, depending on depth to water table and proximity to drains and other boundary conditions. Groundwater heads near GDEs were very sensitive to recharge and ET parameterisation.

How uncertain are our recharge estimates?

Russell Crosbie [1]

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In many areas water allocations are determined by recharge estimates, either directly or indirectly through models. For a water balance component that can't be directly measured it is imperative that the uncertainty in recharge estimates is quantified. It is often recommended that multiple methods should be used as a measure of uncertainty in the recharge, but this will only produce multiple recharge estimates. Different methods of estimating recharge can be estimating different quantities of water. This can be a challenge if relying on different estimation methods to provide uncertainty but can also be an opportunity for constraining recharge estimates if recharge is estimated probabilistically. Baseflow in streams is an estimate of groundwater discharge and must be equal to or less than the groundwater recharge. The chloride mass balance gives an estimate of the net recharge (includes ET from groundwater) and must be equal to or greater than baseflow and also equal to or less than gross recharge (water that reaches the water table). The water table fluctuation method is estimating gross recharge and must be equal to or greater than the net recharge but also equal to or less than the excess water, which is calculated from remotely sensed ET subtracted from rainfall (excess water also contains the runoff component). If each of these water components can be estimated probabilistically then they can be jointly constrained using a rejection sampling approach. Using examples from recent projects we can show that unconstrained modelled recharge estimates are highly uncertain, the range can extend over two orders of magnitude. The chloride mass balance can be estimated probabilistically with a range over a factor of 3. By jointly constraining multiple recharge estimates the uncertainty can be reduced closer to a factor of 2.

Estimating recharge from recirculated groundwater with dissolved gases: an end-member mixing analysis

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Groundwater circulation is an important process in irrigation, mining activities and town water supplies. Tracers that undergo different degrees of re-equilibration with the atmosphere during this recirculation process can enable ambient groundwater and recirculated groundwater to be differentiated. In this paper, the recirculated groundwater has been pumped to dewater open pit mines and discharged into ephemeral creeks. Some of this water subsequently recharged back into the aquifer. CFC-12 (which completely re-equilibrates on exposure to the atmosphere), ^{14}C (partial re-equilibration) and ^{3}H (no re-equilibration) are used in a four end-member mixing analysis to differentiate between (1) ambient groundwater, (2) recirculated groundwater, (3) river recharge from natural flows prior to commencement of mining operations (in 2007), and (4) natural river recharge post-2007. Sampling of the surface water when discharge of mine water was the only source of river flow enabled the extent of re-equilibration of both CFC-12 and ^{14}C to be accurately determined. Since CFC-12 re-equilibrates more rapidly than ^{14}C, recirculating groundwater had a CFC-12 concentration which was close to modern, but a ^{14}C activity that was higher than the original groundwater, but less than modern recharge. Since ^{3}H does not re-equilibrate with the atmosphere, it enabled differentiation between stream recharge due to infiltration of mine water discharge and that due to natural creek flows. Uncertainty of end-member compositions is due to changes in the end-member concentrations over time in the case of natural river flows, uncertainty in the extent of tracer re-equilibration for the groundwater recirculation end-member, and spatial variations in the composition of the ambient groundwater end-member. The mean uncertainty of end-member fractions was estimated to be less than 12%.

Evaluation of natural and anthropogenic factors on changes in river discharge and groundwater exchange in a Mekong sub-basin

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Besides natural climate variability exacerbated by induced climate change, regulation of large surface water reservoirs and connected downstream irrigation systems have well-documented consequences on river discharge patterns. However, these natural and anthropogenic changes may also affect groundwater fluxes, which needs understanding for sustainable water resources planning and management. In the Nam Ngum River Basin, Laos, a major tributary of the Mekong River, hydropower dams were developed in the upper part of the basin, whilst the lower part is mostly undammed and intensively developed for agriculture and domestic water supply. This study investigates the changes to the river flow pattern and groundwater storage from the pristine period (pre-dam) to the near–present period (post-dam). Firstly, we analyzed observed discharge data to detect historical changes in river discharge in comparison with historical climate trend analyses. Secondly, we analyzed how

natural and anthropogenic changes influenced groundwater storage in the sub-basin by looking at the incremental discharge between two gauging stations compared to total Equivalent Water Heights derived from the Gravity Recovery and Climate Experiment (GRACE). The results show that: (i) during the pristine conditions, the river discharge was highly seasonally dynamic. However, under post-dam conditions, there is diminished seasonal response with increased dry season flows and decreased monsoonal peak flows. This phenomenon showed a greater impact of human-made water infrastructures on river discharge than dependence on variability of climatic factors, as no trends in wet and dry season precipitation (Mann-Kendall test) are found in the times series; (ii) Incremental discharge increased by 38% compared to the pristine period, which is understood to be a result of higher groundwater discharge due to an increasing trend in total water storage as indicated by GRACE. Future research is underway to deconvolve the factors that are driving the changes in river and groundwater exchange.

Increased groundwater and contaminant discharge to surface water in response to catchment loading

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Introduction: Groundwater discharge to surface water can transfer contamination from groundwater to streams. This paper describes conditions where the ratio of groundwater contributing to surface water flows increased with increased rainfall and catchment wetting. This is not consistent with the generally accepted model of groundwater discharge dominating streamflow in dry periods; rather, it highlights the dynamics of the groundwater discharge process.

Methodology: Groundwater discharge processes were assessed at sites where groundwater and surface water chemistry allowed their relative inputs to be evaluated. Initial "spot" monitoring events indicated that, at times, surface water quality became more similar to groundwater even when surface water flows had increased. Sites that were instrumented with level, and in some locations EC, loggers in groundwater and streams provided increased understanding of groundwater discharge dynamics.

Results: At one site, spring discharge became more consistent with groundwater than surface water in periods of higher rainfall, indicating that hydraulic loading of the catchment increased groundwater discharge to the surface. At an intermittent flowing stream instrumented with EC and level loggers, after stream flows had been established for several weeks, later increases in surface water salinity continued to occur. This was considered to be related to further wetting of the catchment increasing hydraulic gradients and, consequently, groundwater discharge, even with higher stream flow rates. At a third site, during a temperate winter, surface water salinity continued to increase in response to increasing groundwater discharge until sufficient rainfall events had occurred to reverse hydraulic gradients between the stream and groundwater.

Summary and conclusions: The results highlight the importance of temporal monitoring of stream and groundwater systems to assess the dynamics of groundwater discharge to surface water. Level and EC logger data provide a framework in which to assess temporal variability of groundwater discharge under different surface flow conditions.

Quantifying air–water gas exchange in rivers and lakes using high-resolution time series of dissolved atmospheric gases

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Gas exchange across the air-water interface is a key parameter when using gas tracers such as radon to quantify groundwater discharge to surface waters. We present a novel method for quantifying the gas transfer velocity based on recently developed techniques for the in situ, near continuous measurement of dissolved gases with a field portable mass spectrometer. Concentrations of gases in surface water show diurnal variations due to diurnal changes in water temperature (and thus gas solubility). However, variation in observed dissolved gas concentrations are damped and lagged with respect to equilibrium concentrations, the extent of which depends upon the diurnal temperature variation, the water depth, and the gas transfer velocity. The method fits a model to the measured gas concentrations to derive the gas transfer velocity from the amplitude and the phase lag between observed and equilibrium concentrations. With the current experimental setup, the method is sensitive to gas transfer velocities of 0.05 – 9 m/day (for N_2), at a water depth of 1 m, and a given daily water temperature variation of 10 ºC. Experiments were performed (a) in a controlled experiment to prove the concept and to confirm the capability to determine low transfer velocities, and (b) in a field study in a shallow coastal lagoon covering a range of transfer velocities.

Assessment of PFAS as a novel tool for estimating groundwater recharge and aquifer characteristics

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Optimum sustainable groundwater management requires the collection of detailed hydrogeological parameters. One of the most important parameters is the recharge rate, which can be challenging to determine by conventional methods. Various methods have been utilised to study groundwater recharge mechanisms for several decades including environmental and artificial tracer techniques. In more recent years, contaminated sites investigations requiring the analysis of Per- and Poly Fluoroalkyl Substances (PFAS) in groundwaters have led to a large number of data sets available in aquifer systems. This provides an opportunity to assess its value in estimating recent recharge and recharge rates that can be important input values for modelling and managing the groundwater system.

The premise for determine recharge rates from PFAS concentration is that PFAS can be considered a conservative tracer in groundwater flow in a similar way that chloride or tritium travels through groundwater systems conservatively. Since the time that PFAS enters the groundwater system is known from historical records, the maximum depth and distance that PFAS travels in the groundwater system can

provide a good estimate of the travel time and therefore provides a recharge rate for that system.

Publicly available data sets were utilised in this preliminary assessment of PFAS as a novel approach to recharge estimation. Investigation sites with water quality data that included PFAS measurements and key hydrogeological data such as bore lithology, SWL, multiple screen-depths, and other aquifer properties were collected and analysed. The assessment utilised data from sites that had the most detailed hydrogeological information and examined minimum data requirements.

The results from this initial assessment indicate that providing that a site investigation has a well-planned and detailed monitoring network, PFAS can be used to quantify recharge rates in a groundwater system. Given that there are many water quality/contamination studies across a range of aquifer systems requiring the measurement of PFAS, this data can be utilised not only for determining if a site exceeds health and environmental criteria, but can be used to provide valuable model input data and sustainable groundwater management for regulators in the future.

Community Engagement, Cultural Values and Groundwater Resources

Community involvement in water management in Punjab, Pakistan: A strategy to sustainability of livelihoods of farmers

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Despite being home to the world's largest irrigation system Pakistan's Indus Basin is unable to satisfy the demands of an intensifying agricultural economy. The persistent pressure on canal water, and its failure to adequately deliver, is pushing irrigators to increasingly pump groundwater. Uncontrolled extractions have drastically lowered water tables and is leading to a deterioration in groundwater quality. High yielding crop varieties and increased cropping intensity is seen as the only way forward for a growing population and economy, but this is escalating pressure on groundwater resources. The study presented here focuses on water conservation and enhancement of farmers' livelihood. A co-inquiry method was used to gain an in-depth understanding of the local context in two case study areas. Each case study focused on one of the Indus Basin's canal distributaries to understand changing groundwater use and water conservation patterns along the length of the distributary. Despite incentives to adopt water efficient irrigation methods, costs of maintenance and scarcity of skilled labour refrain uptake. Even though farmers are aware of the need to conserve water, low cost supply and subsidised electricity encourage inefficient water use practices, with flood irrigation still the main method used on farm. The future is also uncertain with rural youth preferring to leave farms and secure employment elsewhere. Gender also plays a role, as women prefer to irrigate with the more readily accessible groundwater for vegetable growing and herding. They are also responsible for domestic use of water. Women have the potential to play a vibrant role in encouraging water conservation. Best practice

technologies and cropping methods are available for uptake, but these need to be accessible, affordable and acceptable to the community. This means community centred programs are necessary, for sense of ownership and liability as a delegate to be infused and self-centred approach is discouraged.

Lining of canals and ground water recharging: socio-economic implications for sustainable agricultural development in Pakistan

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Pakistan has one of the biggest irrigation system but still among those countries which are predicted to be hit by water scarcity hence has implications for sustainable agricultural development. One of the reasons of this poor management is excessive ground water usage without appropriate recharging. This study was conducted under Punjab Irrigation System Improvement Project (PISIP) to have an assessment of the socio-economic implications of canals lining completed under this project. The study was carried out in 4 districts i.e. Faisalabad, Sargodha, Bahawalnagar, and DG Khan of the Punjab province of Pakistan. Triangulated study took 446 respondents for quantitative and around 45 respondents for qualitative data collection. Findings of the study showed mixed opinion of the respondents. Most of the respondents were not happy with the planning, design and construction of the project as to them project did not identify domestic needs in terms of washing places for animals, theft control and garbage cleaning from the water. An important implication of the design was the negative impact on ground water recharging as canals were lined on beds and sideways with the non-porous material. A positive outcome was the increasing awareness level and concern of users about importance of ground water recharging. They also added that design did not identify the importance of bumps to control speed of water where users had to rely on indigenous methods by putting of sandbags which created further problems. A lot of trees were cut for construction work and were not replanted. No significant productivity in major crops was seen before and after the lining of canals, however a positive outcome was the more organized and unified role of Water Users Associations in the areas which strengthen the socio-economic integration among the users. It is suggested that sideways lining of canals either without bed lining or lining with porous material should be considered in future with attention to domestic needs of the respective areas.

Engaging Surat Basin landholders in groundwater monitoring

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Since coal seam gas (CSG) development began in the Surat Basin landholders have voiced concern that this development would adversely impact their groundwater resources. Despite the fact that the Queensland Government established a framework to monitor and manage likely impacts and legislation to protect the landholder's interests, members of the community were not comforted.

Groundwater Net is a grassroots groundwater monitoring program involving community education and engagement designed to address some of these landholder concerns. Landholders are engaged in groups by geographical area, provided with information on local hydrogeology, the CSG industry and existing monitoring data. Landholders were supported and encouraged in monitoring their own bores and provided with a mechanism with which to submit monitoring data directly to the department's groundwater database.

Groundwater Online was a complementary program involving the installation of continuous monitoring loggers and telemetry on 60 strategically sited bores (some on private landholder bores). The community can freely access this data 'live and online' through the Queensland Globe or the department's Water Monitoring Information Portal.

Results from both Groundwater Net (landholder monitoring) and Groundwater Online (continuous loggers) is used to independently cross-reference and verify groundwater monitoring results from the CSG companies.

Annual workshops provide a forum in which to share and discuss monitoring results and other relevant groundwater topics. Participants have expressed confidence in the monitoring data and acknowledged greater understanding of groundwater systems as a result of this program. In response to feedback, amendments have been made, additional information provided, resources developed, and adaptions made to the way data is publically displayed. As knowledge and understanding has increased, so too has the maturity and complexity of the questions that are being asked. An additional by-product of the entire program is the noticeable improvement in the relationships between government staff, landholders and CSG company groundwater staff.

Social and gender constructions associated to water resources in isolated Rural Pakistan

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Women and children play a pivotal role in the management of water in rural areas of Pakistan. On the one hand, they are relatively more vulnerable to water shortage amidst climate change. On the other hand, the food and nutrition security concerns are quite apparent in these exclusive genders. In addition to economic value, water is dubbed as social good which determines the social and family constructions of a community. Access to water is a reflection of social richness which ultimately causes economic strength of communities. The study was particularly aimed at exploring the

socio-economic hurdles that may confront the rural communities in managing water resources. Moreover, this research effort was aimed at exploring the multidimensional role of women and children in the social constructions associated to water management in some selected rural areas of Pakistan. It was noted that 4-6 hrs on average are required to fetch 4-5 pots (50-60 liters) in Parts of Sindh. By reviewing the existing body of literature and situation analysis of some villages in Southern Punjab and Northern Sindh, the storyline so developed clearly reflect the fact that the shortage of water is a psychological concern of women who are to manage it for drinking and domestic purposes. The study narrates that poverty in terms of access to water is most common a phenomenon in these selected rural areas where women had to travel a long distance for getting a few liters of water. It is also imperative to note in some parts of Punjab and Sindh provinces that without the serious efforts of women and children, the overall social and economic survival is very tough. It has also been reflected from some regions that a good number of children may be a good source of water to be brought from far off areas. The conference paper will be based on secondary data, some very suggestive and analytical in-depth case studies and an overview of the historical discourse of traditional water management and conservational techniques.

Out of the comfort zone – stakeholder engagement outside the Ivory Tower

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The Office of Water Science (OWS), within the Australian Government Department of the Environment and Energy, provides technical and secretariat support to the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC). The IESC provides independent scientific advice to Commonwealth and state regulators and ministers on the impact of coal resource development on water resources.

A key component of OWS' support is assisting the IESC in engaging with external stakeholders – proponents; regulators; consultants; peak industry groups and environmental non-government organisations. Over the last two and a half years OWS has worked closely with the IESC to increase the level of engagement with these groups. This has resulted in a change in the perception of the IESC from being considered a 'secret society' to being recognised as an open and transparent entity who is willing to listen to the views of others in order to improve the quality of its advice.

This presentation details the success and failures of this engagement over the past three years. It explores the differences in response from various stakeholders, how that some activities had to be modified both 'on the fly' and at subsequent engagements and will qualify the change in response across this time period.

The presented results provide an interesting and informative case study of engagement with the coal resource industry specifically, but also with others involved in its development.

Integrating stakeholder engagement into bioregion scale assessments

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As part of the "Towards a New Energy Future" package, the Australian Government committed $30.4 million to undertake the Geological and Bioregional Assessment (GBA) program. The GBA program will provide independent scientific advice on the potential impacts of shale and tight gas development on water and the environment in three onshore Australian basins.

The GBA program recognised the need to deliver assessment products that meet the information needs of key stakeholders. To address this, user panels have been established in the target regions as part of the assessment. Comprised of key stakeholders for the regions, panels include state, territory & local governments, commonwealth agencies, traditional owners, land holders, natural resource managers, and petroleum companies. The panels provide an opportunity for users to advise program staff of their information needs, and a forum for the program to engage with and advise members on assessment progress and findings. Members are asked to provide community or organisation views on the unconventional gas industry, potential impacts on the environment & water, and to feedback program progress and findings to their communities. The panels provide a two-way street that allows the program to understand our user's information needs, while building confidence and trust in the underpinning science.

Where appropriate user panel meetings are held in assessment regions and provide opportunities to take panellists into the field to see the environment and industry. By visiting and discussing key environmental, cultural and industry sites, field experiences aim to improve stakeholder understanding of industry practices and the regional environment.

Groundwater recharge and water security for Bengaluru city with traditional well diggers and their knowledge systems

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Objectives: To document the traditional well diggers of Bengaluru city and to involve them in building recharge wells for groundwater security for the city.

Design and methodology: Bengaluru city in South India is a fast growing metropolis with an estimated population of 12 million. It is spread over 1250 sq.km. area. The city is completely dependent on the river Kaveri, 95 km. away and 300 metres below the city for all its water requirements. At present 1400 million litres per day is pumped into the city.

It is estimated that around 400,000 borewells pump 400 to 700 million litres per day. These borewells are broadly undocumented, unmetered and unmanaged. The NITI Ayog, a Central government of India think tank, estimates that Bengaluru will run out of groundwater by 2020.

The Mannu Vaddars are an indigenous community of traditional well diggers who have been digging wells all around the country since centuries. Well digging saw a decline with the advent of the borewell technology especially since the 1980s. About 750 families of well diggers have been identified in 15 villages who still continue the tradition of cleaning old wells and deepening them. About 10,000 wells were documented with the assistance of the well diggers.

Original data and results: Around 10,000 shallow, open wells have been documented around in the city. A constant process of documentation using WhatsApp and simple maps is being developed. Recharge wells being dug by the well diggers are updated. Skills training to the well diggers on rainwater harvesting is given.

A goal of a million recharge wells in the city has been set by the well digger community. Typically, 3 feet in diameter and 20 to 30 feet deep, and leading filtered rainwater from rooftops and stormwater, it is hoped to increase the total recharge to at-least 50 % of the total rainfall. In the meantime, old wells are being identified, rehabilitated, cleaned and brought to service to supplement the city's water needs.

Conclusion Using traditional knowledge of the well digger community, creating increased livelihood options for them , using science to understand recharge zones , using the unconfined shallow aquifer well and by communicating the skill set present with the well diggers to a city , a better understanding of groundwater is being developed and water resilience for the city being built.

1. http://cgwb.gov.in/district_profile/karnataka/bangalore_urban_brochure.pdf
https://www.thebetterindia.com/173853/bengaluru-ground-water-crisis-well-digging-day-zero-zenrainman/

Social research in socio-hydrology

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Socio-hydrology is an emerging discipline aiming to understand and predict the dynamics and co-evolution of coupled human-water systems. In spite of rapidly increasing interests, there is no mechanistic understanding of how social drivers and social responses interact with the hydrological cycles in a co-evolving human-water system.

This paper proposed a framework for representing the social components of socio-hydrologic systems and interactions among them and with hydrological cycles. The key part of this framework are three interactive elements: societal value change (willingness to change), technological progress (capacity to change) and governance reform (change regulated). In this context, societal value (i.e. culture) is a set of common values, beliefs and attitudes shared by the majority of a regional population on water allocation, technological progress is about technology development on storage, distribution, diversion and use of water. Governance reform refers to formal government reform or self-organising informal institution change relevant to water allocation.

Evolution of social values on water in Australia (1843-2017) and in China (1946-2017), irrigated technology progress in China (8000 BC-1911), and transition of water governance in Australia (1843-2017) and in China (1946-2017) were taken as three examples to describe and measure these three interactive elements. Historical documents (newspapers, technology encyclopedia, and government documents)

were used as data sources, text-mining, social network analysis, and mathematical regression were used as the main methods.

These three case studies provided an exploratory approach to understand social drivers and social responses of a human-water system in a measurable way. They enable to integrate these social variables into process-based hydrological models, thus, enable to develop predictive models for how social drivers and social responses interact with the hydrological cycles in a co-evolving human-water system.

An important future research direction is the development of understanding of how societal values, technological progress and governance reform interactively influence water management decision-making in a normative way. This proposed framework and its further developments can be used as a basis for water governance transition toward sustainability.

Posters – Monday 25th November 2019

A finite element 3D model to assess the impact of environmental changes on the coastal groundwater aquifer in Nauru

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Publish consent withheld

A GIS based graph representation for fault and fracture characterisation

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Fault and fracture networks channel or impede fluid flow in the subsurface. They become major drivers of the flow dynamic in low-porosity rocks, where their geometry and topology govern the groundwater flow on a regional scale. As topology is related to the percolation threshold, it represents one of the crucial metrics to characterize fluid flow properties. The objective of this study is to design an efficient and robust method to characterize networks in terms of fluid-flow properties and link the components of the network to raster data for further analysis.

We present an automated framework for data extraction and analysis based on graph representation of 2D fault and fracture networks. Initially, the geometric parameters and their distributions are extracted, and the subsequent analysis is based on a georeferenced graph that is linked to raster data, such as elevation models, magnetic intensities, or gravimetric data. This approach allows for

characterizing geometric and topologic properties of the entire network, for determining potential sub-networks, and for applying standard graph algorithms.

Application of the framework to a synthetic data set and a real-world case study from the Musgrave Province in South Australia demonstrates the efficiency of our method in handling natural fault networks, in analysing these networks statistically, in assessing connectivity, and in linking the networks to geophysical data. The algorithm can also be applied to surface water drainage networks.

The framework produces a georeferenced graph with edge and vertex weights derived from raster data. Minor flaws in lineament digitisation such as gaps in fault traces are automatically corrected. The completeness of mapped network can be evaluated based on the statistic and topological analysis. The graph representation can be used to assess dominant groundwater flow direction, or it can be used to derive equivalent permeability fields for regional groundwater models.

An analytical model for predicting evaporation rates from bare soils

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Prediction of evaporation rates from unsaturated soil surface remains a challenge due to the difficulty in simulating the interactions in the soil-air interface. A physically based analytical model of soil-air interface is critical to predict the evaporation rates from unsaturated bare soils. The conditions of the topmost soil layer (TSL) determine the surface resistance, which is used to predict evaporation rates, when the vaporization plane remains in TSL at initial stage of drying process. The shape of the soil particle in TSL is more similar to sphere, rather than cuboid which has been widely adopted in past studies, thus the sizes of pores between soil particles are gradual. The funnel-shaped pores in TSL is taken into consideration, which can result in the reduction of evaporation area and the increase of thickness of viscous sub-layer during drying process. Through monitoring the distribution and changes of vapor density in TSL by infrared camera, the model is validated against laboratory experiments on the drying process of initially water-saturated soil columns under nonisothermal conditions. The evaporation rates calculated using the surface resistance predicted by model agree better with the laboratory experiments, as the model is based on a more accurate simulation of the soil particle shape in the TSL.

With the consideration of the soil pore size distribution, the model is applicable to different soil types. The model offers a physically based method for predicting evaporation rates from bare soils and provides new insights into the intrinsic links between evaporation rates and soil particle shapes.

Are heat tracers applicable to quantify groundwater-surface water interaction in a tidal wetland?

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Within the last decade the use of heat as a natural tracer has become an established technique in hydrologic research. As the measure of heat, temperature is a robust and stable environmental parameter and can be collected easily. Nowadays, temperature timeseries are collected in the field and analysed with numerical or analytical tools which allow for the calculation of groundwater flow speed and the estimation of physical parameters of the subsurface. While heat tracer methods have proven their usefulness in groundwater-surface water interaction studies in rivers and lakes (i.e. non-tidal environments), they have not yet been applied to tidal wetlands. Our study fills this knowledge gap and investigates the applicability of heat tracers and its limitations in this rapidly changing environment. Moving with up- or downwelling groundwater, heat tracing techniques make use of the influence of the transported heat on the environment. For a meaningful analysis temperature signals must be suitably registered along a groundwater flow pathway. In rivers and lakes, with their cyclic diurnal thermal regime and a relatively steady hydrology this is usually provided. Tidal wetlands on the other hand experience flooding and draining in a fast succession, which challenges the application of heat tracers. Therefore, we investigated if heat tracing techniques are adequate to identify the rapid hydrologic changes in a tidal wetland. Results from a three-weeks long temperature and hydraulic head time series collected in the Hunter River Estuary near Newcastle, NSW, Australia, show that tidal wetlands provide enough information for heat tracer analysis. In comparison to river and lake systems, the variability of the tides and the offset between their lunar cycle and the diurnal temperature cycle creates even additional information for time-series analysis. However, since the period of the cycles is short, most information is only transported into shallow layers of the subsurface. This means that all measurements must take place in a relative narrow section of the wetland's sediments, and hence need to be precise and accurate in space.

Assessing risk to a coastal aquifer using a multi-model approach

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Groundwater from the Quaternary Limestone aquifer in the Uley South Basin has been an important resource for the Eyre Peninsula since the 1970s, currently meeting approximately 70% of water demand through the South Australian Water Corporation's (SA Water) supply network. However, this groundwater resource is sensitive to variation in rainfall (recharge) and extraction and may be prone to risks from over-exploitation including increased salinity via inflow from the underlying Tertiary Sand aquifer and seawater intrusion. Therefore, SA Water commissioned South Australia's Department for Environment and Water to simulate groundwater flow and impacts of potential future groundwater extraction and climate change in the basin.

A multi-model approach was taken to simulating groundwater flow in the Uley South Basin, acknowledging conceptual uncertainty. Additional parameter uncertainty work was also conducted. The Seawater Intrusion package (SWI2) was used in MODFLOW to simulate the position and movement of the freshwater-seawater interface. Model scenarios were developed in consultation with SA Water, and simulate the impacts of various extraction regimes under a changing climate. Model results show that pumping to meet projected demand by 2040 may have adverse impacts on the resource, while reduced pumping in the short term is likely to lead to groundwater level recovery. The results have helped SA Water to plan future supply options for the Eyre Peninsula.

Closing the loop - delivering landholder supplied groundwater data to the community in coal seam gas areas, Surat and Bowen basins, Queensland

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Objectives: Groundwater Net is a project run by the Department of Natural Resources, Mines and Energy (DNRME) in Queensland. It is a monitoring program where landholders in coal seam gas (CSG) areas are engaged in community groups and provided with information on the CSG industry and groundwater systems. A large part of this project is to encourage landholders to measure groundwater levels in their private water bores and submit this data to DNRME. Submitted data is delivered back to the community using the Groundwater Net Digital Report.

Design & methodology: The Groundwater Net Digital Report displays groundwater data in an easy to use, interactive way and provides context to the landholder data by relating it to data provided by both CSG companies and DNRME. Apart from groundwater monitoring data, the Groundwater Net Digital Report contains other relevant information that will be tailored to the needs and concerns of the community. Interactive maps are an important aspect, allowing the user to focus on their area and groundwater formation of interest and easily identify monitoring bores, CSG development and areas likely to be affected by CSG activities. The user is also provided with commentary on the significant groundwater formations, including some of the key hydrogeological characteristics and is guided through the groundwater level trends. Key monitoring points that show a good representation of the formation are identified with links to their location and water level data.

Original data & results: Landholders are encouraged to continue monitoring their water bores when they can see their data is being collected, analysed and delivered back to the community. The additional groundwater monitoring by landholders can also benefit government, increasing data availability and improving relationships with landholders. The Groundwater Net Digital Report helps to inform the community, providing access to contemporary, relevant information.

Conclusion: The CSG industry has brought with it a significant increase in the quantity, quality and interest in groundwater data. Providing a platform that clearly displays groundwater data sourced from the community, government and industry allows users to cross-reference and verify data from CSG companies and government, providing enhanced community confidence.

Complex interactions in modelling the floodplains of the Lower River Murray in South Australia

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Some hydrogeological systems are at the intersection of processes that interact in complex ways. One such example is the lower River Murray floodplain. Regional groundwater flows, river conditions, climate, land use, and environmental watering all impact potentiometric heads and groundwater salinity. This is of concern as the groundwater influences both vegetation health within the floodplain and also river water quality downstream.

Numerical groundwater modelling supports management decisions for the River Murray. South Australia's Department for Environment and Water has built a number of groundwater models of the SA floodplain; these vary greatly in terms of the processes simulated, their spatial and temporal resolution, and approach to salt movement. The models aim to estimate groundwater flux to the river, potential risks from groundwater to vegetation, or both.

This talk presents results from comparisons between four styles of groundwater model: (i) a regional model which neglects short-terms processes, (ii) a regional model modified to include short-term processes, but not further calibrated, (iii) a regional model that simulates flooding and environmental watering, and (iv) a detailed, floodplain-scale model that simulates both short-term flow processes and solute transport.

The development, calibration and validation of these models has demonstrated that the modelled floodplain water balance is extremely sensitive to assumptions, with sometimes unexpected interactions. The findings underscore the difficulties of retrofitting a model designed for one purpose to answer questions of other kinds. They also demonstrate how each key process – changing river levels, evapotranspiration, managed and unmanaged inundation – influences floodplain water balances during and after floods. Some essential parameters are still poorly known, due to heterogeneity or difficulties in data collection. Nevertheless, it is possible to build floodplain groundwater models that produce sound results, as demonstrated from post-audits.

As environmental management of floodplains becomes more nuanced due to water availability, the ability to achieve the best environmental outcomes for the water available becomes critical. Groundwater modelling has a part to play in this and understanding how the model assumptions impact the outcomes is an important step to be able to use these tools in the future.

Effective groundwater monitoring of the Perth Superficial aquifer during a controlled CO_2 release trial at Harvey, Western Australia

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Carbon Capture and Storage is one of the emerging climate change-mitigation strategies and involves the injection and storage of greenhouse gases in deep aquifers/reservoirs. However, studies related to the impacts from storage and leakage of gases on water resources, especially in fault zone areas in Western Australia, have not been undertaken. We report the environmental monitoring results from a small-scale controlled CO_2 release trial where approximately 38 tonnes of food grade CO_2 were injected into a fault zone in the Eneabba Formation at a depth of 350 m in the Shire of Harvey, Western Australia. The aim of the trial was to evaluate the ability to monitor and detect unwanted leakage of CO_2 from subsurface storage by a variety of environmental surveys and geophysical techniques. Groundwater level and samples were collected from wells completed in the Perth Superficial aquifer, located near the injection site. A designated groundwater monitoring well was drilled in close vicinity to the injection well and instrumented with fibre optics providing continuous temperature measurements along the entire length of the well. Water samples were analysed to detect any changes in water chemistry (pH, electrical conductivity, alkalinity, anions, cations, organic species, dissolved CO_2) associated with the CO_2 injection activities. Results were compared with monitoring data from the Western Australia Government's groundwater database, from periods before, during and after injection as well as with relevant water guidelines. Based on environmental monitoring results for the injection site, injection of CO_2 into the Eneabba Formation has not resulted in any significant changes to water quality of the Perth Superficial aquifer. The project demonstrated that major component analysis along with measurement of dissolved CO_2 could satisfy monitoring requirements for the assessment of impacts from storage and leakage of CO_2 on the water resources.

Evaluation of unsaturated zone models coupling to MODFLOW for a more robust modelling of groundwater-vegetation interaction

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Modelling the biophysical interaction occurring in the unsaturated zone (UZ) produces a direct effect on the groundwater dynamic. The simulation of this interaction is performed through different approaches. Conceptual models, which represent a simplified UZ dynamics, are often selected for the coupling to groundwater models when computationally intense uncertainty evaluation techniques are used. On the other hand, physically based models are widely used, particularly at the field scale, for an accurate representation of the water and solute dynamics. Finding the best model balance to improve the representation of groundwater-vegetation interaction while maintaining computational feasibility is essential for the appropriate representation of spatially distributed net-recharge.

We evaluate here the performance of two different UZ models coupled to MODFLOW. A simplified one-dimensional UZ model solves the water balance for each compartment in which the UZ is discretised. The coupling is performed with specific attention posed to the water table-vegetation interaction and to the dynamical calculation of the thickness of the UZ. Model results are spatio-temporally distributed net-recharge values, soil water content and water table levels.

The physically based model SWAP, which simulates the water, solute and heat transport in the UZ by solving the 1-D Richard's equation, was also coupled to MODFLOW. The coupling was performed similarly to the simplified UZ model. Such coupled models were tested at different locations in the south-east of South Australia, under heterogeneous conditions of groundwater-vegetation interaction.

The simple model configuration shows good results and correlation for groundwater heads and soil moisture, particularly for the topsoil column. Because of the reduced computational load, it was found to be suitable for inverse modelling calibration and uncertainty evaluation algorithms. The coupled physical model represents the soil-water content at different depths in more details, accounting for the heterogeneity of soil parameters, capillary rise and solute transport. The latter is not simulated in the simple coupled model and should be considered for some arid environments where salinity affects plant extraction.

The coupling of the simple and flexible UZ model and the testing in a semi-arid South Australia environment have shown that it has the potential to be effectively applied for data scarce regions where remote sensing is the only source of information. Such a model has been also used for data assimilation experiments, providing useful tools for uncertainty reduction techniques.

Field and numerical investigation of the evaporation induced unstable density flow within the tidal wetland system

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Tidal wetlands are a critical interface between land and ocean providing habitat for a large range of flora and fauna. The health and evolution of these wetlands depend on the hydrodynamically-controlled physical, chemical, and biological processes. That is, these processes are affected by tides, water density variations and evapoconcentration of salt. Infiltrated rainwater forms a terrestrial groundwater lens which overlies intruding seawater and flows to the ocean. Tides drive mixing of these waters and have a strong influence on pathways and residence times. The distribution of salt, its concentration and the pathway of nutrients all influence marsh vegetation.

Field monitoring campaigns were carried out to map the temporal and spatial salt distribution across a subtropical wetland system located in South-eastern Queensland, Australia. 2-D numerical simulations were conducted to examine the pore water flow and salt distribution patterns in a cross-shore section of the marsh soils under the influences of the spring-neap tide and evaporation. Simulation results, consistent with the field data, showed that soil surface (especially root zone) salinity in general increases with the marsh surface elevation due to evapoconcentration. The surface topography governs the area and duration of seawater inundation over one tidal cycle. A hypersaline zone may form near the

spring high tide boundary, as long as a hydraulic connection exists between the evaporating soil surface and the water table. This connection is the key to maintaining evaporation. The evaporation induced salt accumulation on the marsh surface can result in unstable flow driven by the upward density gradients, depending on the slope of the marsh surface. The findings from this study may help understand the ecohydrological functioning of these estuarine systems.

GAB Springs Adaptive Management Plan

Lynn Brake [1]

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The Great Artesian Basin has more than 450 spring groups which are made up of more than 7000 individual springs. As these springs are rare water sources in a generally arid landscape, they are recognised as icons of national and international significance. The basin is one of the few large artesian systems in the world that has not been severely degraded by water extraction or land use.

There are two major threats to the basin springs:

- Reduction in water pressures that reduces spring flows
- Surface disturbance in and around springs that impacts ecosystems and cultural values.

An adaptive management plan has been developed for the springs that presents evidence-based strategies for protecting springs while balancing the needs for groundwater extraction and productive land use. The plan is focused on effective adaptive management practices that are cost-effective and acceptable to water users and landholders.

Project team:• Lynn Brake Senior Research Fellow University of South Australia; Founding member of the GABCC • Colin Harris President of Friends of Mound Springs • Simon Lewis Friends of Mound Springs executive • Travis Gotch Chief Researcher on the NWC GAB Springs Study •Professor Megan Lewis University of Adelaide • Assoc Prof Andy Love Flinders University • Anne Jensen Project Officer • David Leek Principal Policy Officer Department of Environment and Water SA

Mr Brake has managed the development of the 'Great Artesian Basin Springs Adaptive Management Plan' on behalf of the South Australian Arid Lands Natural Resources Management Board for the Australian Government Department of Agriculture.

Mr Brake is Chair of the Water Advisory Committee for Far North Prescribed Wells area in South Australia and also sits on the basin governments' Great Artesian Basin Coordinating Committee which advises Australian, State and Territory Ministers on efficient, effective and sustainable whole-of-resource management of the Basin.

Mr Brake's attendance at this conference has been funded by the Australian Government Department of Agriculture through a sponsorship arrangement with the Royal Society of Queensland. Through this sponsorship, the department aims to help raise awareness of the plan and to Qiuying promote its use by basin landholders, governments and industries.

Groundwater quality assessment and its driving factors

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Water quality, ground water especially is paid more and more attention by publics recently. What factors resulted in current ground water in the agricultural zone? more than 200 ground water samples were taken in the North China Plain at the lower reaches of the Yellow River. The results presented that about one quarter of total samples have higher nitrate concentration than that of drinking water standard. Even some heavy metals are over-standard. Human activity and nature resources control current water quality from long-term agricultural to coastal zone where were developed as potential arable farmland in the past ten years. These results will help the authorities to manage ground water and pay more attention to sources.

How groundwater age relates to meandering history: insights from a simplified physical model

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Objectives: The distribution of groundwater age in aquifers is strongly affected by facies heterogeneities. We propose to explore this relationship between heterogeneities and groundwater age in hypothetical fluvial aquifers built up by different meandering histories.

Methodology: We use the fluvial and stratigraphic modules of the Channel-Hillslope Integrated Landscape Development Model (CHILD) [1, 2] to simulate the evolution and deposits of a meandering river using a simplified physical model. Varying input parameters, especially aggradation or incision rate, lead to varying meandering histories. This results in 3D models with variable sand proportions. We assume constant porosity and permeability for sandy and muddy deposits. Then, we use PFLOTRAN [3] to simulate subsurface flow and groundwater age based on a flow direction parallel to the channel belt.

Results: In our models, sandy deposits from the rivers form the only permeable medium. Thus, the channel belt in each model stands out as a major preferential pathway for the groundwater flow, with lower ages than lateral floodplain deposits and the basement below. As they migrate within the channel belt, meanders rework previous deposits. As a result, the channel belt itself becomes heterogeneous, with varying sand proportions creating baffles. These baffles decrease the connectivity within the aquifer and increase groundwater age. Low aggradation rates and periods of incision favour such reworking, leading to more heterogeneous channel belts.

Conclusion: Varying river migration and aggradation or incision rates lead to heterogeneous channel belts with varying proportion of sandy deposits. If the channel belt itself funnels the flow, its heterogeneities lead to heterogeneous groundwater ages, even at short distances. This work paves the way for detailed sensitivity analyses linking parameters controlling river evolution to subsurface heterogeneities and groundwater age.

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How realistic are groundwater drawdown predictions? A quantitative evaluation of reported specific storage values

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Specific storage (S_s) values are important for quantifying groundwater storage and for analysing transient responses within confined aquifers. In contrast to hydraulic conductivity, there are relatively few S_s values available to use in numerical analysis and modelling. The objective of this investigation was to collate S_s values reported from laboratory and aquifer testing and groundwater modelling reports for comparison with the physical limits for S_s recently established using poroelastic analysis (Rau et al., 2018). This quantitative evaluation included in situ S_s values for aquifers and aquitards from tidal subsurface analysis (TSA), as recently reviewed by McMillan et al (2019).

It was found that S_s values used in transient groundwater models were over a larger range ($1x10^{-7}$ to $5x10^{-3}$ m^{-1}, n=115 over 7 site models) than the combined range of both laboratory ($9x10^{-6}$ to $1x10^{-3}$ m^{-1}, n=53), aquifer test values ($2x10^{-8}$ to $1x10^{-4}$ m^{-1}, n=14), and values from TSA ($2x10^{-6}$ to $4x10^{-5}$, m^{-1}, n=17). Some S_s values measured by TSA were higher than the poroelastic limit due to more complex interactions with clay. Laboratory tests typically resulted in S_s values that are unrealistically high, often due to disturbed or re-constituted samples. Field values of S_s from aquifer pump testing are useful, though have limitations.

More than half of S_s values used in these models exceed the poroelastic limit and could result in under-prediction of drawdown in those layers. Consequently, there is a clear need to improve the reliability of drawdown predictions by using appropriate values for S_s, recharge and other factors that control groundwater storage. TSA methods could be further developed and used to obtain in situ S_s values for confined aquifers that are poroelastic, including alluvium and rock. Further collation and quantitative evaluation of S_s values are in progress.

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Hydrochemical assessment and quality classification of the complex terminal Aquifer in the region of Oued Righ (Sahara Algerian)

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Oued Righ valley is part of the north-eastern Algerian Sahara, it is characterized by an arid desert climate with very high temperatures in summer.

The waters of the complex terminal aquifer in Oued Righ pose serious physical and chemical quality problems; they are highly mineralized and the concentration of some elements that surpass the recommended norms stated by the norm of Algeria.

In this work our interest is focused on interpreting the results obtained using different approaches; hydrochemical, statistical to demonstrate the correlation between the chemical composition of water of the Complex Terminal and lithology.

Identifying groundwater-surface water interactions and groundwater geochemistry in the Upper Murrumbidgee Catchment using surface water surveys

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Evidence suggests that potable groundwater occurs within the fractured crystalline rock of the Upper Murrumbidgee catchment, with anecdotal reports that bore yields and fracture networks could form aquifers capable of sustaining regional population growth and agricultural development. However, little knowledge relating to groundwater flow or recharge and discharge mechanisms exists. Hydrogeochemical methods are particularly useful in studying groundwater in complex geological environments. Unfortunately, limited information regarding groundwater geochemistry exists in this catchment. Surface water surveys provide an opportunity to quickly obtain preliminary information regarding groundwater-surface water interactions and likely groundwater geochemistry.

Four surface water surveys were conducted at up to 285 sites during wet and dry conditions from September 2017 to April 2019. Physicochemical parameters were collected at each site where water was present, along with samples for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and dissolved ion analysis.

Surface water geochemistry is influenced by interactions between altitude, rainfall, and outcropping geology. Stream electrical conductivity (EC) is positively correlated with altitude and negatively correlated with rainfall in all sub-catchments except the Yass River catchment. Outcrop geology also influenced stream EC, with the EC lowest over Paleozoic granite and granodiorites; moderate over Paleozoic felsic volcanic, Cenozoic mafic volcanic, and Cenozoic alluviums; and highest over Ordovician metasediments. Dissolved ion chemistry is similarly influenced by outcrop geology and is reflected in preliminary groundwater surveys. The cations Na^{+} and K^{+} dominate Paleozoic granite and granodiorite waters while Ca^{2+} and Mg^{2+} dominate Cenozoic mafic volcanic waters. Bicarbonate (as HCO_3^{-}) is the dominant anion, with elevated HCO_3^{-}/Cl^{-} associated with Cenozoic mafic

volcanics. This suggests that mineral weathering dominates hydrogeochemical processes. Spatial distributions of stream water $\delta^{18}O$ and $\delta^{2}H$ highlight potential baseflow areas. Results suggest that potable water is highly probable within Paleozoic granite and granodiorites, with water Na^{+}-K^{+}-HCO_3^{-} dominated. Potable water is possible within Paleozoic felsic volcanic, Cenozoic mafic volcanic, and Cenozoic alluviums, with water potentially more suitable for agricultural use due to the higher Ca^{2+}, Mg^{2+}, and HCO_3^{-} content. Ordovician metasediment water is more suitable for agricultural use.

Surface water survey data will be used in this study to optimise groundwater survey design and develop improved conceptual models to describe groundwater flow and recharge and discharge mechanisms in fractured rock environments in the Upper Murrumbidgee catchment. This will increase our understanding on how water resources may be utilised to support regional population growth and agricultural development, providing future water security for the region.

Improving FEFLOW well boundary constraints using Theis-forward solution

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FEFLOW's boundary constraints are a robust and efficient measure to establish maximum pumping rates in well boundaries and avoid that unrealistic pumping volumes are extracted from the model. These constraints act on the well boundaries by switching the boundary type from prescribed flux to prescribed head, with boundary values equating to the value of the constraint.

In situations where the groundwater level moves below the constraint level due to different mechanisms (for example, open pit and tunnel boundaries), the prescribed head boundary implemented by the boundary constraint will provide water into the aquifer, which may not be desired in the simulation.

A FEFLOW plugin have been developed to improve the simulation of well boundaries in these situations. A maximum pumping rate for each well is calculated prior to the time-step execution, using a Theis-forward solution. This solution utilises the transmissivity and storage terms defined by the user, and the time-step length. If the prescribed pumping rate is higher than the maximum pumping rate estimated by the forward solution, the boundary value is adjusted to the maximum rate.

The plugin has been tested in synthetic and real-world cases in open pit mines. Preliminary results suggest that the plugin works efficiently and helps with the model stability, since it eliminates the need for boundary constraint checks. Nevertheless, it may not be ideal in situations where multiple boreholes are located close to each other, as the Theis-forward solution does not account for borehole interference.

Incorporating uncertainty in the design of a woodchip denitrifying bioreactor

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Denitrifying bioreactors that target filtration of nitrate from farm drainage water are gaining recognition as a tool for reducing nitrate pollution from agricultural areas. While the hydrologic regime and nitrate concentrations constitute two fundamental environmental variables that determine the size of a denitrifying bioreactor, the issue of over- or under-treatment of water that might otherwise promote undesirable pollution swapping phenomena and construction costs also need to be factored into the overall design process. Conventional methods for optimizing the design of denitrifying bioreactors generally rely on deterministic models, even though many of the design parameters are not known with confidence.

In this work we demonstrate how stochastic optimization can be used to enhance the long-term performance of a groundwater fed, woodchip denitrifying bioreactor. We apply an alternative design philosophy and demonstrate how the bioreactor design process can be improved through application of stochastic methods. The design aspect of an 'in-stream' bioreactor planned for installation on a farm in New Zealand is structured as a multi-objective performance optimization problem that is solved in a stochastic framework, using freely available open source tools. Uncertainty considerations regarding values of physical parameters that govern bioreactor performance are incorporated into the assessment, from which a Pareto set of optimal designs was obtained. A 75 m long bioreactor of 1.5 m height was selected as the preferred choice from the optimal set of design solutions. Assuming a 10-year operational life, it is predicted that the cost of nitrate removal by the planned denitrifying bioreactor will be NZ$9.70/kg-N (approx. AU$9.20/kg-N).

Losing condition or evaporation: Why the Thirlmere Lakes in NSW are falling dry?

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The Thirlmere Lakes National Park is located about 75 km west-south-west of Sydney in New South Wales, Australia. The Park contains five small freshwater lakes in a cut-off meander of a Tertiary-age river valley. Water levels in Thirlmere Lakes are known to have fluctuated over time, but little is known about their hydrogeology and hydrology. Over the last decade a strong decline in water levels has occurred, leading to concern in the local community. Since the cause of the decline is unknown, our project aims to identify the controlling factors for the lake water levels by investigating the spatio-temporal groundwater-surface water interactions and the degree of connectivity between the lakes. While the lakes contained sufficient surface water, we were able to measure lake water and groundwater temperature time series for the application of heat tracing techniques. A piezometric monitoring

network has now been established to provide detailed information of the groundwater water levels near and between the lakes. The piezometer installation also allowed for a stratigraphic mapping of the shallow unconsolidated aquifer/aquitard systems. These stratigraphic logs show heterogeneities in the sedimentary sequence to an extent that, for individual lakes, different degrees of connectivity and mechanisms of groundwater-surface water interaction can be anticipated. Results from the heat tracing analysis illustrate that locations with a low thermal conductivity, which is typical for the prevalent peat layers, show low or stagnant groundwater-surface water exchange; whereas the locations with higher thermal conductivity have higher and gaining groundwater flows. Even during the recent drying phase, some lakes appear to have a net groundwater gain, which is an indication that the declining lake levels are dominated by evaporation. Predominantly losing conditions are expected if the lakes were drying primarily as a result of declining groundwater levels. Hence, in response to recent declining surface water levels, the gaining portions of the lakes might be receiving groundwater inflow from connected shallow conductive layers. Without these groundwater contributions the lakes would likely dry much faster.

Machine learning emulation for reactive transport models

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Reactive transport groundwater modelling is complex and computationally expensive, particularly in the risk-based decision-making framework that requires predictive uncertainty to be quantified. This limits its application in practical engineering solutions for groundwater contamination management and remediation at site/regional scale. Machine Learning (ML), in the form of a versatile data-driven surrogate model, has been tested recently to tackle the huge computational burden for regional groundwater flow modelling. However, its application in more complex numerical reactive transport models is rarely reported. Highly non-linear reactive transport models pose extra difficulty for emulator training. In the present study, three different ML models (Genetic Programming, Gaussian Process and Deep Neural Networks) are tested to substitute the process-based numerical model. Three types of predictions are emulated: (i) the contaminant concentration at a specific location and time (point prediction), (ii) the objective function used for model calibration and uncertainty analysis (lumped prediction) and (iii) the contaminant breakthrough at a specific location (time-series prediction). Although the three ML models can all potentially deliver a good performance, their requirements for the number of training samples and training time are different. The pros and cons of the different ML models will be discussed for each type of prediction. The numerical experiment is conducted based on a generalized reactive-transport model for onshore conventional gas fields in southeast South Australia where potential contamination pathways have been identified. Equipped with the efficient ML models, risk-based decision making can be supported by a reactive transport model. The emulators can also be integrated into operational water resource management platform to allow quick operational modelling.

Modeling Groundwater Budget under increased anthropogenic pressure in the Modjo River Catchment, Central Ethiopia

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Modeling of groundwater budget provides basic information for water resource protection, management, and development in Modjo River catchment. Hydrology information such as rainfall and evaporation were collected from the National Metrological Agency. Pumping well location, pumping rate and aquifer thickness were obtained from the Oromia water works supervision and constructions. In this study, steady-state groundwater flow model was constructed and calibrated to evaluate changes in groundwater budget under scenario of increased groundwater withdrawals and decreased recharge rates. The result of steady-state model shows that, the direction of groundwater flow is from the North (highland area) to the south (rift floor) and coincides with the direction of stream flow in the study area. Increasing the current withdrawal from the aquifer by 20% resulted in reductions of base flow by 11.1%, subsurface outflow by 2.2% and average water level by 2.78 m (with a maximum of 21.1 m and a minimum value of 0.2 m around vicinity of lakes at Bushoftu air force well). Increasing the current withdraw from the aquifer by 40% resulted in reductions of base by 21.7%, subsurface outflow by 4.54% and average water level by 5.16 m (with a maximum of 24.24 m and a minimum value of 1.13 m around vicinity of lakes in Bushoftu air force well). Similarly, increasing withdrawal by 50% resulted in reduction of base flow by 53,359 m^3/day, which is about 27% of the base flow under calibrated steady state mode. The scenario reduced recharge by 25% was investigated and the heads calculated for this scenario shows a maximum decline of the water level by 14.18 m and a minimum of 1.37 m (around vicinity of lake in Bushoftu Air force well) in the catchment In conclusion, increase in groundwater withdrawal and decrease in recharge in the study area will have a negative impact on surface water, downstream groundwater dependent ecosystem and causes an environmental problem in general.

Near real-time decision support insights with fully-integrated hydrologic models

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Providing a scientific basis for water management, and assessing the physical characteristics underlying hydrologic risk, typically requires watershed-scale assessments that encompass a few hundred km2 at a minimum. However, as an example, water resources for agriculture or resource development often require an understanding of river basin scale processes, which can cover areas up to 100,000 km2. Given the recent increase in losses attributed to large-scale extreme climate related events (i.e. overland pluvial flooding, excess moisture, and drought), and the concern that the frequency of these events will progressively increase in response to climate change, there is growing demand for large-scale hydrologic risk forecasts to

support decision making. Because of complex interactions between climate, surface water, groundwater, and soil moisture across large watersheds, robust physically based 3-D integrated hydrologic models provide a holistic means of performing water-related risk forecasts.

In this talk we will present a near real-time hydrologic forecasting platform for 80,000 km^2 of Southern Ontario, Canada. This forecasting system leverages a regional database containing hydrostratigraphy, soils information, land cover/vegetation, and topography. From this database, local high-resolution forecasting models are developed driven by an ensemble of weather forecasts and updated using an advanced data assimilation scheme with field-based sensors. Hydrologic forecasts are generated at daily frequency for a two-week forecast interval, or in the case of an extreme event a high-resolution 18 hr forecast is released hourly for emergency response support. Since the platform uses the fully distributed, physically based model, HydroGeoSphere, it can generate forecasts for both gauged and ungauged locations. The forecasts are disseminated to watershed stakeholders via a cloud-based portal that has been developed with watershed-level dashboards and on-the-fly analytics to support both short- and medium-term decision making for watershed management, flood response, and agriculture.

Numerical modeling of surface water and groundwater interactions in the Stoney Creek Watershed, British Columbia

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The demand for water in the Stoney Creek watershed, British Columbia, necessitates the management of groundwater and surface water as hydraulically connected systems. However, the interactions between groundwater and surface water in this watershed have not been investigated yet. This was addressed by developing a new numerical groundwater model for the watershed that incorporates surface water features. A particularity of the model is that it was bounded by two surface water features (Stoney Creek and the Nechako River/Tachick Lake system). A surface and groundwater level monitoring program was also implemented to independently test the predictions from the model. The simulated regional water table indicated that Tachick Lake is a groundwater flow-through system, with discharging groundwater either exported by surface outflow or groundwater recharge, whereas Stoney Creek was regionally gaining and largely groundwater-fed. The comparison between simulated and observed heads showed that the numerical groundwater model is capable of estimating the location of the water table across the watershed with a reasonable precision (correlation coefficient of 89%) and provides a platform to evaluate potential variations in the groundwater flow system under different climate change and development scenarios. Results of this study could be helpful for decision makers in allocating the groundwater and developing sustainable water resources strategies in the Stoney Creek Watershed.

Numerical modelling of tidal effect on contaminant transport in coastal aquifers

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Groundwater flow in mostly homogeneous coastal aquifers has been widely studied recently. Saltwater with tidal fluctuation leads to transient variable-density flow in a sloping aquifer-ocean interface with a mixing zone affected by e.g., aquifer heterogeneity, tidal amplitude and density contrasts. In particular, the tidal fluctuation is able to change the salt distribution, contaminant travel time and pathway through the aquifer. The tidal range is controlled by many transient factors which act to change the tidal amplitude over time. The research on contaminant transport in these zones, especially with aquifer heterogeneity, a sloping land-ocean boundary and tidal forcing remains limited. To quantify the effect of different tidal amplitudes etc on the contaminant flows, a numerical modelling study is developed. With tidal amplitude increasing, the upper saline plume becomes larger, which leads to the increase of contaminant travel time and changes of the pathway. In layered heterogeneous aquifer system, low-permeability layer in the tidal mixing zone reduce the salt distributions and contaminant concentration discharge to the ocean, while increasing contaminant travel time compared to the unconfined homogeneous aquifers.

Pore pressure modelling of pit slopes - the influence of drill holes

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2D or 3D Pore pressure modelling of mine pit slopes is a key input to pit slope stability evaluations and is often informed by limited piezometric data. Hydraulic data is usually sourced from onsite hydraulic testing, although often modified through numerical model calibration. Modelling typically ignores the hydraulic effects of open drill holes on the hydraulic characteristics of the rock mass. Each of these holes, if not cemented following completion, represents a conduit for groundwater movement, dependant in part on the tendency of the hole to collapse following completion. These drill holes may significantly alter the hydraulic properties of the pit slope, particularly in the case of sub-horizontal geological units with pronounced vertical layered anisotropy.

This paper evaluates the influence of open drill holes on the overall hydraulic properties of the rock mass and on the pore pressures present in a series of "typical" pit slopes. A simple, limited extent 3D MODFLOW model was developed to evaluate pore pressure distributions with, and without, the effects of open vertical drill holes. The evaluation found that the presence of open drill holes can have a significant effect on the vertical hydraulic conductivity characteristics of the rock mass, particularly in rock masses with layered vertical anisotropy. Greatest effects will typically occur in interim pit walls, where density of drill holes is usually highest. Exclusion of these effects can lead to overly conservative estimations of pore pressure. The evaluation also highlights the opportunity for utilizing open pit slope drill holes as passive vertical drains. Where these holes cave, maintenance of the holes through installation of perforated casing may improve pit slope

drainage. Where the holes extend into a deep aquifer, pumping of the aquifer will further drain the slope via the passive vertical drains.

Porewater exchange drives solute export from a temperate mangrove wetland

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Porewater exchange is usually the least quantified process in delivering dissolved material from wetlands to coastal waters, although it has been recognized as an important pathway for the transport of carbon, nutrients and trace metals to the ocean. Here, surface water fluxes of dissolved manganese (Mn), iron (Fe), dissolved organic/inorganic carbon (DOC/DIC), total dissolved nitrogen (TDN) and phosphorous (TDP) were estimated from a temperate mangrove wetland (Kooragang Island, Newcastle, NSW, Australia). Radon, a natural groundwater tracer was used to construct a mass balance model to quantify porewater exchange rates and evaluate the porewater-derived material contribution to the overall wetland Surface water export. A 25-h time series dataset depicted a clear peak of Mn, Fe, TDN, DOC and radon during ebb tides which related to porewater discharge. Porewater exchange rates were estimated to be 14.0 ± 6.3 cm/d, mainly driven by tidal pumping, and facilitated by a large number of crab burrows at the site. Results showed that the wetland was a source of Mn, Fe, TDN and DOC to the adjacent river system and a sink for TDP and DIC. Surface water Mn, Fe, TDN and DOC exports were 4 ± 1, 150 ± 57, 21 ± 5 and 107 ± 29 mmol/m^2 wetland/d, respectively. Porewater-derived Mn, Fe, TDN and DOC accounting for ~ 95, 100, 89 and 54% of the wetland surface water exports demonstrating the important role of porewater exchange in driving dissolved material export from the mangrove wetland. Additionally, mangrove porewater delivered at least 2 orders of magnitude greater TDN and DOC to the coastal ocean compared to the much larger river system. Our study indicates that temperate mangrove wetlands can be a major source of dissolved material to coastal waters and that mangrove porewater exchange should be accounted for in coastal trace metal, carbon and nutrient budgets.

Quantifying groundwater abstraction in the face of imperfect data

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Assessment of resources and modelling of groundwater systems usually require quantification of groundwater abstraction (use). With increasing frequency, water takes are metered and data becoming available. However, there is often a disconnect between the data required for an assessment and that which is available. Furthermore, data for smaller (often permitted or unconsented) takes does not exist.

We will outline two approaches for quantifying groundwater abstraction. The first approach estimates permitted groundwater use based on available permit information, land cover, agricultural statistics, and other data (including probably source of water). The second approach uses consent information and converts this to a likely actual take based on climate, crop types, and irrigated areas.

These approaches have been used to quantify groundwater takes in the face of missing or imperfect data. In one case study, the results have informed policy decisions; in other cases, the results have been used as inputs to a groundwater model.

A more innovative approach to making use of data is often needed to make use of available information and enable us to understand groundwater use, particularly in cases where data are limited or non-existent.

Sediment transport in porous media due to groundwater discharge

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Groundwater discharge (or seepage flow) provides significant fluxes of dissolved chemicals and contaminants to the land surface and water bodies (e.g., oceans, lakes, streams, etc.) which plays an important role to the survival ecosystems in these regions. In some situations, groundwater fluxes may also cause subsurface particles movement and transport them to the surface land and/or surface water bodies. In this study, first the different forms of subsurface particle movement due to groundwater discharge is reviewed and categorized in two main groups including 1) the passage of small particles through immobile pore networks (suffusion) and, 2) the sediment transport through preferential pathways. The latter is divided to three subgroups including preferential flow through a cohesive soil layer leading to the vertical transport of particles from the underlying non-cohesive sediment body, preferential flow within a non-cohesive soil layer caused by localised discharge from below (e.g., due to a fault or fracture) and, widespread fluidisation giving the appearance of boiling sand due to sufficiently high hydraulic gradient. Previous studies do not distinguish between the initial causes and driving processes associated with different forms of subsurface sediment transport; hence, expressions are developed in this study by force balance analysis acting on subsurface particles including seepage (drag) force, buoyancy force and particle weight, to approximate the condition under which groundwater discharge will transport particles to the surface. New simple formulae are developed based on several simplifying assumptions and using existing theories related to piping failure (e.g., of earthen structures), soil fluidization and soil heave. Estimations of critical hydraulic gradients that lead to subsurface sediment transport are then compared to available laboratory test observations to assess the validity of the new formulae developed in this study. The comparison shows that the suffusion more or less is predictable using our simple method, while the condition leading to sediment transport through preferential pathways is poorly matched to the theory. The current study summarises the state of knowledge and knowledge gaps in sediment transport in porous media due to groundwater discharge which has a wide range of applications in coastal sediment transport, to surface water bodies and regions with strong groundwater discharge.

Simulation of contaminant capture by an hydraulic containment system

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Objectives: Using groundwater model to assess the efficiency of the hydraulic containment system (HCS). The HCS has been designed as a pump-and-treat mechanism to contain a nitrate/sulphate plume emanating from several identified contaminant source areas.

Design and Methodology: A 6-month (182-days, 26 stress periods) *transient* MODFLOW-USG model was been built with time from 22nd April 2018 to 20th October 2018, during which forward tracking has been simulated from the southern boundary of Source Zone A towards six extraction bores (EBS1, EBS2, EBS4, EBS5, EBS6 and EBS7, Figure 1) assuming a uniform effective porosity of 0.03 (3%). The assumed extraction at EBS1 follows the same pattern as EBS4. The mod-PATH3DU Version 1.1 particle tracking post-processing package, developed by S. S. Papadopulos and Associates, Inc., has been used in this study to compute and display three-dimensional pathlines based on groundwater flow outputs from MODFLOW-USG.

Original data and results: Four particle tracking model runs results show below:

Run 1 - Source Zone A was completely captured by three extraction bores (EBS1, EBS4, EBS6) after about 30 days, 85 days and a little more than 180 days, respectively.

Run 2 - With increased extraction rates on bores EBS1 and EBS4, all particles are captured after about 25 days and 80 days, respectively, and 180 days by extraction bore EBS6.

Run 3 - has a reduced porosity of 0.02, the same extraction rates as Run 1, and an extended simulation period (182-days plus 5 years). Except for one particle missing, Source Zone A was captured by four extraction bores EBS1, EBS4, EBS6 and EBS7 after about 30 days.

Run 4 - with reduced porosity, had the same extraction rate as Run 2. Source Zone A was also fully captured.

For 3% porosity, all Source Zone A was captured, which means both rates of extraction are optimal, the rates could be reduced if the bores are maintained in more continuous operation. For 2% porosity, the capture efficiency is similar. However, there is one new escape between EBS1 and EBS4 with lower extraction rate.

Conclusion: Despite periods of borefield shutdown, it is evident that the HCS bores are capturing all of the contaminants emanating from Source Zone A. The current average rates of extraction are close to optimal and should not be reduced much. However, the rates could be reduced if the bores are maintained in more continuous operation.

Simulation of the efficiency of Managed Aquifer Recharge schemes to support sustainable development of groundwater resources. The Minderoo- Peepingee (Minderoo) case study

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Upon the Minderoo pastoral station, Big Bend and Peepingee borefields are located alongside the Ashburton River which meanders over the Ashburton Coastal Plain in the Shire of Ashburton, Western Australia. Bores pump from a productive, heterogeneous, multi-layered aquifer system comprising fluvial and gravel interbedded with clay and silt about 30 m thick. Aquifer recharge is mainly by infiltration of intermittent river flows typically from December to August.

The current scheme comprises primary boreholes and a 3.2 m high weir constructed late 2010 for MAR to augment the groundwater storage and support sustainable development of groundwater resources in Minderoo water supply area for irrigation purposes. Extensive hydrogeological investigations undertaken since 2003 over both borefield areas have included airborne TDEM surveys, groundwater exploration and borefield development programs.

Increasing groundwater demand for both irrigation and water supplies for the town of Onslow, combined with the intermittent nature of river flow has necessitated further plans for expansion of the MAR scheme by constructing additional weirs and testing their efficiency and beneficial influence by means of numerical simulations. A finite - element numerical groundwater model was developed to simulate the groundwater regime and assess the reliability of the Big Bend and Peepingee Borefields with and without additional managed aquifer recharge weirs.

The borefield performance and the river aquifer interaction was simulated through 8½ years of typical river flow/aquifer recharge conditions. To test the uncertainty of the predictions to hydrological uncertainty, all modelling scenarios were followed by a 600-day simulated river drought.

The simulated performance of the Big Bend and Peepingee borefields through a 600 day river drought period suggests that both borefields should be able to each sustain abstraction at 2,000 kL/day, albeit that water levels in the Big Bend borefield would drawdown more than 50% of the available saturated aquifer thickness (filling factor) by the end of the drought period and some of the lower yielding bores (in low-K areas) in both the Big Bend and Peepingee Borefields would fail. The construction of a 3.2 m high, leaky MAR weir enhances groundwater seepage in the Ashburton alluvial aquifer, forming discernible groundwater mounding up to 5 km on either side of Ashburton River. The induced mounding takes several months to dissipate. Furthermore, each additional MAR weir has a cumulative effect on regional groundwater mounding, which is most pronounced immediately adjacent to each weir.

Snowy 2.0: pumped hydro-electric power in an alpine groundwater environment

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The proposed Snowy 2.0 project is a 2,000-megawatt pumped hydro scheme with capacity for 175 hours of storage. Snowy 2.0 will connect the Talbingo and Tantangara Reservoirs in the Kosciuszko National Park via an underground tunnel of approximately 30 km. A power station located almost 1 km underground will harness energy from water flowing from Tantangara Reservoir (approximately 1,215 mAHD) to Talbingo Reservoir (approximately 540 mAHD) to create electricity. When there is excess energy in the National Energy Market, the power station will operate in reverse, pumping water up to Tantangara Reservoir to be stored.

Several environmental assets that may be sensitive to groundwater impacts of the project have been identified. These include the Yarrangobilly Caves 8 km north of the project, a number of rivers and creeks under which the power waterway tunnel will be excavated and a number of alpine bogs and fens. A groundwater assessment is being undertaken to identify the risks and appropriate management measures.

Characterisation of the groundwater system and subsequent impact assessment for the project has involved conducting investigations in a challenging environment. Surface disturbance has been controlled to minimise impacts on the flora and fauna of the Kosciuszko National Park which, for months of the year, is covered in snow. Further, prior to the commencement of investigations for Snowy 2.0, there were no groundwater bores in the project area.

Characterisation of the groundwater system has involved collaborative efforts from a number of teams employing a variety of techniques including drilling of numerous bores, primarily along the power waterway tunnel alignment, to identify geological, geotechnical and hydrogeological properties, a range of downhole and ground surface-based geophysical surveys, slug tests and pumping tests, groundwater and surface water chemical sampling, stream flow gauging and isotopic analysis to identify water sources and pathways.

The combination of surface and groundwater chemistry, water balance and baseflow analyses indicate high recharge from rainfall, on the order of 30 percent of rainfall. Hydraulic testing has indicated hydraulic conductivities vary orders of magnitude across the project area.

A MODFLOW-USG numerical groundwater model, capable of representing the fine detail of, and high vertical hydraulic gradients around, a complex interconnection of numerous underground tunnels, shafts and caverns as well as the large scale of the project has been built to predict groundwater impacts on the groundwater system as well as informing design of groundwater control measures.

Taking the wonky out of Wonky Holes

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There has been considerable discussion over the existence and genesis of Wonky holes. Pothole like depressions have been identified on the continental shelf especially in the northern tropics where coral development is present. Some of these are located 20km to 40 km from the shoreline. Hand line fisherman have been targeting these owing to their high biodiversity, while trawler fisherman have been reporting net becoming snagged on these features. It has been postulated that these are due to submarine groundwater discharge from paleo channels and hence may act as possible pathways for contamination of the reef lagoons. Using radon and radium isotopes measurements alone may not be a reliable indicator of fresh groundwater discharge.

For nearly all of the alluvial groundwater flow systems in Queensland at the coastline, the groundwater potentiometric surface equated to sea water density, is marginally above mean sea level. It follows there is insufficient hydraulic head at the coastline to drive and maintain any submarine discharge that is located away from the near shore environs. This poses the question as to whether they are groundwater discharge areas. If so, what is the source of this groundwater discharge and what conditions produce the required hydraulic head for discharge to occur. This paper examines plausible hydraulic head drivers for such phenomena and proposes alternative groundwater flow mechanism should groundwater discharge occur.

The benefits of a multidisciplinary team model for groundwater-surface water investigations, Thirlmere Lakes, NSW

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The Thirlmere Lakes Research Program (TLRP) is a four-year collaborative multidisciplinary program designed to gain a whole-of-system understanding of the hydrodynamics of a complex lake environment. The program was established from concerns that proximal aquifer interference activities were factors in recent lake level

declines. Five research teams were established to investigate five adjacent lakes set within an entrenched meander bend located south-west of Sydney.

The project involved lithological, geochemical and geochronological analysis from lake beds and surrounding slopes to understand lake evolution and determine potential past lake-drying events. Further geological understanding of the lake area was obtained from resistivity imaging (RI), ground penetrating radar (GPR), and analysis of rock cores that were drilled from two deep bores adjacent the lakes. Development of water balance budgets involved fine-scale on-site meteorological measurements including on-site evapotranspiration monitoring, combined with high-resolution bathymetry from RTK GPS, LiDAR surveying and drone photogrammetry. Groundwater-surface water interactions were measured using lake-bed multilevel temperature and pressure arrays, hydraulic head measurements and fine-scale isotope, major ion and environmental tracer time-series analysis.

Preliminary findings indicate that the five lakes have been separated for over ~100,000 years and that the lakes themselves contain sediment that is possibly up to 250,000 years old. Assessing the modern dynamics, we show that current lake level declines during a period of low rainfall are largely evaporation dominated. One lake however appears to have greater water storage in adjacent sediments providing compensatory inflows. In a second lake, there are indications of localised connectivity with shallow (≤18m) groundwater, but no evidence of connectivity with deeper aquifers. Geological surveys indicate a clay layer 6-8 m below the lakes and spatial variations in both sediment and rock geology. The influence of these geological features, including structures projecting towards the lakes, on groundwater storage and flow is the focus of ongoing research as is temporal variability and lake interactions at different lake levels.

The benefits of the multidisciplinary team model include refining the research targeting areas of uncertainty and to enhance and calibrate each team's results. This approach will provide a comprehensive whole-of-system model of the evolution and hydro-dynamics of a complex lake system.

The cumulative impact of potential groundwater extraction under the Murray-Darling Basin Plan

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Under the Basin Plan, extraction limits were set for the first time across the whole of the Murray-Darling Basin, and for groundwater systems at various depths. The aggregate extraction limit is set at 3494 GL/yr, much greater than the average groundwater extraction of 1335 GL/yr. The unused water can be divided into roughly equal buckets, that within extraction limits that existed prior to the Basin Plan (Baseline Diversion Limit) and that above that (unassigned water). There have been concerns that if groundwater use is increased, the impact on streams may be sufficient to partially undermine the recovery of surface water entitlements for the environment under the Basin Plan. This is despite the MDBA and state jurisdictions

implementing steps to minimize the volume of unassigned water in highly connected groundwater systems.

There is no evident increase in extraction over the period 2003-2017. It is thought, however, that over the longer term that changes in technology and economic context would lead to increased use of brackish water and desalination, especially as surface water resources were reduced. The objective of this study was to assess the impact of potential extraction under the Plan on surface water flow. There are two large uncertainties with doing this: 1) the location and timing of future extraction and 2) the connectivity between point of extraction and streams.

A preliminary risk assessment was conducted in which the first uncertainty was addressed by a scenario analysis, and the second by a sensitivity analysis. This showed that:

1. there is a significant probability that the surface water impact from development that occurred within 40 years would exceed 100GL/yr, but not exceed 400 GL/yr;
2. very little of this development within 40 years would occur from unassigned water;
3. most of the impacts were not associated with saline surface water inflows;
4. spatially, the single largest risk was the Southern Riverine Plain, where impacts would coincide with those from reduced irrigation recharge; and
5. should the basin aggregate SDL be reached, the impact is likely to be in the range 190 to 630 GL/yr.

The long time scales associated with growth in extraction and groundwater response times mean that an adaptive strategy could be used to manage risks. Water management plans and associated SDLs could be adjusted to minimize unaccounted impacts, once growth occurred, with triggers and processes being developed beforehand. The results also support an even more precautionary approach to unassigned water.

The impact of groundwater discharge on nutrients and carbon cycles in a freshwater lake

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Lakes are one of the most important components of the global carbon cycle and have the capacity to be a sink of carbon as they potentially can store large amounts of carbon in their sediments. Despite this capacity, lakes are mostly supersaturated in carbon dioxide and methane, resulting in the release of these greenhouse gases to the atmosphere.

We hypothesize that high carbon dioxide and methane emissions, de-oxygenation and eutrophication, in freshwater lakes are significantly influenced by groundwater seeping out along channels and banks. This was investigated by conducting two field campaigns at Manly Dam, Manly Vale, NSW in 2019 to collect surface water and groundwater samples in wet and dry conditions. A surface water survey of radon, carbon dioxide, methane and water quality parameters were conducted on each field campaign and grab samples were collected for DIC, DOC, nitrate, ammonia, and phosphate measurements. A range of groundwater samples were also collected and analysed for the same suit of parameters. All samples were also analysed by the size

exclusion technique, Liquid Chromatography-Organic Carbon Detection (LC-OCD), for organic matter characterisation.

The results showed that areas of groundwater discharge tended to show elevated levels of nutrients (predominately nitrate and ammonia) and greenhouse gases. This work demonstrated that influence that groundwater discharge had on the carbon and nutrient dynamics, and greenhouse gas emissions. Overall this confirmed our hypothesis that the high carbon dioxide and methane emissions in lakes are significantly influenced by groundwater seeping out along channels and banks.

The role of shallow groundwater as a nutrient export pathway under subsurface drained pastoral agriculture

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Artificial subsurface drainage is necessary to enable viable agricultural production on imperfectly to very poorly drained soils. These soils make up approx. 40% of land used for dairying in NZ. However, artificial drainage also provides a "short-circuiting" pathway for unattenuated delivery of nutrients from paddocks to streams. There is a particular knowledge gap concerning the extent of vertical nutrient recharges into the shallow groundwater underlying artificially drained land.

To determine the lateral and vertical water and N and P fluxes, and the fate of nutrients recharged vertically into shallow groundwater from two drained dairy farms (Tatuanui and Waharoa) on the Hauraki Plains (Waikato).

Artificial drainage flows were continuously monitored, and flow-proportional samples analysed for N and P over two drainage seasons. Sub-soil coring permitted the controls on the drainage hydrology to be understood, with shallow wells installed to monitor water table dynamics. Depth profiling, using a dual packer system, allowed for monitoring of N and P and redox status through the shallow groundwater.

A water balance over the drainage seasons confirmed the soil coring results that the Tatuanui site was hydraulically sealed in the subsurface and no vertical recharge and contaminants were being exported through this pathway. In contrast, between 39 and 46% of the rainfall over the drainage season recharged vertically into the shallow groundwater at Waharoa.

The predominant form of N lost via artificial drainage was nitrate-N (72-86% of total N). The cumulative annual mass exported of each form of N (nitrate, ammonium, organic) at each site increased linearly from the origin with the amount of annual drainage, except for nitrate-N at Waharoa.

The average nitrate-N concentrations measured in the groundwater at both sites were all less than 0.2 mg NO3-N/L. Concomitantly, indicators for redox conditions showed the shallow groundwater to be strongly reduced at both sites. These results indicate that at both sites any vertically recharged nitrate-N is likely to be denitrified in the shallow groundwater.

To understand and quantify the export of nutrients from artificially drained land it is essential to also consider the role of the shallow groundwater beneath the installed drainage. Where soil hydraulic properties and the landscape position favour vertical

recharge into the underlying shallow groundwater, the redox status of this zone becomes crucial for the fate of nitrate-N.

This work was supported by MBIE-funded 'Transfer Pathways' and 'Critical Pathways' programmes and co-funded by Waikato Regional Council and DairyNZ.

Using geochemistry to understand sources of groundwater inflow to intermittent rivers: the upper Wimmera catchment, southeast Australia

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Documenting the sources of water that contribute to streamflow is important for understanding and managing river catchments. Especially in semi-arid areas, groundwater inflows commonly contribute a significant proportion of river flow. For many rivers, the distribution of groundwater inflows and the composition of the groundwater is poorly known, which hampers the understanding of catchment functioning. Intermittent rivers, such as the Wimmera River, cease to flow during summer months and commonly consist of disconnected groundwater-fed pools. These pools provide a unique opportunity to investigate the distribution and geochemistry of groundwater inflows to the river. In this study, major ion concentrations, stable isotope ratios and ^{222}Rn were analysed from shallow pools (depth < 1.5m) along the Wimmera River.

The pool waters have EC values of 2430-15,330µS/cm, Cl concentrations of 800-6210 mg/L, and Na concentrations between 440 and 2960 mg/L. The water is sodium chloride type, similar to the regional groundwater. $\delta^{2}H$ and $\delta^{18}O$ values are -24‰ to +37‰ and -3.3‰ to +10.3‰, respectively and define an array with a slope 4.5. The stable isotope values and major ion geochemistry demonstrate that the pools are largely fed by groundwater that has subsequently evaporated. ^{222}Rn activities up to 2380 Bq/m^3 also imply that the pools are derived from groundwater.

Understanding the distribution and geochemistry of groundwater inflows permits a better analysis of groundwater-river interaction using chemical mass balance at times when the river is flowing. Future work will involve using geochemical tracers including Sr isotopes and ^{3}H to assess whether the groundwater originates close to the river or is part of the regional groundwater system.

Modeling salt leaching from coal mine waste rock - upscaling from laboratory to meso-scale

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Coal mine waste rock dumps generate salt that may leach into pits or other water bodies. The potential leach rates need to be predicted over decadal time scales in order to inform management of pit lakes and waste rock after mining ceases. Due to the difficulty of representative in-situ monitoring of leaching, parameters for models and/or salt decay curves are usually derived from laboratory experiments. The various scaling uncertainties, including particle sizes and hydrological conditions, mean there are questions about the reliability of model predictions. To address this, we have set up a meso-scale experimental facility, representing a one cubic meter

volume of waste rock, subject so far to 15 months of imposed wetting-drying cycles for two rock types. The water balance and salt load data collected permit simple flow and transport models to be calibrated, and comparisons to be made to upscaled laboratory-derived leaching parameters, both for total salt (by converting electrical conductivity) and individually for six major ions. Results show that the calibrated models represent observed total salt loads well and permit preliminary derivation of empirical scaling factors. The variance of results between the rock types and between ions calls for further investigation of the scaling processes and optimisation of experiments.

Big Data & Innovation Applications

Groundwater field data capture: custom mobile apps for the groundwater industry

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Objectives: This study presents a range of case studies which develop tailored mobile applications to streamline groundwater field data capture that automatically syncs to Microsoft Platforms for seamless integration.

Design and Methodology: Tailored groundwater field collector mobile applications were developed in the PowerApps platform, providing field staff with the ability to customise the data collection, management and storage process to meet individual project needs. Examples of different applications and features are presented, including:

- Direct data entry: groundwater level, quality and geological bore logs
- Google maps integration: Maps of bore locations to plan driving directions, and using mobile GPS to extract bore coordinates and elevation for sites where survey is not warranted
- Camera integration: Ability to take photos and videos of the site and automatically upload them to project SharePoint site
- Project information: links to health and safety documents, project background and communication information.

We avoid double handling of information by creating live connections between our mobile apps and clients existing Microsoft platforms (OneDrive, SharePoint, Outlook, Excel, Power BI) to streamline data processing and automate tasks.

Original data and results: The results from this study is a suite of tailored field collection mobile applications to streamline data capture and processing, providing an alternative to written data entry and rigid field collection apps currently applied in the groundwater industry.

Conclusions: The custom mobile application tools presented in this study have broad and wide-ranging applications across the groundwater and environmental industries. These tools can be used to both streamline data processing and improve project reporting, facilitating a culture of data driven decision making to help manage the future sustainability of our groundwater resources.

Documenting provenance of science in a state government agency – a groundwater example

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The South Australian Department for Environment and Water (DEW) has developed a comprehensive suite of standards, tools and guidelines to improve the quality and transparency of the science we produce. The approach is named MEK (Managing Environmental Knowledge). The MEK suite of resources supports the department's Information Management Framework and is aligned to South Australia's Digital by Default and Open Data agendas. DEW Project Management Framework (PMF) does not currently address data management in projects. The MEK fills this gap by adding steps to the project phases which enable data supply chain management. This reminds projects of the importance of early data management planning and which standards or guidelines to refer to during the execution and delivery of a project. MEK tools support project managers and scientists to explicitly document data supply chains so that provenance of intermediate data outputs and publishable products is clear and accessible.

MEK tools include (i) data planning form for estimating resources and broad needs of a project in relation to data management, (ii) data charts that provide a visual way of describing data supply chains and (iii) data catalogue for storing detailed metadata of each element in the data charts. The guidelines that underpin these tools include: data storage describing how to make use of the various corporate systems and applications, evaluation detailing the peer review procedures for major deliverables and evaluation guidelines for other project outputs, data handling describing information classification and sensitive data handling, and publication including proofing and publishing procedures.

These tools and guidelines are applied and used to help manage and map groundwater data in a range of applications including groundwater modelling, resource condition reporting, and approval processes. Utilising MEK tools improves the integrity and availability of groundwater data whilst ensuring transparency and effective use of existing information systems. In addition, the MEK resources are enabling the Groundwater Team to improve its culture around data management, deliver improved groundwater science outputs and thereby enable evidence-based decision making to support the management of our State's groundwater resources.

Coding to automate groundwater data analysis and visualisation

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Objective: Long term groundwater level monitoring is conducted for a variety of purposes, including characterising existing hydrogeological regimes, identifying temporal changes in hydrogeological regimes, and monitoring groundwater remediation projects. Networks of hydrostatic pressure loggers are often utilised to gain long-term, high resolution groundwater elevation data in groundwater monitoring projects. The large amount of data generated by these long-running data logger networks is time consuming to process and display manually in hydrographs. A custom R code, or script, has been created to streamline this process and automate the production of hydrographs for several large-scale groundwater investigation projects.

Design and Methodology: The script was developed to import raw hydrostatic pressure files and convert them to groundwater elevation, as the well location of each data logger file is identified within the code and matched to manually recorded standing water levels. Additional information can also be displayed to aid in the visual interpretation of the data. Folders of rainfall, tidal, and irrigation information can be imported and matched to the relevant groundwater elevation time series. The script then produces formatted figures displaying these data.

Results: The script has significantly reduced time spent on hydrograph production. The implementation of a defined, repeatable process for data transformation has decreased the potential for human error, and the resulting visualisation of the data has allowed groundwater trends within the monitoring periods of these projects to be observed, including the tidal and rainfall dependent nature of recharge.

Conclusion: The creation of this data processing script made the visualisation of groundwater elevation and environmental data more efficient in several groundwater investigation projects, allowing more time for interpretation. As the collection of high-resolution environmental data becomes more common, the lessons learnt from the development of this code can be applied to a wide range of projects.

Hidden water in remote areas - using innovative exploration to uncover the past

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Reliable water availability is critical to sustaining community water supplies and determining economic development opportunities. In many cases, particularly in remote and arid areas such as in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands in the far northwest of South Australia, groundwater is the only viable source of water. However, there is limited knowledge of the groundwater resources in these remote regions and the Musgrave Province, where the APY Lands is located, is no exception. Consequently, there is a need to identify and determine the potential of groundwater resources in regions – such as the APY Lands – to supplement their

community water supplies and to provide water for sustainable economic development which leads to employment opportunities.

The Goyder Institute for Water Research's Facilitating Long-term Outback Water Solutions (G-FLOWS) suite of research projects has developed new techniques to interpret airborne electromagnetic (AEM) geophysical data, coupled with hydrogeological techniques, to identify groundwater resources buried by deep sedimentary cover which is a major constraint to identifying water sources in the northern parts of South Australia.

In its third stage, G-FLOWS is utilising AEM data collected in 2016 to undertake a targeted program of data acquisition, interpretation and mapping of groundwater resources in the Musgrave Province. The research, a partnership between Department for Environment and Water, CSIRO, Flinders University and the Geological Survey of South Australia, is applying new and innovative geophysical and hydrogeological techniques developed in the previous G-FLOWS projects, combined with a variety of field evaluation techniques, to map the groundwater resources in the APY Lands.

The discovery of a new fresh groundwater resource (<1,000 mg/L) in the APY Lands has enormous potential for the future development of this remote region in outback South Australia. Availability of a high yielding groundwater resource within the Lindsay East Palaeovalley could unlock the potential for economic development in the region.

Hydrogeol_utils: an open-source, data processing, integration and visualisation toolkit for hydrgeology

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Groundwater science in Australia and internationally faces enormous challenges in the years and decades to come. Increasing water demand for agriculture, industry, domestic supply and the environment will put pressure on already stressed groundwater systems. To manage our groundwater resources in the face of competing interests, regulators require transparent, reproducible and defensible science delivered in political timeframes to underpin decision making and investment. Competing demands for groundwater resources will continue to politicise groundwater science, as demonstrated by controversies surrounding fracking and coal mining, which will result in continued public scrutiny.

The current scientific landscape presents enormous opportunities. Decreasing data acquisition, storage and computing costs and advances in computational sciences allows access to a larger volume and greater variety of data, which may greatly increase our ability to understand groundwater systems. However, processing, analysing and visualising these data is currently complicated by the proprietary and black-box components in many groundwater research workflows.

We propose open-source science, where data and methodologies are freely available, as the best approach to ensuring science is sufficiently transparent and reproducible to withstand both professional and public scrutiny. Open-source science also allows greater collaboration and sharing of ideas between groups, which reduces duplication of efforts and frees scientists to focus on their specific research. This is particularly advantageous in code development, which is important in extracting information from large data collections in realistic timeframes

We present, hydrogeol_utils (https://github.com/GeoscienceAustralia/hydrogeol_utils), a GitHub repository of python-based tools and workflows for processing, analysis, integration and visualisation of hydrogeological data. This toolkit aims to provide a user-friendly Application Protocol Interface (API) for accessing analysis-ready hydrogeological and geophysical datasets stored in efficient, standardised and open formats (netCDF4 and Spatialite). It applies common scientific processes such as plotting, interpolating, filtering, exploratory analysis and modelling. A major focus of this package is in the integration of a range of datasets including airborne electromagnetics (AEM), surface nuclear magnetic resonance (SNMR) and borehole information (including wireline logs, water levels and lithology) to create maps and models and assess groundwater systems against management objectives.

The package utilises mature and powerful scientific computing packages including *numpy*, pandas and *scipy* for data analysis, *matplotlib* for visualisation, *scikitlearn* for machine learning techniques and *rasterio*, shapely, *xarray* and *gdal* for spatial analysis. Workflows for calculating hydrological parameters including aquifer properties, groundwater salinity and water table depth are contained within *Jupyter Notebooks*, which are used to document the workflow including runnable code.

The Exploring for the Future web portal – democratising access to geoscience data, tools and information

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The Exploring for the Future program is a four-year, $100.5 million initiative by the Australian Government dedicated to boosting investment in resource exploration and agriculture development in northern Australia. The region is underdeveloped and offers enormous potential for industry and agricultural development as well as being advantageously located close to major global markets.

The Exploring for the Future program comprises data acquisition using geophysical surveys, geochemical sampling, hydrological mapping and stratigraphic drilling. The data collected has been integrated to provide a holistic picture of the mineral, energy and groundwater resources. Data will be made publicly available via the Exploring for the Future web portal (https://eftf.ga.gov.au) that allows direct access to the data and tools to inform policy and planning decisions within government, resource sector and agribusiness. The portal has been designed with a human centric interface to allow a user with little prior knowledge to rapidly access information they require so that they can make informed data driven decisions about natural resources, including groundwater resources.

Emerging Analytical & Numerical Methods

Modelling groundwater-surface water interactions with the Double-Averaged Navier Stokes Equations: a step towards next-generation tools for integrated limit setting

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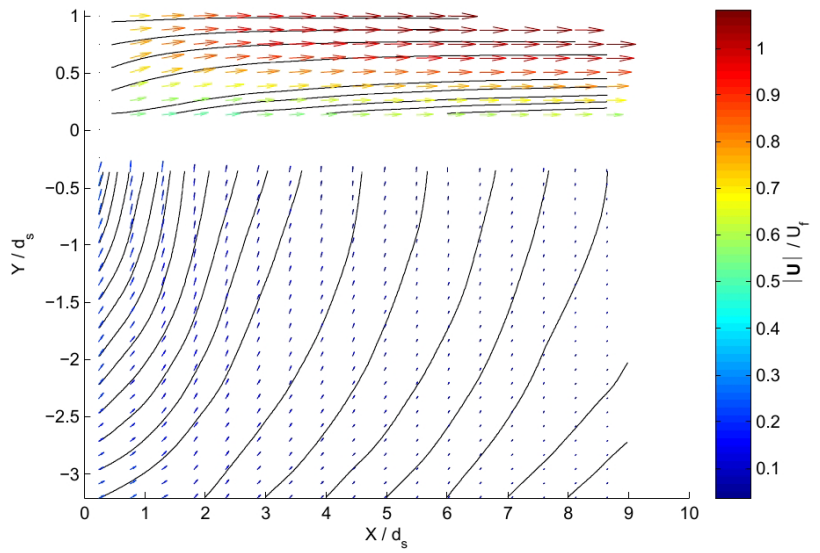
Objectives: Existing coupled models for groundwater and surface water flows use different governing equations for the different components, making them reliant on numerical coupling methods that can be the source of instability and mass-balance errors. This is currently a barrier to their use in integrated limit-setting processes.

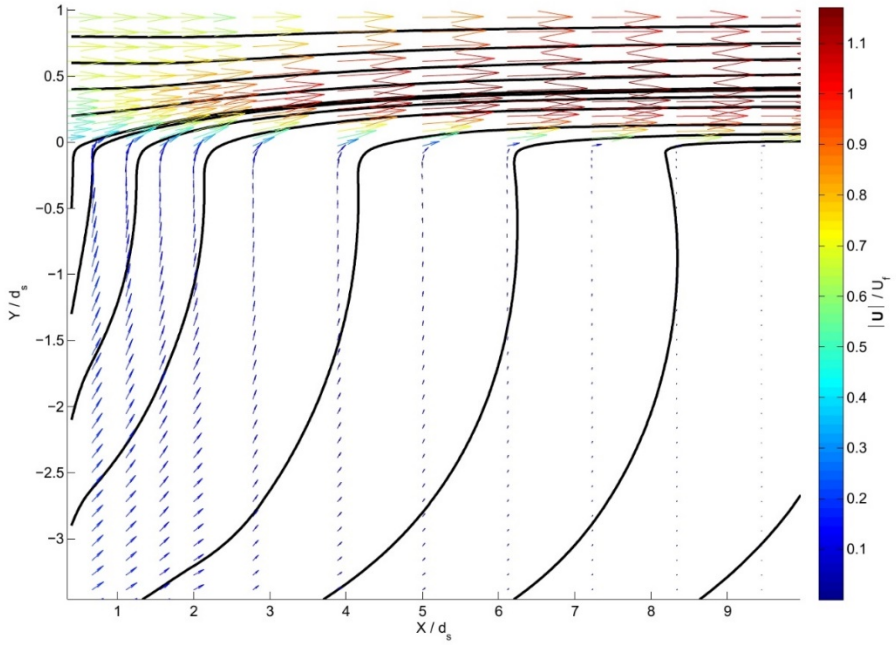
This project investigated the feasibility of resolving these issues by using a single system of equations for both surface and subsurface flows.

Design and Methodology: A 2D numerical model (a vertical slice) was developed to solve the Double-Averaged Navier Stokes (DANS) Equations (Nikora *et al.,* 2007), using a finite-volume implementation. This allows the horizontal and vertical velocity components to be modelled over the depth of a stream and the underlying hyporheic zone or aquifer.

The most significant challenge in the development of the DANS numerical model was the implementation of a turbulence model that allows a transition between a turbulent free-surface flow and laminar Darcian flow in the underlying porous medium. The model determines whether flows in the near-bed region are in a turbulent, non-linear laminar or Darcian regime, rather than specifying this *a priori*.

Results: Considering "book-end" scenarios (i.e. groundwater only; surface water only), the numerical model successfully reproduced analytical solutions and published experimental results. For the full groundwater - surface water case, velocity and turbulent kinetic energy fields from the numerical model were compared to data from innovative particle-tracking experiments in a laboratory flume, using transparent beads as the porous medium. The following figures show velocity fields from the lab experiments (above) and the numerical model (below) for a "gaining stream" configuration.





Features of the flows measured in the laboratory were well replicated by the numerical model.

Conclusions: This project confirmed the technical feasibility of using the DANS Equations for modelling groundwater and surface water flows as one system. Proposed further research will extend the model to 3D and improve the representation of processes such as the free surface, creating a model that can be used at a practical scale. Analogies between the turbulence transport equation used in the model and the governing equations for contaminant transport suggest that the model could be extended to model contaminant transport. The ability to model groundwater and surface water flows and transport in a single consistent mathematical framework would be a substantial step forward in reducing the cost and complexity of quantifying interdependencies between water allocation and nutrient discharge limits.

1. Nikora, V., McEwan, I., McLean, S., Coleman, S., Pokrajac, D. and Walters, R. (2007), Double-averaging concept for rough-bed open-channel and overland flows: Theoretical background. Journal of Hydraulic Engineering - ASCE, 133(8), 873-883.

Seepage analysis through the body and the vicinity of an earth water dam by using unstructured-mesh finite element modelling. The Mornos - dam case study

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Analysis of groundwater flow through earth dams and embankments is commonly conducted by developing and running 2D-vertical profile numerical models along selected transects (Gikas and Sakellariou, 2008), assuming they are aligned with the major direction of groundwater flow, and negligible flow components at different directions.

This above approach seems to work sufficiently well for the majority of the problems, representing standard geometrical structures and simplified flow patterns. In problems involving complex geometries and geological structures, the use of the 2D profile-modelling methodology fail to realistically represent the pattern and the dynamics of groundwater flow in the system.

The application of numerical models based on 3D-structured mesh, is burdened by several limitations and functional constraints that reduce their suitability in simplified cases. The requirement of large number of elements/cells in many different layers with significant number of redundant elements at pinch out parts, discretization difficulties in approaching key structural details, significant model run times, and convergence difficulties are few examples of the above limitations.

Recent developments of the industry-standard numerical code FEFLOW (Diersch ,2104, DHI, 2018), in the field of 3D-unstructured finite element mesh, proves to work sufficiently well in overcoming the above limitations, providing improved solutions in simulating groundwater flow systems with significant 3D flow components in complex geometrical structures.

This paper presents the application of 3D unstructured - mesh finite element technique in simulating transient seepage of groundwater flow through the body and the vicinity of an earth water dam, in Mornos river catchment, Greece. This dam is 135m high and constitutes the major source of potable water supply of the metropolitan area of Athens, Greece.

The model was designed to incorporate all the structural components of the dam and the surrounding bedrock. It was calibrated at transient state conditions, against monthly water level data observed at various piezometers installed at multiple locations in the body of the dam. The model was run for a simulation period of 30 years, replicating with sufficient accuracy the field observations and the anticipated patterns of groundwater flow. Potential impacts of preferential flow patterns and seepage through underlying bedrock fractures are discussed. Alternative model designs comprising traditional structured mesh as well as 2D profile modelling and the unstructured mesh technique are explored.

Practical examples of numerical modelling techniques to inform groundwater impact assessments for major infrastructure projects

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Objective: Groundwater impact assessments for major projects rely on the outputs from numerical groundwater modelling to quantify potential project-induced changes to groundwater levels and fluxes. For major infrastructure projects, groundwater modellers are often required to accurately simulate the geometry of complex engineering structures and their interaction with the geology and hydrological features. Additionally, predictions are commonly required for stresses larger than those of the natural range of seasonal variations and for a period of time longer than the period of historical observations. This presentation provides practical examples of modelling techniques applied to assist with the preparation of Environmental Effects Statements for major infrastructure projects in Victoria.

Methodology: The presentation will draw on GHD's recent experience with the following two projects:

1. Edithvale-Bonbeach Level Crossing Removal Project which will involve the construction of pile walls near Ramsar listed wetlands of high ecological importance.
2. Northeast Link Project which will involve the construction of 6 km long twin tunnels, mined tunnels and cut and cover excavations.

Data and results: The presentation will provide an overview of:

- The use of unstructured grids to accurately simulate the geometry of engineering structures, geology and hydrological features within regional model domains.
- Loose coupling of MODFLOW-USG with SOURCE to simulate interactions between groundwater and wetlands.
- Rigorous automated calibration in a highly parallelized computing environment using PEST_HP.
- Predictive uncertainty analysis based on PEST's Null-Space Monte Carlo methodology.
- Climate change impact assessment using Victorian Government's climate change guidelines, with benchmarking of the model against long term historical climate data.

Conclusion: Recent advances in modelling capabilities provide modellers with the opportunity to assess groundwater impacts in greater detail, including probabilistic outcomes that are particularly suited to the risk assessment framework adopted in major infrastructure projects.

Dynamic meshing for integrated hydrologic modelling in mining

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The impact of anthropogenic activities on water resources is of considerable interest to water resource managers, industry and the public. Anthropogenic activities including land-use change, agriculture and mining, can have significant impacts on the sustainability and quality of the existing surface and groundwater resources. The evaluation of the impact of an evolving engineered environment on surface water and groundwater systems necessitates evolving landscape models that accommodate dynamic surface and subsurface topography and property changes. Traditionally, fully integrated models are applied to understand changes in water availability or quality as a result of changes in climate or water extraction. In these cases, the geometric structure of the model remains fixed and it is either the boundary conditions or the material parameterizations that are changed during the simulation. However, in cases where significant landscape evolution is occurring (e.g., the development of an open pit mine), accurately representing these changes within the model is difficult because of the limitations of the fixed model that cannot reflect dynamic changes in the surface water and groundwater flow system. The dynamic mesh scheme described in this study and implemented in the fully integrated model HydroGeoSphere was verified with a previous study, which focused on groundwater seepage locations under static hillslope conditions. The groundwater discharges computed with the evolving-landscape model shows a high level of agreement with those from the study. For a proof-of-concept demonstration, the dynamic meshing scheme is applied to a synthetic open-pit mining site to represent the time-varying engineering designs within a fully coupled surface/subsurface numerical model.

Time series analytical modelling using HydroSight to investigate drivers of groundwater level fluctuation

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Variations in groundwater levels are complicated by natural and anthropogenic drivers and processes. For instance, a decline in groundwater water level could be the combined result of, but not limited to, reduced recharge, evapotranspiration, and groundwater pumping. Effective groundwater management often requires identification and separation of these drivers and the prediction of the groundwater level under differing scenarios.

Numerical models are usually built for such groundwater level investigations. However, numerical modelling often involves significant labour cost and they require prior assumptions about the hydrogeology and the dominant drivers.

As an alternative to numerical techniques, the hydrograph time-series model (HydroSight) has been recently introduced for simulating the impacts of multiple drivers of groundwater level variations. HydroSight is simple to apply and requires fewer prior assumptions about the hydrogeology compared to numerical models.

HydroSight consists of a soil-moisture layer to account for non-linearity between rainfall and recharge, as well as different response functions to account for pumping from multiple wells and/or mine induced drawdown. In this study, HydroSight was applied to an area surrounding a mine in Australia. The results showed that HydroSight can separate the effects of pumping from the effects of climate on groundwater-head variation. The results also gave insight into the potential extent and magnitude of drawdown in a basalt aquifer surrounding a mine and helped to quantify the potential impact on a nearby landholder bore. We encourage others to apply HydroSight when numerical models are either not warranted or the prior assumptions about the hydrogeology are not well understood.

Simulate the impact of external loading on groundwater level

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External loading such as flooding, and tailings emplacement can potentially influence deep groundwater pressure. However, the current groundwater numerical models such as MODLFOW cannot simulate these effects. In this study, a new MODFLOW package was developed to simulate the impact of external loading on groundwater levels. In doing so, the current subsidence and aquifer compaction package (SWT) was modified and a new component was added to the geostatic equation to account for the external load. The SWT package uses updated geostatic stress and hydraulic pressure to estimate effective stress. Upon the calculation of effective stress, skeletal storage and compaction changes were calculated and changes in groundwater storage were translated into flow and added to finite difference equations. Given that the loading impact decreases with increase in depth, two types of equations (i.e. linear and power) were also introduced in the package to simulate the loading dissipation. The new package was tested on an identical sample simulation to the one provided in the SWT package. A model run was undertaken with the presence of external load assuming flood waters of 0.1 m deep. The result shows that the groundwater levels increase by approximately 0.04 m in response to 0.1 m of flooding at the surface. The result also shows a depressurization response to the sudden removal load, before quickly recovering by the end of the stress periods. In the next step, the package will be tested in the real case scenarios. We also encourage others to test the package and investigate numerically the impact of external loading.

Nutrients Diffuse Pollution in Aquifers & Catchments

The nitrate load to come: a tale of two porosities

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In 1975, Foster described the "Tritium anomaly" in the British Chalk, where very low levels of post-bomb tritium were observed in groundwater, as compared with concentrations in the vadose zone above it. This was hypothesised to occur due to

the concentration gradient between rapidly recharging water through fissure, and relatively immobile pore water. Since then, research in the UK has focused on this process, and more recent work has highlighted the critical role that dual porosity/permeability mechanisms play in controlling the "nitrate load to come".

Simplistically, when recharge events occur, water moves through high permeability pathways (fissures), and diffusion occurs from this high nitrate recharge into the low concentration matric water. As the concentration in the matric water increases over time, the concentration gradient can be reversed, and concentrations in the recharging water may then be enhanced (load to come). This has been observed in the UK Chalk, with the matric water becoming a 'source' of nitrate as land use changes have resulted in lower nitrate concentrations in recharge. Similar processes occur in the saturated zone and have been observed through failed aquifer storage and recovery trials, and tracer experiments.

In New Zealand alluvial gravel systems, as in the Chalk, there are two contrasting components of flow, with the same opportunity for movement of solutes between the two phases. The fine-grained matrix is almost always close to saturation, but has very low intrinsic permeability, whereas the open framework gravels (OFGs) within the gravel sequence, as with the fissures in the Chalk, transport most of the flow but are usually unsaturated in the vadose zone.

This paper explains the process of nitrate transport in dual porosity/permeability systems, providing evidence from the UK and New Zealand. Whilst the work in the UK has been carried out over several decades, quantification of the nitrate load to come has not yet started in New Zealand. There is a crucial need to fully quantify the extent to which nitrate has been retained in immobile pore water. Until we measure this, we cannot have confidence in modelling the impacts of land use change on groundwater and surface water quality.

Nutrient transfer through the vadose zone under sugarcane in the Wet Tropics

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Agriculture has a substantial impact on the quality and quantity of groundwater. The excessive usage of nitrogen fertilizers and manure on agricultural lands can increase the nitrate concentrations in surface water and groundwater. Over the past 150 years, the catchments adjacent to the Great Barrier Reef (GBR), Australia, the world's largest coral reef ecosystem, have been drastically changed with the development of the catchments for farming activities. Therefore, there is potential for nutrients (carbon, nitrogen and phosphorus) to be discharged beneath the plant root zone to the vadose zone, then to groundwater or be transported in runoff from sugarcane fields and eventually into creeks and rivers that feed into the GBR. This paper has investigated the fate of nutrients that leach through the vadose zone under a sugarcane field in the South Johnstone catchment, in the Wet Tropics. Using a real time monitoring technique, the vadose zone monitoring system (VMS), the

temporal and spatial distribution of nutrients in the vadose zone has been studied. NOx-N concentrations in leachate under sugarcane varied over time at different depths. Generally, the concentration of Nitrate decreased over time but increased with depths. Ammonia was found to range from 0.01 to 0.49 mg/L, showing a difference between samples collected before and after fertilization in 2016 -2018. Total Organic Carbon (TOC) losses in the vadose zone also varied with time. Phosphate in the vadose zone was found below the detection limit, demonstrating plant uptake and hereafter the phosphate attenuation in the soil. The processes affecting the transport of nutrients through the vadose zone and time lags that occur before these contaminants reach ground water have also been determined.

Denitrification walls as a tool to reduce nitrate load to the Greats Barrier Reef whilst reducing nitrous oxide emissions: results from the southeast Queensland trials

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Nitrogen (N) used in excess in agricultural systems can leach to shallow groundwater and reach the ocean via submarine groundwater discharge. Excess N inputs can also be lost into the environment as greenhouse gas (GHG) emissions, contributing to anthropic climate change via nitrous oxide (N_2O) production. The Great Barrier Reef (GBR) receives increasing harmful nutrient loads including nitrate (NO_3^-), linked to the dramatic growth of corallivores. The GBR is also subject to coral bleaching as a response to elevated sea surface temperatures as a direct consequence of GHG emissions induced by global warming.

Denitrification walls are a low-cost technology for NO_3^- remediation and consist of organic carbon (OC) media-filled permeable trenches able to intercept NO_3^- polluted groundwater and catalyse denitrification. Denitrification progressively reduces NO_3^- to dinitrogen with N_2O as an intermediary. The process is performed by microbes that use OC as an electron donor to perform their respiration under anaerobic conditions.

Two denitrification walls (30 m^3 volume) filled with different OC sources were installed on a sandy aquifer in Southeast Queensland. The water table height in the bioreactors and aquifer was monitored using a dipmeter and pressure transducers. Water samples were collected and analysed photometrically to evaluate NO_3^- concentrations. Chemo-physical parameters were collected with portable instruments. Dissolved N_2O in groundwater was determined using gas chromatographic techniques. The hydraulic characteristics of the bioreactors were tested using saline tracing tests.

Both the walls supported full removal of NO_3^- and N_2O and resulted suitable to reduce NO_3^- load to the GBR whilst reducing N_2O emissions. The results of this study will provide the Queensland Government with a technical tool to improve the use of this cost-limited technology.

The study was funded by the Queensland Government Office of the Great Barrier Reef in collaboration with the Queensland Department of Agriculture and Fisheries.

Removing nitrate from artificial subsurface drainage under pastoral agriculture using woodchip bioreactors

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Objectives: Artificial subsurface drainage controlling high seasonal groundwater has been found to be a substantial pathway for nutrients from agricultural lands into surface waters. Thus, mitigating the impacts of agriculture on surface water quality needs to address nutrient transport via subsurface drainage. Woodchip bioreactors are a promising mitigation option as demonstrated in arable agriculture in the US. However, research is needed to understand their efficiency in removing nutrients from very flashy drainage flows from NZ pastoral agriculture and any possible pollution swapping.

Methods: A lined 60-m^3 woodchip bioreactor was constructed on a dairy farm in the Hauraki Plains (Waikato, NZ). Rainfall, flow, hydrochemistry and dissolved gases in the inflow and outflow were monitored for two drainage seasons (part of 2017, 2018).

Results: The mean nitrate-N concentrations in the inflow and outflow respectively, were 5.59 and 0.01 mg/L in 2017, and 13.72 and 7.45 mg/L in 2018. Based on the nitrate-N fluxes, the estimated nitrate removal efficiency of the bioreactor was 99 and 48% in 2017 and 2018, respectively. The higher removal efficiency in 2017 could be attributed to; the much longer residence time of the water in the bioreactor (mean=22 days vs 5 days in 2018) allowing more opportunity for microorganisms to reduce the nitrate in the water; and the availability of electron donor (DOC) to support denitrification. In 2017, greater DOC available within the bioreactor was indicated by the higher DOC flux from the bioreactor (17.9 kg vs 9.3 kg in 2018).

Very long residence times in 2017 promoted strongly reduced conditions, resulting in the production of hydrogen sulphide and methane. However, short residence times constrained complete reduction of nitrate resulting in higher nitrous oxide concentrations in the outflow vs inflow in 2018. Elevated discharges of DOC and DRP were evident during the start-up phase of the bioreactor in 2017. Significant removal (89%) of DRP was observed in 2018.

Conclusion: Woodchip bioreactors are a useful tool in removing nitrate, and possibly DRP, from subsurface drainage water. Enhancing their efficiency may require a combination of; adding another electron donor (e.g. methanol) to promote complete denitrification during flow and N load peaks and preventing very long residence times to minimise the production of odorous or greenhouse gases.

Acknowledgement: This work is part of the SSIF-funded 'Enhanced Mitigation of Nitrate in Groundwater' programme led by ESR. We gratefully acknowledge the co-funding by Waikato Regional Council and the co-operation of the Mourits family.

Reducing N-discharges from agriculture: modelling the potential benefits of spatially targeted regulation

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Diffuse nitrate leaching from agricultural areas is a major environmental problem in many parts of the world. Understanding where in a catchment nitrate is removed is key for designing effective land use management strategies that protect water quality, while minimizing the impact on economic development.

The aim of this study is to assess the effects of spatially targeted nitrate leaching regulation in a basin with limited knowledge of the complexity of chemical heterogeneity. We incorporate three alternative nitrate reactivity spatial parameterizations in a catchment-scale flow and transport model. These are used to evaluate the effectiveness of four possible spatially targeted regulation options.

Our findings confirm that there are potential benefits of implementing spatially targeted regulation compared to spatially uniform regulation. Focusing regulation in areas where nitrate residence time is short, such as riparian zones or areas with low natural N-reduction, results in greater reduction of N-discharges through groundwater. Management efficiencies are significantly improved when delineation of management zones considers the chemical heterogeneity and groundwater flow paths. These improved efficiencies are achieved by adopting management rules that regulate land use in discharge sensitive areas, where leaching changes contribute the most to the catchment nitrate discharges. In our case study, regulation in discharge sensitive zones was twice as efficient compared to other management options.

A participatory approach to better understand well water quality in Canterbury, New Zealand

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Groundwater nitrate nitrogen levels in Canterbury, New Zealand have been gradually increasing. A project was carried out from 2016 to 2019 to seasonally monitor 51 randomly selected wells of varying depths between the Ashburton and Rakaia rivers. The objective was to identify the variability in nitrate nitrogen levels in groundwater and to see how concentrations vary seasonally, sub-regionally, by depth and over time. This area is primarily farmland built on gravelly alluvial plains overlaying tertiary sediments of braided river deposits and greywacke. The project was initiated by farmers wanting to engage with the process of better understanding trends in water quality in their region. The sampling was carried out by the Foundation for Arable Research working closely with hydrologists to ensure protocols and procedures were consistent and valid. Recharge of aquifers further from the rivers and coast is achieved through a combination of rainfall, irrigation, snow melt and infiltration from rivers. Piezometric contours running between the two rivers illustrate that water movement is from the foothills to the coast, with groundwater levels becoming shallower approaching the coast. The sampling found there to be no differences in nitrate levels from north to south, but concentrations increased as

groundwater moved down the catchment accumulating as it moved towards the coast. Four wells were consistently over the maximum acceptable level for safe drinking water of 11.3mg NO3-N/L but the majority of wells had acceptable levels of nitrate nitrogen over the duration of the project. The information has enabled farmers to develop a better understanding of the high and low risk zones in the area. Importantly the participatory approach involving researchers and farmers has enabled the farmers to engage with regulatory bodies in constructive dialogue to develop outcomes that meet the environmental, economic and social needs of farmers and the community.

Coastal Processes & Tropical Island Hydrogeology

Seawater intrusion and aquifer compartmentalisation in the Darwin rural area

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Groundwater is the primary source of water for residential and agricultural use in the Darwin rural area, and also supplies part of Darwin's city water. In the Howard East area, groundwater bores are screened in the Koolpinyah Dolomite aquifer, a 'spill and fill' aquifer that responds to wet-dry seasonal cycles. The 2018-2019 wet season saw low levels of rainfall and groundwater recharge, resulting in significant water stress. The Koolpinyah Dolomite aquifer is geologically complex and is intersected by faults and/or shear zones that may compartmentalise the aquifer or act as preferential flow paths for groundwater. This project was initiated to better understand the influence of these geological features on potential seawater intrusion.

The geology and hydrogeology of the Howard East area has been refined using airborne electromagnetic (AEM) and airborne magnetic data collected for this project as part of the Geoscience Australia's Exploring for the Future Programme. This AEM dataset was compared with previous AEM and borehole data to investigate changes in groundwater quality and dynamics. Water level loggers were installed in existing monitoring bores close to production bores for town water supply and the fault/shear zones. Pumping data were supplied by the bore-field operator, and data were interrogated to capture background groundwater dynamics and drawdown responses to pumping. Drawdown responses from either side of different geological structures were compared to test if aquifer compartmentalisation is occurring. Groundwater samples were collected throughout the area to investigate groundwater age and quality, and to test if possible, aquifer compartmentalisation is affecting groundwater composition.

Preliminary analysis suggests that geological faults/shear zones compartmentalise the aquifer. Work is ongoing to assess the role of structures in seawater intrusion. The findings from this project will be used to inform bore-field and seawater intrusion management.

Effects of dispersion on the offshore fresh groundwater extent

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Objectives: The most easily applied approaches to estimating offshore freshwater limits are based on sharp-interface assumptions, which neglect dispersive mechanisms and offshore circulation of seawater. The difference between sharp-interface and dispersive models has been investigated extensively for onshore coastal aquifers; however, the role of dispersion in controlling offshore freshwater-seawater interactions is not well understood. The main purpose of this study is to explore how dispersion affects the key features of offshore freshwater-seawater interactions, which includes the interface location and width, freshwater and seawater circulation rates.

Design and methodology: We conduct a series of dispersive numerical experiments in SEAWAT using cross-sectional models of uniform characteristics, i.e., isotropic and homogeneous, to represent simplified offshore aquifer conditions that allow us to compare it with the Werner and Robinson (2018) solution.

Original data and results: Results show that dispersion affects the tip (i.e., where the interface intercepts the top of the aquifer) and toe (i.e., where the interface intercepts the bottom of the aquifer) differently. Enhanced dispersion causes the toe to advance seaward, as expected; whereas the tip shows a non-monotonic relationship with dispersion that depends on the contrast between aquifer and aquitard hydraulic conductivities. The mixing zone at the toe widens as dispersion increases, similar to onshore cases, whereas the mixing zone at the tip has a surprisingly non-monotonic relationship with dispersion. The freshwater and seawater circulation rates increase with dispersion, as opposed to the non-monotonic relationship found in onshore aquifers.

Conclusions: Counteractions between dispersion, refraction, density and advective forces explain the different behaviour caused by dispersive processes in offshore aquifers to that observed in onshore settings.

References: Werner, A. D., Robinson, N. I. (2018). Revisiting analytical solutions for steady interface flow in subsea aquifers: Aquitard salinity effects. *Advances in Water Resources*,116, 117-126, doi:10.1016/j.advwatres.2018.01.002.

The value of geophysics in understanding the variability of groundwater systems in low carbonate islands

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Fresh groundwater in low carbonate islands normally occurs within the upper unconsolidated sediments as a lens-shaped body that is buoyantly supported by dense underlying saline water. The thickness of a freshwater lens generally depends on the recharge rate, the width of the island, the hydraulic conductivity of the sediments, the depth of the Thurber Discontinuity, and the presence (or absence) of a reef flat plate. Various examples from the Pacific are presented where recent investigations using Electrical Resistivity Tomography for the quantification of fresh groundwater resources have indeed revealed that island width alone is not enough of

an indication for the thickness of a freshwater lens. In Tuvalu, for example, resistivity responses along relatively wide islands (Vaitupu, Motulalo) have indicated the presence of limited groundwater whereas resistivity models along smaller islands (Fale, Lakena) have suggested the presence of significantly thick freshwater lenses with high development potential for potable and other domestic purposes. High resolution profiles depicting the spatial distribution in the resistivity of subsurface media can reveal patterns and provide insights on the genesis and evolution of carbonate island hydrogeology/geomorphology and freshwater lens development. The value of drilling logs and groundwater monitoring bores is once again highlighted as a means of calibrating resistivity results and extrapolating along modelled survey profiles.

Evaluation of hydrogeophysical data to constrain a 3D variable density numerical groundwater model of a freshwater lens in a multi-layered, Island Aquifer System

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Groundwater is often the primary source of freshwater supply on remote small islands, where it exists as a freshwater lens, it is extremely vulnerable to over-extraction, pollution and seawater intrusion. Ensuring long-term sustainable management of the groundwater resource is of the utmost importance when there are growing water demands, sea-level rise and/or recharge decline. This study used a three-dimensional (3D), variable-density numerical groundwater flow and solute transport model to investigate freshwater lens dynamics in a multi-layered aquifer system on a small tropical island. The model was used to explore the feasibility and impacts of increased groundwater demand on the freshwater lens, its volume, geometry as well as the thickness of the freshwater/saltwater transition zone. The risks of saltwater intrusion, both laterally from the ocean and by localised up-coning from the deeper, more saline aquifers beneath the freshwater lens, were also evaluated. Model calibration used observed hydraulic heads and salinity observations from pumping and observation wells. Subsurface bulk conductivity values, which were calculated from inverted airborne electromagnetic (AEM) data, and near-surface geophysical data, were used in the calibration process. The results showed that the hydraulic heads and observed salinity achieved the 'best fit' in the calibration process, whilst the addition of the geophysical data helped constrain lens geometry in the steady-state model. The models' sensitivity to the range of measured salinities could be enhanced by improving the conversion factor between the derived AEM conductivity values and the observed salinity data. This would best be achieved by targeted monitoring wells and improvements in the sampling/restoration of existing ones. The numerical model was used as a framework to evaluate the key underlying hydrogeological processes on the island, as well as an important decision-making tool to ensure a sustainable and reliable water supply for the island community.

Investigating submarine groundwater discharge at Sellicks Beach, using hydrogeophysical techniques

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Submarine groundwater discharge (SGD) is a noteworthy source of freshwater and nutrients to oceans. It is acknowledged as an important component in groundwater budget calculations, in freshwater-seawater interaction studies, and in the evaluation of nutrients loads to marine systems.

Objectives: This project aims to identify SGD zones occurring as freshwater seeps, in Sellicks Beach, South Australia, located in the south-western part of the Willunga Basin. The basin comprises a multi-aquifer system that provides freshwater to the McLaren Vale region.

Design and methodology: The study characterised a groundwater discharge site, in the form of a bubbling seep, at Sellicks Beach. Techniques included the installation of piezometers to monitor water level and temperature fluctuations, in addition to hydrochemical and stable isotope analyses to investigate the origin of the discharging water, and a near-surface geophysical survey to obtain the spatial distribution of the ground conductivity. Thermal imagery was also used to locate the distribution of groundwater expressions within the intertidal zone.

Original data and results: Salinity measurements showed that discharging groundwater is approximately 10,000 mg/L during low tide but increases to 28,000 mg/L during high tide periods due to the influence of seawater. The near-surface geophysical survey mapped the subsurface distribution of freshwater, showing an upwelling freshwater plume significantly wider than the width of surface seepage zones. Thermal imagery was able to identify three additional discharge sites in the surrounding area.

Conclusion: The use of multiple techniques to characterise these intertidal springs provided a robust characterisation of the near-surface conditions and demonstrated complementary aspects of each method in identifying freshwater-seawater interactions in a dynamic setting.

Adding spatial comprehensiveness to the characterisation of remote freshwater lens systems in tropical island settings in Northern Australia using airborne electromagnetics

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Despite being the primary source of freshwater supply for indigenous communities, small island groundwater resources in the tropical north of Australia are often poorly characterised. The hydrogeology of these systems also remains generally poorly understood. In part this is linked to their remoteness, the practicalities of undertaking ground investigations in isolated areas, but also to culturally related access issues. Extending this knowledge is critical to groundwater management in

such settings and is increasingly important where the effects of climate change and the projected future water needs have the potential to compromise the limited fresh groundwater reserve through saltwater intrusion, over pumping and pollution.

Geophysical, and in particular electrical and electromagnetic methods have been used extensively in characterising freshwater lens systems in Island settings, providing information that is less expensive and time consuming to acquire than direct sampling approaches. However, information provided by ground methods (direct or indirect) is often limited by site access in culturally sensitive areas, as is often the case in northern Australia. Airborne geophysics, most notably airborne electromagnetics (AEM) offers an efficient and effective alternative to employ in extending the conceptual hydrogeological framework for remote islands. It also circumvents the access issues. We describe results from an "island-scale" survey over Milingimbi and Sout Goulburn Islands in Australia's Northern Territory, demonstrating the spatial comprehensiveness of the hydrological data acquired and the value of the data for extending relatively sparse spatial information from existing bore fields and more recent ground geophysical surveys. The helicopter EM data used, maps the extent and thickness of the fresh groundwater lens system, and defines the geometry and extent of the saltwater interface around the two islands. The lens systems are primarily confined to the weathered "lateritic" sediments, with weathering creating realatively isotropic unconfined aquifers. When coupled with surface NMR soundings, and available hydrological information, estimates of the available freshwater resource have been defined suggesting the available resource on both Islands is greater than previously thought. The inverted airborne geophysical data has been used to determine the chloride content of the lens systems and, in the case of Milingimbi Island, constrain the development of a calibrated steady state numerical groundwater model.

The results suggest that airborne geophysics could be used as an effective aid to further groundwater resource determination and management other remote parts of the Territory.

Geophysical & Petrophysical Methods & Groundwater

Deriving groundwater volume estimates for Managed Aquifer Recharge: an interdisciplinary approach

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Estimating groundwater storage volumes is part of assessing the potential capacity and recovery efficiencies of managed aquifer recharge (MAR) options. However, such storage estimates are challenging, particularly in areas of poor data density- as found in most of Australia. This study reports on recent advances made in storage estimation methods and sensitivity analysis to quantify uncertainties.

Workflows developed by Geoscience Australia for the estimation of groundwater volumes for various salinity categories involve: (1) using salinity measurements of sonic-core pore fluid extracts to define a simple relationship between airborne electromagnetic (AEM) conductivity and groundwater salinity; (2) determining bulk aquifer volumes using hydrostratigraphic textural classes, and potentiometry to map the distribution of saturated coarser-textured aquifer zones in AEM depth slices; and (3) estimating the likely range of effective porosity for texture classes based on a combination of borehole nuclear magnetic resonance (NMR) data and surface nuclear magnetic resonance (SNMR) data.

Sensitivity analysis has been undertaken for both 1D and 3D AEM inversion methods. Variables assessed include: (1) the AEM inversion method; (2) the regularisation used in 1D AEM inversion; (3) the AEM conductivity thresholds for categorising groundwater salinity; and (4) limitations placed by hydrostratigraphy, texture and saturation.

This analysis shows that volume estimates of good quality (<600 mg/L TDS) and acceptable quality (600-1200 mg/L TDS) groundwater are particularly sensitive to the AEM inversion method and regularisation constraints used. For example, tightening the regularisation constraints on 1D AEM inversions resulted in order-of-magnitude fresh groundwater volume reductions. Similar magnitude reductions also occurred for saline (>3000 mg/L TDS) groundwater volumes when textural constraints were included. The impact on volumes from changing the effective porosity ranges or the AEM thresholds used to map groundwater salinity were comparatively low.

This study has highlighted the significant uncertainties surrounding estimation of fresh groundwater volumes using AEM data, particularly in heterogeneous aquifers with variable groundwater salinity distribution. While AEM technologies continue to improve, they resolve conductive targets better than resistive (fresh water) domains. The study has also revealed that careful consideration needs to be given to AEM data processing and the use of spatial filters, while the use of 3D inversion methods provides more accurate estimation of overall conductivity distribution except in near-surface (<15m) geology. Other improvements being explored include the use of stochastic approaches that incorporate a range of sedimentary and petrophysical models to better forecast the range of possible aquifer properties.

The utility of shallow geophysics to contribute to the characterisation of shallow groundwater conditions

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Measuring depth to groundwater in monitoring wells is one of the most fundamental observations in hydrogeology. Using interpolation (and extrapolation) maps of depth to water table are created, which can have significant errors due to sparse measurements and also subtle changes in low lying topography. In semi-arid regions, like the Northern Adelaide Plains (NAP), South Australia, assessing zones with shallow groundwater depths is crucial; especially as extension of irrigation with treated sewage plant effluent could result in rising water tables. However, limited availability of and/or high costs of installing piezometers means that we still lack

methods of fast and reliable characterization of shallow groundwater. An obvious interesting opportunity is to use non-intrusive hydrogeophysical sensing techniques.

We have collected geophysical data sets at three study sites within the NAP. Techniques evaluated include: a frequency domain, shallow terrain conductivity meter (CMD); a fast-sampling time domain electromagnetics system (TEM); a resistivity system (ERT); and a shallow reflection seismic system. Additionally, to provide further information on soil variability, as well as groundwater depth and quality, 47 geoprobe boreholes were drilled, 20 of them were logged using a shallow borehole nuclear magnetic resonance (NMR) system.

Results suggest that a) the main river systems, as well as much more subtle ephemeral streams, appear to be important recharge zones; b) the seismic survey provide useful information about depth to groundwater; c) geophysical techniques that measure the ground conductivity (i.e. TEM, ERT, CMD) can determine the depth to groundwater when there is a sufficient contrast between the conductivity of the groundwater and the background soils; d) borehole NMR results of water content and water boundness were generally consistent with those obtained from samples evaluated in the laboratory; and e) NMR has the potential to identify the presence of heavy clays that could impede infiltration.

Improving hydrogeological characterisation with borehole magnetic resonance for managed aquifer recharge

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Increasing pressure is being imposed on Perth's water supply due to population growth and a drying climate. In order to ensure long-term water supply for the city, the Water Corporation has introduced a Groundwater Replenishment (GWR) Scheme (Water Corporation, 2019). The Perth GWR scheme is in its' second stage and is currently being expanded to enable a 28 billion litre recharge capacity into the Leederville and Yarragadee aquifers. GWR involves injecting treated wastewater into confined aquifers for storage to supplement traditional groundwater supplies.

Considerable analysis at the injection sites has been undertaken to improve well management and performance during drilling, injection and clean-up operations as part of the GWR project. Wireline logging technologies have been used to provide hydrogeological characterisation of the aquifers. Of particular interest is borehole magnetic resonance (BMR) which provides accurate measurement of reservoir porosity and an estimate of well permeability using well-known empirical correlations (Kleinberg, 2001, Neville and Hopper, 2017). The BMR estimated permeability can be translated into hydraulic conductivity and hydraulic transmissivity measurements. The permeability model typically used for sandstone reservoirs is the Timur-Coates model (Timur, 1968, Coates et al. 1991). This model requires calibration to local well information such that the model parameters correctly reflect the local geology. This is typically achieved by core analysis of plugs obtained from the well-sites of interest.

GWR project included flow-logging measurements at the injection sites to measure well transmissivity. We provide an alternative method of calibrating the Timur-Coates parameters using the transmissivity determined from flow logging tests

across multiple wells (Dlubac et al. 2013). The measured Timur-Coates parameters and resultant transmissivities are compared to results obtained from the standard core calibration method. The proposed method allows permeability to be more accurately captured at the well-scale. Permeability measurements via BMR can then be used at other small monitoring bores for aquifer management.

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Is there a fault in the geology or in the geophysics?

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Accurate delineation of fault systems and characterisation of fault zone hydrogeology in sedimentary basins and paleovalleys is challenging and expensive. Over the past few years, considerable progress has been made in the development of airborne electromagnetic (AEM) technologies for rapid and accurate mapping of hydrostratigraphy, structural elements and groundwater systems and resources. Compared to seismic operations, AEM surveys are orders-of-magnitude cheaper and being airborne, have advantages in terms of land access and impacts.

New calibrated AEM systems have the proven ability to map conductivity contrasts in the near surface at high-resolution. AEM inversions map the subsurface distribution of bulk electrical conductivity, hence provide a different perspective to seismic datasets, and support the mapping of multi-layered hydrostratigraphy (lithology + porosity), hydrology (groundwater salinity + water saturation), as well as evidence of geological displacement (faults). However, until recently, fault geometries, displacements, and fault zone properties remain ambiguous. This is due to the combination of AEM footprint resolution, the non-uniqueness of the conductivity models and derived hydrostratigraphy and fault geometry solutions produced by AEM equivalent inversion models, and the inherent uncertainty of 'standard' 1D AEM inversion models. The resultant uncertainty in fault zone characterisation inhibits investigations into the permeability heterogeneity and anisotropy introduced by faults, making it difficult to resolve the significance of these structures for groundwater processes.

In recent projects new inter-disciplinary workflows have been developed to optimize AEM data. This commences with AEM system suitability assessment, while acquisition strategies take into consideration all relevant prior data and knowledge. Careful consideration of AEM data processing workflows is also vitally important, particularly in removing noise (e.g. from VLF sources and cultural coupling), while the use of spatial filters must be used judiciously, if at all, particularly for 3D inversions. The development of new 2.5D and 3D AEM inversion procedures is particularly important in removing topographic effects and imaging the hydrostratigraphy and geometry of faults with high fidelity.

While AEM mapping technologies and inversion procedures have evolved to permit accurate 3D mapping of fault geometries, supporting borehole, hydrochemical and hydrodynamic data are required to assess the influence of faults on dynamic groundwater processes. A combination of deterministic and stochastic modelling approaches are required to understand complex fault zone conduit-barrier system behaviour that determines lateral and vertical groundwater flow, inter-aquifer leakage and recharge. These methodologies can foster more robust, realistic and sophisticated parameterisation of numerical groundwater flow models, including the incorporation of structural elements, like faults.

Origin of ultra-basic, strongly-reducing groundwater conditions within an epithermal gold-bearing system

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Ultra-basic, strongly reducing conditions combined with depleted magnesium and sulfate proportions were observed in groundwater down-gradient of the Twin Hills gold mining operations in North Queensland. These conditions are atypical of groundwater systems beneath metalliferous mining sites, which are often characterised by acidic to circumneutral pH, minor to moderately oxidising redox conditions and elevated sulfate proportions. Beneath most areas of the Twin Hills mine site, evapotranspiration during recharge is the dominant mechanism controlling the solute concentrations in the groundwater. This has led to moderately saline (EC ~5,000 µS/cm), circumneutral pH (6-8) groundwater with major ion proportions similar to rainfall of the region. The sulfate-chloride ratios in most areas suggest limited alternative sources of sulfate (gypsum dissolution and/or sulfide oxidation). One monitoring bore situated down-gradient of the mining operations has historically exhibited significantly higher salinity (EC ~ 15,000 µS/cm), ultra-basic pH values (pH > 11), extremely low redox potentials (Eh < -200 mV), unique major ion signatures, and elevated concentrations of numerous metals/metalloids. Hydrochemical and mineralogical observations were combined with geochemical modelling techniques to assess the roles of various mine-related and/or natural mechanisms. The observed conditions likely evolved naturally from chemical weathering of olivine and pyroxene group minerals associated with olivine-gabbro intrusives. These mechanisms, collectively referred to as serpentinization, are solely responsible for the natural origin of ultra-basic pH and strongly reducing conditions that are rarely observed in groundwater systems but are well documented in the literature. These conditions have led to sulfate and magnesium depletion due to sulfate reduction and precipitation of brucite ($Mg(OH)_2$), which was observed to be present as significant mineral deposits at the base of the monitoring bore. This study highlights the importance of rigorous data collection and interpretation to identify causes and implications of groundwater quality "issues" beneath mine sites.

Insights into subsurface properties from sonic core drilling in the Keep River region, East Kimberley, northern Australia

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In 2018, as part of the Australian Government-funded Exploring for the Future program, Geoscience Australia drilled fifteen sonic boreholes in the Keep River region in north-western Northern Territory. The boreholes averaged 49 m in depth with 99% core recovery and were completed as piezometers. Boreholes were geophysically logged (induction, spectral gamma and nuclear magnetic resonance) and sampled for hydrochemistry; the data from these measurements facilitating the calibration and validation of satellite and airborne geophysical measurements.

Recovered core was immediately extruded into polythene tubes on site, sealed, and refrigerated. At a nearby field laboratory core was split, transferred to core trays, measured, geologically logged, and duplicate sub-sampled at ~30 cm intervals. Sub-sampled material was stored in sealed vials and refrigerated to ensure suitability for hydrochemical analysis. One of each sub-sample pairs was hydraulic pressed to acquire pore water samples, which were rapidly analysed for pH and EC. The remaining half core was air dried and scanned using a Hylogger multispectral system. The refrigerated pore water and core samples were kept for further study, including magnetic susceptibility, grainsize, palaeontology, and hydrochemistry.

The sonic drilling technique combined with our workflow has many advantages over conventional rotary drilling, including:

- High core recovery.
- Recovery of uncontaminated sub-samples, including pore fluids, for further study.
- Clean bore construction and ease of completing bores as piezometers.

The results of the drilling program analyses have enabled discrimination of Ord River palaeovalley sediments from underlying weathered Paleozoic basin sediments, with valley fill up to 50 m thick. Facies analysis of sonic core permitted discrimination of fluvio and fluvio-estuarine sediments. Porewater salinity in the unconfined water table zone varies widely and increases up to an order of magnitude with depth. The core will also facilitate experiments to determine salt mobility within a range of material grainsizes, which is vital for determining salinity hazard.

Abstracts presented on Tuesday 26 November 2019

Groundwater Contamination & Remediation

Clever Communication: Applying data analytics and dashboards to communicate groundwater quality data

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This study presents a range of case studies which apply the latest business intelligence tools to process, analyse and visualise groundwater quality data through interactive dashboards, to quickly communicate trends and statistics for groundwater quality compliance monitoring.

Historical groundwater quality data from 'messy' Excel workbooks was collated and processed into a centralised database within Microsoft Power BI, the world's leading Business Intelligence platform. Data cleansing was performed through the PowerQuery tool to automate common data cleansing tasks such as unit conversion, outlier detection and identified limits of detection. Interactive dashboards were developed within the Power BI Desktop tool, combining dynamic maps, groundwater level hydrographs, water quality data, box and whisker plots and key statistics. Water quality data was compared against various guideline values to highlight exceedances reflecting non-compliance. By incorporating DiscoverEI's own Power BI Custom Visual, the geological logs for the groundwater bores were dynamically displayed, providing additional context for analysing and interpreting results. The reports were published online, shared with clients and groundwater managers via the cloud and mobile platforms, and updated in real-time.

The results from this study is a suite of interactive groundwater quality reporting dashboards which provide an alternative to the traditional written compliance reports, which can be used to help manage and communicate groundwater quality data.

The data analytics and visualisation tools presented in this study have broad and wide-ranging applications across the groundwater and environmental industries. These tools can be used to both streamline data processing and improve communication, facilitating a culture of data driven decision making to help manage the future sustainability of our groundwater resources.

Sustainable outcomes with surfactant enhanced aquifer remediation of coal tar NAPL

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Background and Objective: The former Bacchus Marsh gasworks (1889 – 1973) is located within a wide alluvial plain of the Werribee River. Shallow groundwater on the alluvial plain occurs in an upper alluvial aquifer and is highly utilised for irrigation and rationed through the auctioning of water shares. The presence of coal tar NAPL (and associated dissolved phase groundwater impacts) emanating from former gasholders and tar and liquor disposal wells into the upper alluvial aquifer impinges further on upper alluvial aquifer utilisation. This presentation focusses on remediation of two coal tar NAPL plumes that was conducted *in-situ* attempting to meet Victorian EPA and client sustainability goals.

Methodology: After extensive review of possible sustainable remediation options, surfactant enhanced aquifer remediation (SEAR) was selected to address the coal tar NAPL in the aquifer at the site. The surfactant selected was a non-ionic surfactant engineered to dissolve long-chain petroleum hydrocarbons. The surfactant was used in a variety of push-pull and recirculation methods to enhance coal tar recovery. The majority of coal tar NAPL was slightly denser than water (1.03 SG), had low viscosity at 15 degrees Celsius and rested within the poorly sorted clayey, sandy gravel lenses of the upper alluvial aquifer. After initial push-pull applications of SEAR, recirculation was established between the injection well and an average of three extraction wells. Approximately 7 different injection wells were utilised in each of the two coal tar NAPL plumes.

Results: The mobilised NAPL and emulsified hydrocarbons were removed using multiphase extraction (MPE) technologies. Wastewater was treated on-site and reinjected under permit from the regulatory agency to the extent that was practicable. Reinjection of the water was conducted in a manner to optimise the surfactant plume behaviour while it was being extracted.

SEAR remedial efforts are ongoing and have resulted in the extraction of coal tar LNAPL and DNAPL, while extracting dissolved contaminants (benzene, naphthalene, ammonia, cyanide) on to activated carbon and resin filters. Most extracted groundwater was returned to maintain/restore aquifer capacity, thereby meeting the EPA's and the client's sustainability goals.

Conclusion: SEAR is a viable method of groundwater remediation to reduce recalcitrant hydrocarbon mass and decrease overall plume lifespan in unconsolidated aquifers.

Sources of nutrient contamination in groundwater at Recycled Water Plants and implications for management

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EPA licences for operation of recycled water plants (RWPs) often require that no change in groundwater quality occurs as a result of RWP operation. However, nutrient contamination of groundwater at RWPs is ubiquitous. The non-compliance with EPA licences leads RWP operators to explore methods of reducing groundwater contamination that often includes significant capital expenditure for limited, or uncertain, reductions in contamination. This study characterised nutrient contamination in groundwater at seven RWPs, aiming to find more appropriate and cost-effective approaches to managing and remediating groundwater contamination. It also explored the management tools available to the EPA to manage remaining contamination and reduce expenditure on remediation.

Conceptual modelling and analytical modelling was used to develop a detailed understanding of background groundwater quality, and likely contaminant transport pathways for nutrients. Data availability meant it was difficult to distinguish between two key nutrient sources: lagoon leakage, and on-site irrigation. Lagoons liners were mostly constructed to industry standards, which would impose a delay of several decades between lagoon leakage and groundwater contamination. Nevertheless, nutrient contamination had occurred. Conversely, irrigation occurs with little regulation and no constructed liner to prevent infiltration to the subsurface. The likelihood of irrigation being a significant source of nutrient is therefore high.

A holistic conceptualisation of the sites and surrounding catchments put the risks from groundwater contamination into perspective, and suggested that as risks were low, significant investment in actions of unknown effectiveness (such as relining lagoons) was not warranted. Instead, a remediation program was designed that focused on a series of cost-efficient measures. These included adoption of policy measures such as attenuation zones, different interpretations of licenced discharge points, and review of irrigation efficiency.

The results present an alternative approach to managing contamination issues at RWPs, which combines policy measures, an improved understanding of the water balance, and tweaks to irrigation practices. The approach shows how policy tools and engineering measures can be used in conjunction to help operators achieve their goal of keeping water prices low for their customers.

Changing nitrate to nitrogen gas in a gravel aquifer, using a woodchip denitrification wall

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Nitrate concentrations in many New Zealand groundwater systems continue to increase, as a response to land-use intensification. Concerns over degrading water quality have prompted changes to freshwater management and raised interest in nitrate mitigation tools that includes woodchip denitrification walls to target removal of nitrate in shallow groundwater. While denitrification walls are a tried and tested concept in sandy aquifers (e.g. Schipper et al., 2000; Schmidt and Clark, 2012), there are no reported examples of them having being applied in alluvial gravel aquifers, such as constitute the most important aquifer systems in New Zealand.

We are piloting a denitrification wall in a shallow alluvial gravel aquifer impacted with nitrate. The project aims to assess whether such passive, in situ groundwater remediation systems are a viable nitrate-mitigation option for New Zealand farmers. The permeable wall, constructed using a 50/50 (v/v) woodchip/gravel mix, measuring 25 m long x 5 m wide, and entrenched 2.5 m below the water table, was built in November 2018. The changes the remediation system has had on groundwater chemistry, groundwater ecology and hydraulic function of the shallow gravel aquifer are being monitored. Electrical resistivity tomographic methods have been used to acquire knowledge of the subsurface conditions and to inform design of the wall. Also, to evaluate the treatment performance of the wall. Results to date show the woodchip denitrification wall is proving effective at reducing groundwater nitrate in the shallow aquifer. Notable pollution-swapping phenomena that have been quantified include arsenic mobilisation from the aquifer sediments, and greenhouse gas production. Our study demonstrates first-hand the technical challenges of installing a denitrification wall in an alluvial gravel aquifer, such as addressing the issue of complex heterogeneity, and associated preferential flow phenomena.

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Using environmental isotopes to constrain pollutant migration pathways in an intensive agricultural area – Pampas, Argentinia

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This study is examining pollutant migration in groundwater in an area of intensive agriculture - the Argentinian Pampas (Cordoba Province). Groundwater is of critical importance to the region's communities and is facing multiple water quality threats. These include release and migration of geogenic arsenic as well as input of nutrients, herbicides and pesticides from expanding agribusiness. A multi-isotopic tracer approach is being used to better constrain groundwater flow, mixing and ground-surface water interaction in the system, with a view to assisting long-term protection of groundwater quality.

Samples for stable and radiogenic isotopes ($\delta^{2}H$, $\delta^{18}O$, ^{3}H, ^{14}C and ^{36}Cl) have been collected from groundwater wells and surface water bodies used for irrigation and domestic supplies, in the Tortugas sub-basin in the central Argentinian Pampas. The samples have been analysed for a suite of agri-chemicals, including commonly applied herbicides and insecticides (Glyphosate, Atrazine, AMPA and others).

Preliminary results show significant inputs of agricultural chemicals into shallow groundwater and surface water. Additionally, certain herbicides and pesticides (e.g., 2,4-D and AMPA) were detected in some deep supply wells (>100 m) which are thought to be confined and thus isolated from input of pollutants at the surface. These data indicate that the confined aquifer may be affected by leakage and/or bypass flow via rapid pathways. Tritium, radiocarbon and other environmental isotope data will be used to refine these interpretations and improve understanding of the extent of inter-aquifer connectivity.

The preliminary results indicate that deep, confined aquifers in the region may be subject a greater degree of water quality threat than previously assumed. The study highlights the value of combining environmental isotopic data with sampling for contaminants during assessment of vulnerability to water quality threats in water supply aquifers

Considerations for mine planning to reduce potential groundwater impacts

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Objective: The objective of this review is to identify key considerations for the siting and design of mines and associated activities during planning stage, to reduce potential groundwater impacts.

Design and Methodology: This review is based on sites where mining and associated activities have led to groundwater contamination. Data from multiple sites across Australia have been evaluated in terms of a source, pathway and receptor framework to identify common themes.

Original Data and Results: At each site, waste material (wastewater and/or solid waste) from the mine or other associated activity represents the key potential contamination source. In addition to waste rock (overburden or tailings), other solid waste may be dispersed throughout the waste rock, placed in designated areas or encapsulated within engineered landfills. Wastewater may be stored or irrigated on site.

Pathways between the source and receptor may be enhanced by mine activities, including artificially high permeability (e.g. mine voids and collapse), heterogeneous fill material and/or increased hydraulic gradients.

Common receptors include groundwater supply, the mine and neighbouring operations, as well as surface water and ecological features.

Common themes identified from the review were:

Groundwater data – often there is a disconnect between data collected for environmental monitoring purposes vs data collected to support site operations. This can delay collection of appropriate data to assess site contamination and identify potential risks to receptors;

Regulator involvement – there can be a disconnect between the expectations of regulators who are primarily focussed on operational compliance vs those that are focussed on environmental performance; and

Conceptualisation – a conceptual site model may not be required at the planning stage, but this is essential for contaminated site and risk assessment.

Conclusion: Most mine sites have contamination sources with the potential to cause groundwater impacts. The common themes identified highlight the importance of considering mine siting and design within a groundwater contamination assessment framework during the planning stage. Consideration of these themes may reduce impacts on groundwater during mine operation and closure stages, with associated environmental and financial benefits.

Are there interactions between per- and polyfluoroalkyl substances and in situ microbial populations at a legacy firefighting training area?

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Per- and polyfluoroalkyl substances (PFAS) have exceptional interfacial properties and, as such, they have been widely used since the 1950s for a range of applications, including aqueous film forming foam (AFFF). Recently there has been significant concern regarding the environmental fate and impact of PFAS. In this study we collected over 40 groundwater samples from a PFAS impacted legacy firefighting training area in Canada. Using these samples, we conducted an in-depth assessment of the relationship between PFAS and *in situ* microbial communities. Specifically, *in situ* microbial communities were characterized using 16S rRNA gene amplicon sequencing to obtain a profile of the relative abundance of most microbes in sampled aquifers. Metagenomic data were analysed in conjunction with available site data, monitoring well data and soil data. Results suggest differential transport of PFAS of differing chain length and head group which is substantiated by PFAS retardation coefficients estimated from field data. There is also evidence of PFAS degradation, in particular 6:2 FTS telomer degradation. Although PFAS constituents were not major drivers of microbial community structure the relative abundance of over one hundred individual genera were significantly associated with PFAS chemistry. For example, lineages within the Oxalobacteraceae family had strong negative correlations with PFAS whilst the *Desulfococcus* genus has strong positive correlations. Additional correlations between PFAS and individual genera were evaluated to assess the possibility of biostimulation at low concentrations and potential inhibition at high concentrations. Results suggest a range of genera may have been stimulated at low to mid-range concentrations (e.g., *Gordonia*), with some genera potentially inhibited at high PFAS concentrations. Any correlations identified need to be further investigated to determine the underlying reasons for observed associations as this is an open field site with the potential for many controlling factors. Positive correlations may ultimately provide important insights related to development of biodegradation technologies for PFAS impacted sites while negative correlations further improve our understanding of the potential negative effects of PFAS on ecosystem health.

Investigating the bioattenuation of emerging organic contaminants in managed groundwater environments to protect human health and the environment

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Objectives: The discharge of stormwater and wastewater from urban environments is increasing at a global scale while population growth and climate change are concurrently placing many cities under increasing water stress. Managed aquifer recharge (MAR), where water is captured and stored in controlled aquifers underground, presents an opportunity to reuse this stormwater and wastewater. Many emerging organic contaminants (EOCs), such as pesticides, pharmaceuticals and firefighting foams are becoming ubiquitous in the environment, including in the water used to recharge aquifers. This is leading to increased concern regarding the risks that water from MAR could pose to public health.

Design and Methodology: Natural biological processes, referred to here as bioattenuation, are often key to EOC removal in water environments, either directly through biodegradation or indirectly by facilitating suitable conditions for chemical degradation or sorption to take place. This study utilises novel batch and column experiments to determine how factors such as biofilm formation and water composition affect EOC bioattenuation. Authentic aquifer materials were used in experiments. Reverse-phase HPLC was used to quantify EOC concentrations and CLSM microscopy to visualise and quantify biofilm formation.

Original data and results: Experimental data from batch studies display how biofilm effects the material's adsorptive properties. Column experiments contrast how transport behaviour changed under three experimental conditions: biological activity suppressed, standard operating conditions by conditioning with stormwater, and enhanced biological activity by conditioning with nutrient rich wastewater. By contrasting these three experimental conditions, it will be possible to discern the physical, chemical and biological factors which affect transport of EOCs in MAR environments.

Conclusion: By better understanding the fate and transport of organic contaminants in MAR schemes, better informed management decisions can be made. This in turn assists in ensuring this important water reuse solution can be implemented in a safe and sustainable manner.

Groundwater Resources Vulnerability in a Changing Climate

Managed aquifer recharge feasibility assessment, City of Rockingham WA

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Increasing population, drying climate and historical over-allocation are placing groundwater resources under increased pressure within the Perth Metropolitan area. The City of Rockingham, located to the south of Perth, currently utilises ~5GL/yr of groundwater for irrigation of parks, reserves and streetscapes, with this water requirement set to increase in the coming years due to continuing urban expansion. Most of the groundwater resources in the Rockingham area are currently at or above allocation limits, thus groundwater availability is becoming increasingly limited and the feasibility of alternative water sources needs to be considered. Managed Aquifer Recharge (MAR) offers a means to recycle water into aquifers to provide licencing credits for abstraction. As part of a preliminary study, RPS and the City identified and assessed the feasibility of several potential MAR sources, following the Australian Guidelines for Water Recycling. Potential source volumes for MAR totalling over 100 GL/year were identified across the city, however key issues in assessing the viability of a MAR scheme in the Rockingham were identified. These include the shallow depth to groundwater which limits infiltration into the Superficial Aquifer, and the uncertainty of regional confining layers when considering injection to the deeper Leederville Aquifer. Based on the outcomes of the degree-of-difficulty assessment, initial focus has been placed on the harvesting and MAR of urban subsoil drainage water. This talk summarises the results of the regional MAR feasibility and details a case-study at the Rivergums residential development. The case-study has included: monitoring and analysis of several years of subsoil drainage flow volumes and quality; an assessment of the aquifer's suitability for MAR; and the next steps towards practical implementation of a trial MAR scheme using harvested subsoil drainage water.

Increased recharge due to land clearing Vs decreased recharge due to climate change - observations and modelling from the northern Perth basin

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The Dandaragan Plateau area of the northern Perth Basin contains a number of regionally important aquifers notably the Yarragadee and Leederville-Parmelia aquifers that support horticulture, mining development and public water supply. This area is characterised by a mild Mediterranean-type climate conducive to groundwater recharge as rainfall (typically 350 – 550 mm / year) occurs primarily during the winter months when evapotranspiration rates are low. Clearing of native vegetation that took place 1950s-1970s has resulted in significantly increased recharge that is manifest in large rises of the regional table (over 20m increase in some areas).

However, recent rainfall 2010-2018 is around 80-85% of long-term average rainfall and the decline in rainfall since 1990 is consistent with a 2030 dry scenario rainfall trend determined from climate models. The reduction in rainfall has resulted is a significant tapering or even reversal of increasing hydrograph trends.

We present analyses of hydrographs of over 70 long term monitoring bores installed in the 1960s and 1970s. Estimates of pre-clearing recharge using the chloride mass-balance method are made based on chloride concentrations in groundwater and chloride deposition in rainfall (Leany et al. 2011). Additional recharge since land clearing took place is assessed using the hydrograph method (Healy and Cook, 2002). Daily recharge rates are then modelled with the 1D water balance model U3M-1D Class (Vaze et al. 2005) based on unsaturated flow Richards equation. Historical rainfall and reference FAO56 evapotranspiration (EVT) (Allen et al. 1998) from interpolated SILO (Queensland government 2018) data along with soil parameters, rooting depth profiles and leaf area index for the crop growing season are key model parameters. The 1D recharge model is calibrated and verified over different portions of observed hydrographs. Simulations with the calibrated 1D recharge model estimate future recharge for future wet, median and dry future scenarios based on climate model data.

A useful result from the recharge modelling is estimation of the rainfall recharge relationship which shows approximately that a threshold amount of annual rainfall of around 300mm is required before any significant recharge in any particular year. The modelling also highlighted the importance of the timing of rainfall to generate deep infiltration and recharge especially at the end of the winter rainfall season when the soil profile is saturated. Long term dry climate scenarios indicate large reductions in the amount of recharge which significantly impacts the long-term sustainable yield of groundwater resources.

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A 35 ka record of groundwater recharge using stable water isotopes for Perth Basin in south-west Australia

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Objectives: As most large groundwater basins can contain 'old' groundwater where extraction exceeds groundwater recharge, knowledge of the past conditions and timing under which groundwater was recharged is needed to sustainably manage groundwater resources. Moreover, the isotopic composition of groundwater can be a useful indicator of rainfall isotope compositions and help to determine the drivers and impacts of rainfall and climate change. Applying isotopic tools to groundwater contained in regional aquifer systems can provide low-resolution information on recharge intensity, recharge source and past climatic conditions for the region.

Design and Methodology: A dataset containing groundwater ages ($^{14}C_{DIC}$) and stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) from two regional groundwater systems within the Perth Basin, the Leederville Formation and Yarragadee Formation, were compiled to create a low-resolution palaeo-archive of groundwater recharge.

Original data and results: The trends in stable isotopes of water over time in the regional groundwater data are consistent with groundwater flow line data supporting our hypothesis that groundwater stable isotopes are a proxy for palaeo-recharge.

A comparison between modern groundwater and rainfall water isotopes indicates that recharge is biased to months with high volume and/or intense rainfall from the westerly wind circulation and that this has been the case for the last 35 ka. Lower stable water isotope values are interpreted to represent recharge from higher volume and/or more intense rainfall from 35 ka through the Last Glacial Maximum period although potentially modulated by changes in recharge thresholds.

Conclusion: The groundwater isotope record is interpreted to be a low-resolution archive of recharge driven by changes in the relative intensity of past rainfall and recharge thresholds. This long-term stable isotopic recharge record provides a greater understanding of groundwater palaeo-recharge, and the connection between recharge and climate in the past.

Port Phillip Bay - the real value

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Changing climates and higher sea levels are affecting all coastlines globally, and with over 85% of Australians living within 50km of the coast, this is a pressing national issue (Clark & Johnson 2017). In Victoria, rising sea levels are affecting Port Phillip Bay in many ways, one of which is altering the services provided by groundwater systems (SRW 2014). While there have been numerous investigations into the groundwater and geology of Port Phillip Bay (Phillipson 2010; Dahlhaus *et al* 2004; Leonard 1992), this PhD research project focuses on conceptualizing the hydro geological systems and groundwater flows into Port Phillip Bay and the services they

provide. The investigation takes a holistic view, based on the beneficial uses defined in the State Environmental Protection Policy (waters) guidelines, and the Victorian Water Plan set out by the Victorian Government (EPA 2018). The conceptual models will identify economic, environmental, social and cultural values of the groundwater along the coastline of Port Phillip Bay, linking them to flow paths, the coastal Ghyben-Herzberg relation, recharge and discharge, and water quality. These conceptualizations will be used to predict how groundwater services might respond to modelled climate change and sea level rise as defined by the Intergovernmental Panel on Climate Change Fifth Assessment report (IPCC 2014). A much larger study, led by CSIRO, will use this information in development of high-resolution climate and hydrodynamic models as well as inundation and coastal erosion models. Creation of hydro geological conceptual models, together with the CSIRO models, will contribute to better managing the impacts of rising sea levels to Port Phillip Bay coastline. The values identified and investigated through this research project highlight the holistic values of groundwater, rather than the traditional view that solely focuses on the economic value of groundwater extraction.

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Groundwater availability and climate change - assessing the combined influence of reduced water availability and increasing demand on the Barwon Downs groundwater resource

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Climate change has the potential to reduce future groundwater and surface water availability at times when demand will be increasing. The combined influence of less water availability and increase demand was considered for the future operation of the Barwon Downs borefield in south west Victoria. The Barwon Down's borefield is an important drought supply for the region and supplied up to 70% of Geelong's water during the Millenium Drought. The aquifer is primarily recharged from infiltration of rainfall in outcrop areas.

To support the licence renewal of the Barwon Downs borefield, the influence of climate change on demand forecasts and recharge to the aquifer were considered. As part of the numerical modelling assessment, a number of predictive modelling scenarios were used to address future climate change. The assessment initially involved implementation of DEWLP Guidelines on future climate change to determine appropriate changes to groundwater recharge. A total of four climate change scenarios were considered in accordance with the Guidelines. Initial model results suggested that the predicted impacts were not particularly sensitive to the changed recharge condition. This reflects the fact that future groundwater extraction is sustained through changes in water stored in the aquifer and by changes in groundwater discharged at the surface.

Subsequent simulations included the increased future groundwater extraction that would be required to sustain the increased water demand under future climate change. The combined influence of increased demand and reduced water availability generated significantly greater impacts revealing the true impact of a drier future climate.

Uncertainty analysis in groundwater modelling and its environmental management applications

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The environmental models are mostly very complicated and virtually unbounded. This complexity results in uncertain modelling results. The two main sources of uncertainty are model and parameter uncertainty. The available mathematical and numerical groundwater models may not represent the exact natural process in the groundwater aquifers. The material properties are poorly known due to limited number of measurements and the natural high heterogeneity in soil properties.

The groundwater model parameter values are generally estimated using calibration processes using limited number of observations. The real-world systems are highly complex and even large calibration databases can provide multiple estimates of all system parameters which are equally probable. This is called non-uniqueness issue.

There are various methods presented in the literature to quantify the groundwater model uncertainty and/or estimate the reliability/possibility of the outcomes of the

groundwater model. This paper tests the Iterative Ensemble Smoother (IES) tool in a regional scale real-work groundwater model with hundreds of parameters. The IES is an open-source and model independent tool which was developed to overcome the computational burden associated with matching large database of groundwater history in real-world scale environmental models. IES is a tool to quantify the uncertainty in highly dimensional parameter spaces. This paper explains the application of IES in real-world groundwater models and its effectively and efficiency to estimate posterior forecast uncertainty when the future projection involves large number of parameters.

The model independent IES is an emerging technology which enables environmental modellers to account for model input uncertainty at realistic spatial and temporal scale. The application of this technology will lead to better forecast uncertainty estimation and improve the usability of environmental models in decision making. The results of this case study can help environmental managers to select informed decisions by having reliable information about likelihood of environmental phenomena.

Meeting growing water demands in an uncertain future: a case study of current and future groundwater supply challenges and opportunities for Honiara, Solomon Islands

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Currently, groundwater bores and springs make up the total water supply source for Honiara. Current demand is starting to overcome supply, with reliance on aging or under-performing assets and spring supply shortages due limited treatment capacity of high turbidity in high rainfall periods. By 2050, water demand is projected to double to around 80 ML/day [1].

The work presented is a situational analysis of current and future challenges, as part of work for the water utility, Solomon Water, on bore field performance and feasibility studies to secure further groundwater supplies for Honiara in alignment with the utilities 30-year Strategic Plan.

Honiara has two aquifers, the deep confined fractured rock aquifer and the semi-confined alluvial Guadalcanal Plains Aquifer. Much of the conceptual understanding of the aquifers has been developed through old, discontinued, government programs [2] or via major donor projects on development of Honiara's water supplies in 1997 and 2013 [3,4]. To date, the boundaries of the aquifers and inputs and outputs of the system are loosely defined or are not defined. However as is a common challenge in many Pacific nations, monitoring and understanding of the overall capacity of the aquifers has not been adequately funded, leading to incremental and reactionary developments.

In terms of Honiara's bore water supply, the majority of bores are constructed within the confined fractured rock aquifer, with bore fields spread across the city. Four out of six bore fields are producing less than 65% of their target yields. Ongoing work is showing that the reduced yields are a combination of well interference and screen clogging.

The semi-confined aquifer has not been developed extensively for Honiara's water supply. Honiara sits on the western edge of the 40 km wide Guadalcanal Plains, which consists of deep unconsolidated sediments (up to 200 m thick) [2]. This area has

potential for further development as indicated by many privately-owned bores already drilled here. Given the current level of monitoring and understanding about Honiara's groundwater resource, a precautionary approach is required.

Having a broader understanding of groundwater systems can lead to better responses to these challenges, such as stronger water policy, more effective water sector collaboration and skills capacity building. This in turn will help build climate change resilience in the Solomon Islands.

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Seawater intrusion in a warming world

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Coastal aquifers are under permanent threat of seawater intrusion (SI), the process of seawater driven landward at the base of the aquifers by variable density flow. Density contrast between fresh and saline waters, however, does not solely depend on salinity difference as considered in most SI studies but also their temperatures. Based on survey data, we show that temperature variation of up to 15°C is fairly common between seawater and groundwater in various parts of the global coastline and the difference could be either expanded or shrunk under the warming climate depending on their current situation and their location in the world. Therefore, temperature effects should not be readily neglected. Furthermore, temperature and salinity gradients coexisting alongside each other suggests interesting changes of flow patterns and circulation following double diffusive mechanism. Using results from laboratory experiments and numerical simulations, we figure out that the intrusion process enhances with colder seawater and reduces with warmer seawater. More importantly, pore-water flow in the saltwater wedge was modified significantly with a second circulation cell formed near seaward boundary and the regular circulation cell is squeezed into a smaller area with stronger inflow from the beach surface. The thermal impact and coastal vulnerability were then calculated for all coastal areas around the world based on their current temperature contrast and projected future change. The results reveal that a large portion of world coastline is thermally sensitive and vulnerable to changes of land surface and ocean temperature in the warming climate.

Social Engagement, Attitudes & Connection to Groundwater

Water impacts from unconventional gas development: more than just fracking

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Development of unconventional gas resources in Australia has risen exponentially since the 1990's. However, this industry can be considered still in its infancy in Australia, compared to the relatively mature state of technology, regulation, and public opinion that has been reached in other parts of the world. This discrepancy becomes apparent when considering that public concern mainly focuses on the use of fracking despite the fact that this concern does not align with our best scientific understanding of the most probable risks to water resources from unconventional gas development. According to our review (Shanafield et al. 2018) of the likelihood of water resources impacts, combining empirical and first principles analysis, the greatest immediate risk is from surface spills at the wellhead; yet, this risk receives little attention. Our analysis shows that the risk of surface spills is 1 in 10, and 1 in 100 for contamination of groundwater from a surface spill- this is a risk we should have better technical and engineering control over as well as regulation for. Further, we do not have a national view, strategy or position on unconventional gas development. For example, a moratorium on hydraulic fracturing was put in place for part of South Australia as the ban on fracking in the Northern Territory was lifted. Finally, we must consider that there is a lot more to this matter than just science; for example, gaining a social license to operate means that science is necessary but insufficient. This broader concern is often overlooked in the debate on unconventional gas development. Therefore, in this presentation, we suggest a whole-of-cycle perspective on unconventional gas production in which every risk in all phases of the production cycle are put into broader context and perspective to achieve social, economic and environmental triple bottom lines.

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Case studies on community engagement to achieve groundwater allocation reductions

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The reduction of the volume of groundwater entitlements is frequently a necessary but potentially painful part of sustainable groundwater management. The success of this process is highly dependent on effective community engagement. Two case studies from the Upper South East of South Australia illustrate the importance of engagement and provide ingredients for successful outcomes that may be applicable elsewhere.

Grassroots education of groundwater

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Objectives: A recent opportunity to showcase the science of hydrogeology to a local primary school allowed the presentation of an important yet relatively misunderstood scientific topic to an enthusiastic and young audience of potential future scientists. The object of the presentation was to raise awareness of hydrogeology and highlight the role a hydrogeologist has with the management and responsibility of the precious resource of groundwater.

Methodology: The presentation introduced the science of hydrogeology and the roles of a hydrogeologist to a young, impressionable and enthusiastic audience. Importantly, content was presented, and links were made respectful of the audience level of experience, using the water cycle as the focal point of the discussion. The delivery of the presentation included the use of physical props, videos and an interactive Q&A session. It was important to keep the information relatable and present reasons why it was important to know this information. Examples emphasised everyday activities which the listeners could relate to and how they interacted with groundwater.

The level of delivery and the enthusiasm of the audience allowed rapport to be developed, while interactive activities allowed engagement of the audience with the subject. This two-way form of interaction is something Kreamer (2016) believes to be very important when it comes to the understanding and sustainability of projects (water and sanitation and health projects specifically).

Problems in poor communication underpin challenges such as a lack of consideration for regional norms, customs, traditions or a lack of community participation. This in turn can promote the feeling of stewardship which has been observed to impact the long-term outcome of a project (Breslin, 2010).

Solutions to these issues include investing time to establish communication and build rapport and understand local traditions, history and appreciation for the community. Additionally, overall involvement and engagement of the community in the project tended to enhance the sustainability of the project (Kreamer (2016) and McConville & Mihelcic (2007)).

Conclusion: The presentation aimed to empower future generations with knowledge and motivation to take up a positive attitude with hydrogeology and the sustainable and environmentally responsible management of groundwater resources. Passing on stewardship at a "grassroots" level has the capacity to improve sustainable management of groundwater by future generations. Further, the promotion of STEM subjects to such a young audience is also great advocacy not only for the science of hydrogeology, but for scientific career options for young women and men alike.

Raising a glass to citizen science: collecting more data and establishing better relationships between water users and government

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The SA Department for Environment and Water (DEW) has recently trialled a citizen science program in South Australia's winegrape growing regions where increasing groundwater salinity may pose a threat to soil structure and winegrape yield and quality. In 2017, a pilot program was implemented in the McLaren Vale region where a new salinity monitoring network was designed to measure salinity from licensed bores in aquifers that are used for viticulture irrigation. These new salinity data are augmenting the existing state-funded salinity surveillance network.

The program comprised a mail-out to each landholder that included an instruction letter, a map showing the location of the target bore and a labelled sample bottle. Irrigators were asked to submit their groundwater samples at a local drop-off station. The results of the analysis were sent to each irrigator in an email that also contained a link to DEW's public environmental database Enviro Data SA where all of the state's environmental data can be viewed in a variety of formats.

Of the 83 parcels sent to McLaren Vale irrigators, 65 groundwater samples (78%) were received. Results helped to confirm the presence of localised 'hot spots' of increasing salinity caused by inter-aquifer leakage. In early 2018, following completion of the pilot program, the network was extended to the Barossa Valley region. Of the 103 parcels sent to Barossa Valley irrigators, 86 (83%) of samples were submitted. In 2019, the program has been further extended to the Angas Bremer region.

The information gained from this program will help improve the quality of annual reporting of the resource status and aid in identifying emerging risks and focus any subsequent management actions. Other potential benefits include strengthening of professional relationships between irrigators and DEW staff charged with managing groundwater resources and greater stakeholder engagement in water planning and management.

Supporting better management of groundwater in Pakistan: a collaborative approach

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NOTE: This abstract is for the first in a series of five connected presentations related to the ACIAR LWR-2015-036 project

Like Australia, Pakistan is a country of droughts and flooding rains. Pakistan is among the top ten countries most severely impacted by climate change and is expected to be declared water scarce by 2025. The Indus Basin irrigation system no longer provides enough supply for Pakistan's agricultural needs, meaning farmers increasingly rely on groundwater. The Australian government is supporting a four-year research project to provide Pakistan's irrigation managers with strategies to improve groundwater management and farming family livelihoods. We present a series of case studies from this project to demonstrate benefits of a collaborative approach.

The project used participatory rural appraisals to develop a shared understanding of problems associated with groundwater use in each case study area, and to build a network of stakeholders responsible to identify and deliver on changes needed. Stakeholder forums were established to enable co-design of subsequent research activities.

Loggers have been installed to enable automated supply of groundwater depth and salinity data for modelling purposes. Irrigation departments are acquiring the capacity to build and use groundwater models. By establishing and engaging stakeholder forums, local-level farming organisations and others are determining how to access and benefit from information created by improved groundwater monitoring and modelling. This includes the development of mobile Apps made available to farming families, and the analysis of socio-economic data to investigate benefits of changed farming practices.

Adoption of a collaborative approach is crucial for practice change. It allows farming families to understand why and how they can improve their use of groundwater. More importantly, the practices of irrigation department officials and agriculture extension agents are also changing, with greater appreciation for improving groundwater management through collaboration, rather than relying on regulation alone.

Improving groundwater management using a participatory research approach in Balochistan, Pakistan

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NOTE: This abstract is part of a series of five connected presentations related to the ACIAR LWR-2015-036 project

Pakistan is one of the most water-stressed countries in the world. The situation in Pakistan's Balochistan province is especially bleak due to extreme depletion of groundwater, which provides 50% of Balochistan's water for irrigation. In view of the severity of the problem, a four-year research project for improving groundwater management in Pakistan was extended to include Balochistan.

At the provincial scale, the project relied on collaboration and partnerships established through participatory rural appraisals (PRAs). In Balochistan, these were undertaken in Pishin and Kuchlak sub-basins. Activities included group interviews, transect walks, direct observation, interviews with householders, and a subsequent survey administered to understand socio-economic conditions. Stakeholder forums were established to further co-design subsequent research activities. Piezometers were installed at four sites across the two sub-basins to enable water users, researchers and the irrigation department obtain real time date on groundwater depth. A mobile App has also been developed and introduced to help farmers monitor water table levels, schedule irrigations and determine suitable cropping patterns.

PRA activities showed that small landless farmers are unable to afford modern technologies, so larger farmers lead adoption due to their wealth and influence. Cropping patterns are dominated by high water use horticultural crops using traditional flood irrigation. Groundwater is pumped from a depth of 100-170m mainly using electric motors. Because government subsidises electricity for this purpose, there is little incentive to use water efficiently, leading to an alarming 3-10m annual decline in the water table.

The project research activities are helping farming organisations and partner government and non-government organisations promote improved irrigation practices, use of high efficiency irrigation systems, and lower water use crops. The involvement of stakeholder forums in the design of local research activities has been critical for developing strategies to enhance practice change among water users.

Exploring options for improved groundwater management using a participatory research approach in Sindh, Pakistan

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This abstract is part of a series of five connected presentations related to the ACIAR LWR-2015-036 project

Pakistan ranks third among countries facing acute water shortage and could reach absolute water scarcity by 2025. Sindh, being the lower riparian province of Pakistan, is facing grave surface water shortages and problems of soil and groundwater salinity, exacerbated by mismanagement. Our four-year research project used a participatory case study approach to explore issues and options for improving groundwater management with water managers and users.

In Sindh, six villages were selected along the head, middle and tail of two case study canal distributary systems in Nawabshah and Naushehro Feroze districts. Groundwater use and quality varies considerably across the canal distributary system, undermining equity of access of water for irrigation. Social mapping, discussions with farmer groups and interviews with people with a stake in groundwater management led the participatory research approach. Stakeholder forums in each case study area were then established to enhance ongoing collaboration on research activities, including exchange of groundwater and agronomic information from community piezometers installed and mobile Apps provided. A novel cultivation model called N4veg is also being used to improve both water management and farming family livelihoods.

The participatory research confirmed that groundwater management issues vary with the location of farms along irrigation distributaries. At the tail of minor distributaries more than 90% of farmers depend on tube wells for irrigation and use mostly marginal quality (1500-2500 µS/cm) water. Groundwater depth is 30-60m contributing to higher pumping costs.

While there is a need to identify management strategies for more equitable distribution of water used for irrigation, including groundwater, there is also an immediate opportunity to use the Apna Pani mobile App, small cultivation planters and salinity meters as low cost interventions to improve irrigation farming practices among smallholder farmers unable to afford more expensive technologies.

Evolution of groundwater concerns over the Carmichael Mine: 2014 to 2019

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Objectives: In this presentation, we explore critical elements of the hydrogeological science and its evolution applied to the assessment of Carmichael Mine impacts over a five-year period – 2014-2019. The aim is to offer insights and lessons learned regarding the role of hydrogeological science throughout the approval process.

Design and Methodology: Key scientific inputs relating to datasets, conceptual model design, and groundwater modelling are synthesised to provide a historical account of the scientific evolution throughout the approvals process.

Original data and results: The approval of the Carmichael Coal Mine by the Queensland Department for Environment and Science (13th June 2019) was the culmination of a lengthy journey by Adani though Federal and State approvals processes. During that time, groundwater-related concerns were raised, debated and reviewed at several junctures, most notably in relation to potential impacts to the nationally significant Doongmabulla Springs Complex (DSC). The approval process for the Carmichael Mine produced, arguably, the most polarizing, public display of hydrogeological debate in Australia's history. Opinions on groundwater science were tested in public fora and the Queensland Land court, creating a time-stamped evolution of hydrogeological investigation and understanding regarding the likely future impact of the Carmichael Mine.

Conclusion: This presentation offers a rare audit of hydrogeological science applied at various stages of the assessment/approval of a large-scale and high-profile development with major implications for groundwater.

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Geophysical & Petrophysical Methods & Groundwater

Advancements in frequency domain electromagnetic surveys and their interpretation and effectiveness for determining flow in mine waste rock dumps and below Tailing's storage facilities

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1. AquaGeo, Craigie, WA, Australia

Objective: Understanding where water is occurring and its movement in mine rock waste dumps (MRWD's) and below tailings storage facilities (TSF's) is critical to the management of the waste rock dumps and tailings storage facilities during operation and closure.

Design and Methodology: A combination of frequency domain electromagnetic geophysics (FDEM-8B) developed in 2018 and statistical interpretation using a newly developed program, Vlex4D, has allowed the definition of flow paths through TSF's and MRWD's in Northern Queensland, Western Australia and Egypt.

Although ground electromagnetic geophysical systems are well known in the geophysical industry namely the EM34, the FDEM-8B system, is unique as eight frequencies are read at each station. This allows faster traverses and quicker data capture. Files can be generated for pseudo sections as well as frequency specific grid contour maps. Using the Vlex-4D software platform, three dimensional iso-surfaces are generated from the ground geophysical data and "wrap" the similar conductivities.

Data and results: The FDEM system used in conjunction with Vlex 4D has been effective in determining flow paths and acid metalliferous drainage areas (AMD) within the waste rock dumps and TSF's. This was confirmed through drilling and monitoring of groundwater bores drilled on the MRWD's and below TSF's.

Conclusion: Applications define in which areas and what relative depths AMD generation is occurring within rock waste dumps, understanding flow paths below TSF's into groundwater and allowing a more focussed approach to investigation of groundwater through drilling and sampling. This methodology has been shown to be repeatable and allows the targeting of AMD generating areas in waste rock dumps and leakage areas in TSF's for priority rehabilitation.

Testing innovative technologies for Atoll groundwater mapping

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The atoll's increasing vulnerability to ENSO-driven droughts and their water-related impairments prompted the assessment of the electrical resistivity tomography (ERT) and ground penetrating radar (GPR) to generate subsurface models that inform/guide drought response actions and investments with confidence. The ABEM Terrameter resistivity kit and the Mala Easy Locator Pro WideRange GPR (dual frequency, 160 and 670 MHz) were tested on Nukulau Island, Fiji, and on South

Tarawa, Kiribati. The test was conducted under high rainfall conditions with the identification of the water table and the estimation of freshwater lens thickness being the main objectives.

On Nukulau island, high resolution ERT data was generated with the Res2DInv software with a distinctive lateral and vertical variation in resistivity exhibiting an estimated freshwater lens thickness of up to 7 m atop basal saline water. Clear distinction between unsaturated and saturated zones (water table) was easily made. Contrasts between saturated materials at depth based on salinity levels and the possible presence of undulating and porous limestone was easily noticed – calibration of these models was made through known depth and salinity records from similar atoll settings.

The respective GPR survey was completed faster and the data processing, using the RadExplorer software, required signal improvement techniques, such as background removals, and assigning appropriate velocity values to subsurface materials at different depths and salinity composition, converting arrival time models to depth models. The model showed similar freshwater lens shape with a lens thickness of 3.5 m, 50 % less than the ERT model estimation.

The second GPR traverse was undertaken in Bonriki in South Tarawa, Kiribati. Two monitoring bores along the profile provided freshwater lens thickness of up to 18 m before decreasing to 7 m towards the end. GPR results, again, showed a reduced lens thickness of up to 6 m. GPR is limited in confidently defining the lens, possibly attributed to the limited signal strength and penetration of the two frequencies as opposed to the detailed depth varying ERT. The availability of monitoring bores to provide known depth and salinity measurements are critical to both methods to allow for calibration. Further, the identification of the water table can be difficult during the wet season and in moderate to high vegetation areas due to the increased moisture content in the unsaturated zone coupled with the influence of the capillary fringes causing reflections, and thus, increasing uncertainties of around 0.2 m as tested in similar conditions elsewhere.

Revisiting old cased bores for new hydrogeological data; borehole magnetic resonance

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Nuclear Magnetic Resonance is a measurement technique used in a range of fields including medical, industrial, pharmaceutical, and the energy sector. In the Oil and Gas industry it has been used since 1958 to quantify volumes of hydrocarbon and porosity. The physics of the measurement involve the use of a static magnetic field and perpendicular radiofrequency pulse to stimulate hydrogen atoms in water (or hydrocarbon) and recording their return to steady state over time. Primarily the measurement technique gives a direct, lithology independent measure of total porosity. Secondary values include information regarding pore size, specific retention, specific yield and hydraulic conductivity from the use of empirical equations. The technique has been described in great detail elsewhere (Neville & Hopper, 2017; Kleinberg, 2001). With the measurement based on magnetic fields, the Borehole Magnetic Resonance (BMR) tool can be operated in open hole, PVC and GRE cased holes without an impact on the measurement.

The purpose of this study was to demonstrate that reliable hydraulic parameters can be obtained from existing cased bores. Validation of received data was done on the East Midlands project geophysical logs by comparing data obtained from a new bore, where BMR was run in open hole versus GRE/PVC cased holes. BMR was logged in nine shallow PVC - cased holes tapping the Perth superficial aquifer. The selected bores intersect three main lithologies: Bassendean Sand, Tamala limestone and Guildford clay. Geophysical logging results were validated in two bores where CRT - pump test data were available. Evaluation and interpretation of the available data indicates this methodology can be successfully employed to discern aquifer hydraulic parameters from existing bores at an affordable cost.

1. Kleinberg, R. L. (2001). NMR Well Logging at Schlumberger. Concepts in Magnetic Resonance, 13(b), 396-403.
2. Neville, T., & Hopper, T. (2017). Principles and applications of borehole magnetic resonance logging. FastTIMES, 22(2).
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GAB Bore Doctor

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Great Artesian Basin (GAB) springs were used by the indigenous people for millennia. European settlements in the GAB regions would have been impossible without artesian bore water supplies for stock and domestic uses.

Currently, there are about 4167 registered bores in Queensland, with depths ranging from 120 to 1750 m. Due to issues associated with bore integrity (bore construction practices of the past, age of the bores, and groundwater quality), a large number of the bores required reconditioning/rehabilitation.

This paper describes borehole-geophysical logging surveys (physical probing, down the hole camera survey, calliper; temperature, gamma and density logging). Based on the experience of the last three decades, the suite of methods selected, are the most cost-effective methods to determine thickness and physicochemical properties of geological layers in production and monitoring bores in the GAB. This information is essential for proper construction of water-supply bores, assessment of groundwater quality and rehabilitation of GAB bores.

A series of case studies to highlight the use of geophysics for hydrogeological applications

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Geophysics is useful in a range of hydrogeological settings. A series of short case studies will cover geophysical applications in coastal sedimentary aquifers, fractured rock aquifers, paleochannel aquifers and mine dewatering. Case studies of coastal sedimentary aquifers at Exmouth, and North Perth Basin, Western Australia will highlight the successful use of airborne electromagnetics (AEM) and ground electrical resistivity imaging to map the aquifer structure and saline water interface.

Airborne magnetics, radiometrics and electromagnetics have proved successful in mapping fractured rock aquifers in South West, Western Australia. Magnetics is highly effective in mapping significant faults and fractures while airborne radiometrics and electromagnetics have highlighted areas of shallow bedrock and deeper weathering.

Three paleochannel examples highlight the effectiveness and limitations of airborne and ground electromagnetics (EM), gravity and passive seismic methods. AEM is a successful and fast method to cover large areas but in highly saline areas, mapping the base of the channel is often ineffective. Ground EM, gravity and passive seismic techniques can all be effective in detailed mapping of channel structure and thalwegs.

Pit wall dewatering is necessary to prevent wall failure which may impact safety and production in operating mine sites. A controlled source audio magneto-tellurics (CSAMT) survey was completed at the Gold Quarry mine on the Carlin Trend in 2009 following a pit wall failure. The survey successfully identified several perched clay aquifers and the main water table. It also delineated the location of faults, structures and saturated sediments. Depressed water tables surrounding dewatering bores were also clearly identified in the data. The survey allowed for rapid, effective placement of dewatering bores and reduced the risk of future pit wall collapse.

These case studies highlight how geophysical techniques can be used as cost effective tools for both detailed and broad hydrogeological problems including de-risking bore placement.

Characterising the access constrained valley by using non-destructive investigation methods – Thirlmere lakes case study

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The Thirlmere lake system comprising four lakes is part of the Greater Blue Mountains World Heritage area located about 100 km south of Sydney, NSW. Large changes in water levels in the lakes in the past 50 years have prompted a multidisciplinary investigation to understand how this lake system functions including underlying geology. Given the logistics of drilling access near the lakes, there has been limited investigation of the underlying rock and geological structures that could influence the hydrology of the lakes.

This study was conducted using three different geophysical techniques to improve understanding of the depth, extent and variability of unconsolidated sediments and underlying sandstone. This included undertaking two transects by electromagnetics (EM34) across the sills, 12 km of ground penetrating radar (GPR) surveys along and across the lakes and sills, eight resistivity transects between the lakes. EM34 was found to provide relatively rapid means of measuring shallow electrical conductivity of the ground but lacked detail and resolution.

A combination of GPR and resistivity have been the most successful methods to date. These surveys have identified dry peat horizons to a depth of around 2 m, a clear boundary with the underlying saturated clay layer at a depth between 2 to 5 m below ground and a layer of sandier sediment beneath the clay and along the valley

sides. Typical resistivity of less than 30 Ωm and presence of fresh water indicates a saturated clay layer, with variable thickness between lakes. Across the lakes and partially across the sills, the clay layer has attenuated the GPR signal, but enabled clear differentiation from the overlying peat layer. Strategic drilling has enabled some verification of the resistivity transects with additional targets identified for further work. In addition, GPR has revealed areas of steeply dipping beds in the northern part of the lake system and possible structures, in areas where outcrop is limited.

Looking beyond wells: geophysical methods for improved groundwater assessments

Kevin Hayley [1]

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Geological heterogeneity and variations in groundwater composition can result in material properties and water concentrations varying over several orders of magnitude within small distances. Despite this reality of groundwater investigations, traditional hydrogeological assessments are generally restricted to point measurements of the subsurface at boreholes and, highly uncertain extrapolation is necessary to develop a conceptual model of the hydrogeology.

Geophysical methods can provide a spatially extensive complement to traditional hydrogeological investigations in locations where contrasts of the appropriate physical property exist in the subsurface. In academic and niche consulting environments, geophysical methods have been applied to improve groundwater understanding for decades. However, wider adoption of geophysics by the hydrogeological community is limited due to lack of technical knowledge, cost, equipment availability, and project budgets and timelines.

The purpose of this talk is to provide an overview of common geophysical methods used for groundwater investigations; highlight the pros/cons, relevant physical properties, and initiate a discussion on how greater application of geophysical methods can further our understanding of groundwater in Australia.

Two examples of geophysical groundwater investigations will be presented from both consulting and academic studies, ranging from low cost non-intrusive studies to high resolution time-lapse imaging of groundwater changes. The studies highlight the potential application of multiple geophysical methods and time-lapse geophysical monitoring, to provide insights into groundwater systems that are not otherwise available.

Use of Big Data & Groundwater Databases - Mapping, Cleansing & Maintenance

Groundwater intelligence: applying data analytics and visualisation tools to process, analyse and communicate groundwater data

Alice L. Drummond [1] , Christian M. Borovac [1]

1. DiscoverEI, Melbourne, VIC, Australia

Objectives: In this age of 'Big Data' and real time monitoring, the groundwater industry is literally drowning in data. This study presents a range of case studies which apply innovative ways of processing, analysing and visualisating groundwater data, to help bridge the communication gap between the scientists and decision makers and facilitate a data driven culture.

Design and Methodology: This project combines the latest business intelligence tools and computer animations to create a shared understanding of the complex groundwater systems we manage. Groundwater data was sourced from publicly available databases (such as the Victorian Water Management Information System). Interactive dashboards were developed within Microsoft Power BI, the world's leading Business Intelligence platform. One-page reports combining dynamic maps, geological bore logs, groundwater level hydrographs, water quality data and statistics were developed, providing water managers with key information in an accessible format to drive decisions. Animated conceptual site models were developed in the Adobe Creative Cloud to help communicate how these complex groundwater systems operate and describe the key findings from groundwater studies.

Original data and results: The results from this study are a suite of interactive dashboards, infographics and computer animations which can be used to help manage and communicate groundwater data, providing an alternative to traditional written reports.

Conclusions: The data analytics and visualisation tools presented in this study have broad and wide-ranging applications across the groundwater and environmental industries. These tools can be used to both streamline data processing and improve communication, facilitating a culture of data driven decision making to help manage the future sustainability of our groundwater resources.

Managing an extensive regional groundwater monitoring network in the Surat Basin – key challenges, opportunities and innovation

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1. Office of Groundwater Impact Assessment, Brisbane, QLD, Australia

The Surat and southern Bowen basins are complex multilayered aquifer systems extensively developed for private water use and more recently for petroleum and gas (P&G) development. The Office of Groundwater Impact Assessment (OGIA) is responsible for the design of a regional monitoring network to support hydrogeological research, system conceptualisation, impact assessment and regional groundwater modelling in the Surat Cumulative Management Area (CMA).

In this area, OGIA produce an Underground Water Impact Report (UWIR) every three years which sets out monitoring obligations for petroleum tenure holders across the Surat CMA. These include construction and installation of groundwater monitoring equipment, the measurement of groundwater pressure and chemistry, aquifer injection and associated water extraction volumes. As of late 2018, there are around 500 monitoring bores – with up to 1,000 individual monitoring points – and more than 7,000 CSG extraction bores.

There are a range of unique challenges in managing a network extending over across an area of 100,000 km2 encompassing more than 20 hydrostratigraphic units, varying hydrochemical conditions, multiple fluid phases and with monitoring depths up to 1,500 m. Across the area, construction and instrumentation differ significantly and necessitate careful data treatment and density correction requirements.

Responsible tenure holders capture and compile four groundwater datasets – pressure, chemistry, extraction, and injection – to OGIA every 6 months. OGIA complete an extensive series of checks on the received data. Given the scale of data received, OGIA have developed a number of in-house data assessment tools to verify data format and quality.

There are unique challenges in the management of OGIA's dataset: multiple data providers, data types, large volumes of transient data, quality control of data format and content, and preparing data for internal and external release. This presentation will provide a summary of the challenges and unique data management tools developed by OGIA.

Moving towards near real-time groundwater level data. Providing an automated and consistent groundwater level dataset for Australia

Brendan Dimech [1] , Todd Lovell [1] , Mario Mirabile [1] , Elisabetta Carrara [1]

1. Bureau of Meteorology, Melbourne, VIC, Australia

Objectives: As part of the Water Act 2007, the Bureau of Meteorology is required to collect, hold, interpret and disseminate Australia's water resource data. One of these is a nationwide dataset for groundwater levels, containing 230,000 bores with a recorded water level. This data is made available through the Bureau's Groundwater Explorer - bom.gov.au/water/groundwater/explorer – for download at bore level or by state or river catchment scale.

The Bureau was publishing this data on the Groundwater Explorer twice a year. Following customers feedback for increased data currency, the Bureau is now increasing the frequency of groundwater levels ingestion and publication. A project was developed to automate the ingestion of data and the publishing to the Groundwater Explorer.

Design and Methodology: Under the Water Regulations 2008 all state and territory water agencies are required to deliver water resource data to the Bureau. This is ingested into the Australia Water Resources Information System (AWRIS). AWRIS is a database developed to hold all water resource information submitted to the Bureau. Currently the majority of data relates to surface water.

This project was developed to complete several tasks:

Working closely with lead water agencies to enhance and facilitate their data submission.

- Extending AWRIS to better accommodate groundwater information.
- Further automation of data processing and quality checking to allow automatic publishing to the Groundwater Explorer.

Results: This means Bureau's Groundwater Explorer is now publishing water levels at days after being read, at sites where available. This standardised dataset is available at a national scale for most states and territories.

Lead water agencies are required to deliver monthly, however in most cases it is delivered more frequently. Automation has allowed for the data to be ingested and published as it is delivered with minimal latency. About 500 sites are telemetered, with readings being updated weekly. 5,000 more are logged sites than have readings within 2019.

Internally, the Bureau staff has now access to automated and consistent water level data for use in analysis and assessment across Australia. For example, this data has been used to provide up to date and relevant groundwater information to the NSW Drought Taskforce and the MDBA/CEWO's Climate and Water Briefing.

When groundwater strikes: mapping shallow groundwater risks

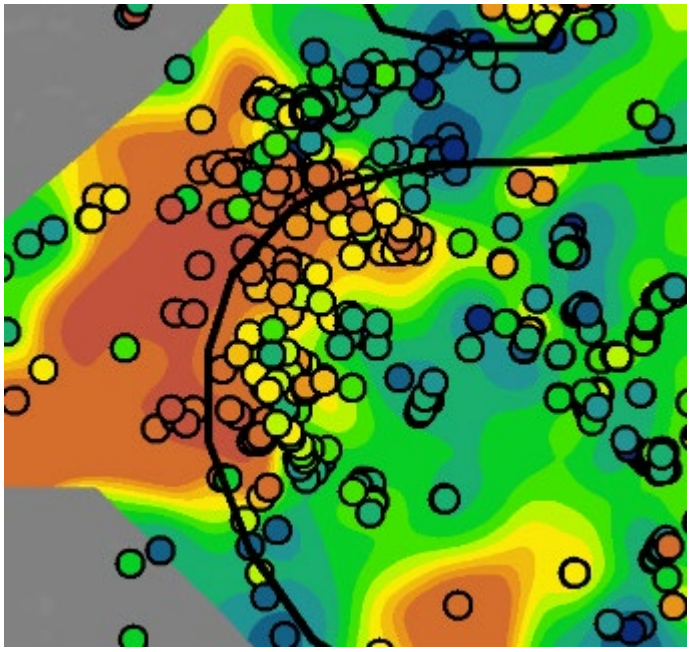
Jeremy Bennett [1] , Tara Forstner [1]

1. Tonkin & Taylor Ltd, Newmarket, Auckland, New Zealand

Objectives: Hydrogeological studies typically focus on groundwater as a resource for both human and ecological activities. Shallow groundwater is often neglected as these resources may be considered too vulnerable to surface contamination, or the yield may be too variable. Despite shallow groundwater often not being a viable extractive resource, it can present a significant risk to infrastructure. These risks are likely to be exacerbated under changing climatic conditions (flooding, sea-level rise) and are applicable to a variety of risk mechanisms.

Design and methodology: Although shallow groundwater is subject to the same governing laws of flow as deeper groundwater resources, there is often far less information available about the spatial distribution of shallow groundwater surfaces. This lack of information makes traditional groundwater flow modelling difficult as data scarcity leads to greater model parameter uncertainty. As many shallow groundwater risks are dependent on hydraulic head, rather than flow or aquifer yield, simplified maps of shallow groundwater head can be used to understand these risks. We have developed a workflow for mapping shallow groundwater levels that incorporates a range of spatial and temporal information. The information is obtained from regional authority databases and environmental data sets. We used geostatistical relationships between variables to improve estimates of shallow hydraulic head in data-sparse areas.

Results: The results honour groundwater observation data and provide a continuous shallow groundwater surface across the area of interest. The workflow is flexible and allows for different scenarios (i.e. seasonal variation) to be efficiently mapped.



Conclusions: The shallow groundwater level maps produced in this study can be used to quantify risks to infrastructure, including liquefaction risks and groundwater inundation. Regional shallow groundwater maps are also applicable as design criteria for water-sensitive urban design and construction. The automation of mapping workflows allows for maps to be produced more efficiently and offers the opportunity for further development using more advanced approaches, such as machine learning.

Validating and scaling metered groundwater use data for the development of the Central Condamine groundwater flow model

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This presentation describes the process used in pre-processing of groundwater use data for the MODFLOW unstructured grid (MFUSG) model for the Central Condamine and Tributaries. The objective was to validate and to scale groundwater use data to the model temporal and spatial scales where metered use data existed, and to derive and infill data where metered used data did not exist. The model domain is vast when compared to other alluvial systems in Queensland and covers an area of approximately 7,720 square kilometres with approximately 8,950 registered bores. Of these there are approximately 3,340 bores with a water entitlement (licence). Metering of some bores commenced in 1979, and to date 1,340 bores have been metered.

Groundwater use data were captured at various time scales ranging from fortnightly, to annual and at different time intervals. Since metering commenced water use data were stored in a variety of systems ranging from initially paper to various database, and with a variety of index systems ranging from registration number (one to one) to property number (many to one)

One of the challenges was to derive groundwater use at the day scale for all 3,340 bores, for the period from 1960 to 2017. The first step in this process was to collate information on when and where the bores were drilled; and to establish if the bore is presently being pumped or when it ceased to be pumped. The second step was to

determine the likely extraction rate. For bore drilled before 1979, information on use and extraction rate were also obtained from property surveys and interviews with landholders.

The next step was to establish time intervals when bores may have been pumped at the day scale. For most bores and particularly since 2005 bores, the granularity of meter use data at the annual scale precludes the identification of individual pumping sequences. For some irrigation bores close to observation bores with equipped with data loggers, pumping sequences could be readily identified in the water level behaviour. For more distant bores, pumping sequences were derived from an irrigation scheduling model.

Pre-processing software was developed using a hierarchal approach to derived daily groundwater use data with a data quality index identifying reliability and method. The index was used to assign weights for calibration purposes. Where possible, the quantum of the metered use was retained.

Porosity and permeability of the Springbok Sandstone, Surat Basin – integrating wireline and laboratory data

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1. Queensland University of Technology, Brisbane, QLD, Australia
2. Origin Energy, Brisbane, QLD, Australia

Objectives: The Late Jurassic Springbok Sandstone in the Surat Basin is highly heterogeneous in terms of lithology and hydrogeological properties. This heterogeneity is poorly defined in well logs, due - in part - to clay phases that do not exhibit a prominent gamma ray signature. The resulting uncertainties in the hydrogeological properties are transferred to uncertainties in the groundwater models of the Springbok Sandstone. Further, only a small amount of porosity and permeability data is publically available and no petrophysical model of the Springbok Sandstone has been published in the peer-reviewed literature. At the same time, accurately predicting the potential groundwater impact due to coal seam gas production from the underlying Walloon Subgroup is of significant societal and economic importance.

Design and Methodology: We present new porosity and permeability data from more than 50 core samples from the Springbok Sandstone alongside a review of existing data. Based on this dataset and wireline data from five study wells a new petrophysical model for the formation is proposed.

Original Data and Results: The results show that (a) the Springbok Sandstone is highly variable in terms of hydrogeological parameters, (b) this variability can be captured with a petrophysical model that draws on a full log suite (i.e. triple-combo) and (c) electrofacies classifications based on gamma ray and bulk density log cut-offs do not reflect this variability.

Conclusion: Ultimately our results can be utilized in combination with 3D geological models to predict the presence of rock units that have the sufficient transmissivity to constitute aquifers. This work also forms the platform, which allows in combination with future detailed (sequence) stratigraphic analyses to define geobodies and their facies affiliations to predict aquifer properties and their spatial distribution in the Springbok. Our results therefore provide key inputs into a potential regional aquifer characterisation of the Springbok.

Field-scale downscaling of passive microwave soil moisture retrievals using a neural network trained on integrated hydrological model predictions

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Passive microwave satellite remote sensing systems (e.g., SMAP and SMOS) can provide reliable near-real-time observations of surficial soil moisture at a coarse resolution of 9-to-30 km. Recent efforts to downscale these observations have focused on the fusion of Visible-Infrared or Synthetic Aperture Radar imagery. However, these methods are limited by the availability of the ancillary satellite imagery datasets, and their resolution is limited to 1-to-2 km. The state-of-the-art in neural network downscaling methods is also limited by the extreme sparseness of soil moisture probe datasets. We present an alternative downscaling procedure that leverages fully integrated groundwater-surface water models for their insights into the spatial distributions of soil moisture.

We constructed a feedforward neural network with 30-m aggregated input parameters including topographic wetness index, hydraulic conductivity, land cover class, and soil moisture observations interpolated from daily passive microwave soil moisture products. The neural network contained one input layer, two hidden layers, and one output layer. The novel aspect is that the neural network was trained on nodal soil moisture values predicted at daily intervals by a HydroGeoSphere model spanning Southern Ontario. With ~900,000 total nodes at surface, this vast training dataset spans ~75,000 km^2 at a resolution of 10-to-500 m.

The trained neural network was able to delineate sharp features such as wetland boundaries and produces plausible-looking soil moisture patterns over various geophysical features such as ravines and moraines. Neural network predictions were comparable to in-situ soil moisture probe data.

We demonstrate that a neural network can be trained using the outputs from a fully integrated hydrological model and applied in practice for the downscaling of passive microwave soil moisture retrievals.

The importance of quality assurance and quality control for making the most out of hydrogeochemistry data

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Geoscience Australia's Northern Australia Hydrogeochemistry Survey (NAHS) has been collecting groundwater samples across the north-eastern Northern Territory, investigating water-rock interaction to identify regional mineral prospectivity and establish geochemical baselines. Given the sensitivity of groundwater composition to a range of confounding variables, the program adopted an approach to ensure it minimised (and captured) as much uncertainty as possible in chemical results from the sampling, processing and analysis aspects of a groundwater survey through robust Quality Assurance and Quality Control (QA/QC) protocols. This presentation will share a systematic approach to adopt for future sampling campaigns, useful scripted methods for quickly visualising QA/QC data to make judgements on the quality, and examples from the NAHS of major problems caught through our QA/QC process.

QA/QC begins before the survey commences, with a plan (and budget) for additional samples that need to be collected. We follow a triplicate sampling approach with field and lab duplicates every 10 sites. Our field duplicates capture the errors introduced through the sampling process and field heterogeneity, while our lab duplicates capture variance in the laboratory analysis. Additionally, water and filter blanks are collected on every sampling trip to measure any systematic contamination resulting from sampling, storage, transport and processing. For non-isotope systems, standards are included to assess accuracy of response as well as track batch effects. Overlapping samples are used to check for consistent performance when a new laboratory or method is trialled. Consideration is given both to how these blind QA/QC samples perform, as well as holistically whether the batch chemical results make sense using both charge balance and element ratios.

Using this range of QA/QC samples and semi-automated scripts, this project has been able to quickly calculate statistics and visualise performance of each new analysis batch. Worryingly, in several instances' lab duplicates were found to have much poorer agreement than field duplicates. As a result, instrument-specific problems, changes in an instrument/calibration within and between batches, sample number mix-up, dilution errors, and systematic offsets attributed to instrument software errors were caught. By identifying these problems at an early stage, which is only possible with independent and blind QA/QC samples, an opportunity to work with the laboratory to deduce and resolve issues quickly was afforded. As a result, greater confidence both in the true uncertainty in our datasets, and that interpretations are being made from a validated view of the groundwater system, exists.

Data Assimilation & Metrics for Models in Decision Support Roles

A novel approach to collating and mapping groundwater recharge and aquifer property data to communicate variability from temporal and spatial scales

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Objective: The Victorian Department of Environment, Land, Water and Planning (DELWP) have been undertaking a data enhancement program to improve accessibility to existing groundwater data and understand the uncertainties in data used to inform management decisions. The challenge to date is that historical data sets (recharge and aquifer properties) are not readily accessible, have varied levels of attribution of the data in regard to the method, formats (e.g. vector, raster, text), units (e.g. mm/year vs % rainfall), and project extents and coordinate systems (e.g. AGD84, GDA94, MGA).

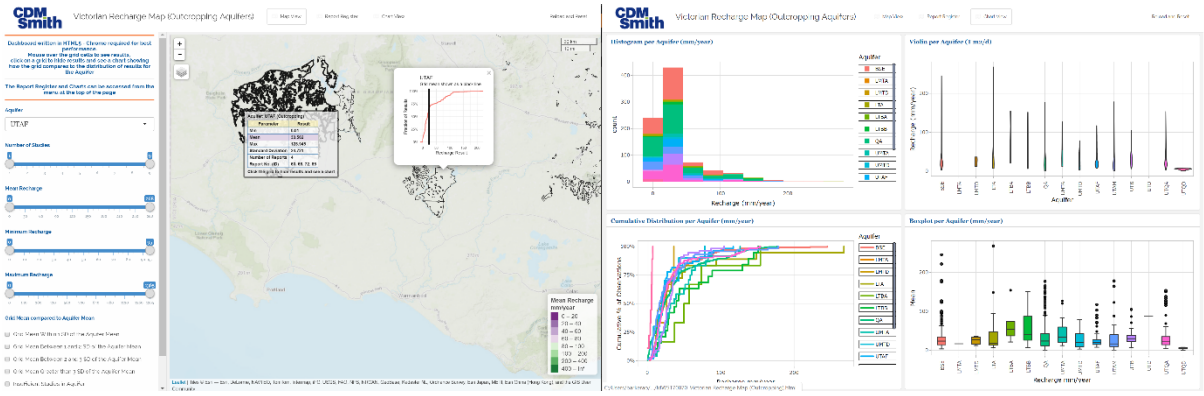
This paper presents a semi-automated methodology by which the variability in formats and units of recharge and aquifer property data sets are organized such that they are consistent (e.g. data formats/scales/units), mapped spatially and presented in an interactive manner, including the ability to determine the reliability of the data sets. This mapping project builds on work undertaken to develop a statewide groundwater inventory.

Design and Methodology: This challenge was tackled by developing visual products for recharge and aquifer properties data sets, the approach included

- data collation – from 65 studies from the last 50 years;
- data preparation – a process required to generate a consistent set of data for mapping;
- development of various mapping methods to consider the most appropriate technique for presenting the available data sets; and
- construction of the mapping products.

Results: The end product was a mapping product that includes:

- conversion of data to a variable grid to communicate data intensity, with grid size driven by data density. This allowed higher resolution results in areas where more data was available to inform the mapping.
- Interactive functionality to communicate variability and data sources across locations, and cumulative distribution graphs that compare results with state-wide distributions



Conclusion: The outputs of this project can inform groundwater resource assessments and groundwater management decisions now and in the future for Victoria.

Data fusion – Merging model results with telemetry data to obtain design water levels, real-time monitoring and virtual sensors

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Groundwater levels and pore pressure distributions are important input data for many engineering calculations in civil engineering and mining. Direct measurements and numerical models are the main tools for obtaining this input, each having different strengths and drawbacks. Models provide a continuous distribution in space and allow forecasting but are associated with a model-to-measurement misfit. Direct observations are usually very accurate and allow real-time monitoring but are spatially sparsely distributed.

Consequently, optimal knowledge of hydraulic heads requires combining both methods. The standard method is model calibration. This method can - if performed wisely – reduce the model predictive error associated to a minimum. At the end of the process however, the model's output still contains a bias that propagates into further engineering decisions and can reduce their robustness. Also, assimilation of new measurement data into the model that is continuously collected in the field traditionally requires recalibration of the model. This process still requires high effort of labour and time, making it less suitable for real-time monitoring and fast decisions.

To face these challenges, this presentation demonstrates how the results from a calibrated model are augmented using a bias correction method based on geostatistical principles. Based on past performance of the model, the likely spatial and temporal distribution of the model error is estimated at unsampled or forecasted locations. By correcting for this bias, we can estimate the most likely "real" system state based on Bayesian principles including uncertainty margins.

The process is illustrated using case studies on generating design water levels and pore pressure distributions for civil engineering, pit dewatering and slope stability projects.

The presentation shows why augmented estimates are generally more accurate than those of the calibrated model or interpolated data alone, especially in complex hydrogeologic environments like mining areas. Additionally, we obtain confidence intervals for the estimates, which is useful for choosing appropriate safety factors and proposing new measurement locations.

On regional groundwater models as tools for informing management: an example of effective and efficient decision-support modelling (Wairarapa Valley; NZ)

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Publish consent withheld

Is Steady State Model Calibration sufficient?

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Parameter estimation and uncertainty analysis theory provide a series of guiding principles which can be used to assess the costs and benefits of model simplification in decision making. It can be shown that if a modelling prediction is data-informed, partially data-informed or not data-informed, then the approach to modelling can be very different.

We present an empirical demonstration of these guiding principles for the most challenging context of model simplification, e.g. partially data informed. Successful strategies for partially data-informed problems must avoid the perils of model complexity which include long run times and numerical instability. These strategies must also navigate the perils of model simplification, i.e. errors in uncertainty estimates and predictive bias, so that such models retain the benefits of complexity, namely the ability to quantify uncertainty. This requires that prediction-specific complexity is retained, while those parts of a model that are of secondary importance to management-critical predictions can be simplified.

The empirical demonstration explores the costs and benefits of adopting the concept of "steady state" as our simplification strategy in the context of predicting the increase in the duration of low stream flows in response to pumping of a nearby well.

The full Monty for a regional-scale CSG groundwater impact model

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Since 2010 the Office of Groundwater Impact Assessment (OGIA) has been responsible for assessing the impact of coal seam gas (CSG) extraction activities on groundwater resources in the Surat Cumulative Management Area (CMA) and preparing an Underground Water Impact Report (UWIR) every three years.

As part of the 2019 UWIR, a regional groundwater flow model has been redeveloped to assess aquifer impacts from current and future CSG development. The groundwater flow model is constructed using a modified version of MODFLOW-USG and simulates 34 layers of geological strata over a 450 km x 650 km area. It is a large, complex model, containing over 1.3 million active cells and accounting for dual phase flow, faults, aquifer reinjection and the partial completion of CSG wells into non-CSG reservoirs. The model was calibrated using a highly parameterized, regularized inversion approach implemented using PEST and requiring adjustment of more than 18,000 parameters on the basis of nearly 65,000 observations. This dataset of observations included transient observations of head and head changes at 480 monitoring locations throughout the Surat CMA. Model calibration was followed by the generation of 450 alternative calibration-constrained parameter fields using the PEST-supported null space Monte Carlo method in order to explore post-calibration predictive uncertainty.

Predictive uncertainty results included ranges of predicted short and long term CSG impacts on springs, water supply bores and overall aquifer water budgets. These results are used to support make good arrangements for water supply bores, inform spring impact management strategies and estimate aquifer recovery times.

This research demonstrates how the results of a predictive uncertainty analysis for a complex regional groundwater flow model can be used to support assessment of cumulative CSG groundwater impacts for a key groundwater system in Australia. Although important predictions are obtained to support CSG impact assessment, it is becoming increasingly apparent that regional modelling should be supplemented by predictive uncertainty modelling at smaller scales to better represent local aquifer interconnectivity features and capture local groundwater system dynamics.

PEST ++ IES and cloud computing: case study of a numerically challenging mine-closure model with rigorous uncertainty analysis, within the confines of a realistic consulting timeframe and budget

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Numerical groundwater modelling to support mining decisions is often challenging and time consuming. Simulation of open pit mining for model calibration or prediction requires models that include, unsaturated flow, large magnitude hydraulic gradients, and often require transient simulations with time varying material properties and boundary conditions. This combination of factors typically results in models with long simulation times and/or some level of numerical instability. In modelling practice, this fact can result in reduced effort for predictive uncertainty analysis, and ultimately decrease the value of the modelling to support decisions. This study presents an early application of the iterative ensemble smother (IES) method of calibration constrained uncertainty analysis to address the challenges of mining models and uncertainty quantification. The IES method was applied with PEST++ IES software and facilitated by highly parallelized computing using the Amazon EC2 cloud computing service.

An operating open pit mine in South Australia required estimation of long-term recovery pit water levels and inflow rates to support decisions regarding the long-term environmental impact of the project, and the feasibility of a proposed pumped hydro energy storage system. A groundwater observation dataset was available consisting of static water level measurements taken prior to the most recent mining

activity from both project specific observation bores and public databases at 98 locations. Transient observations of groundwater level changes over 7 years of mine development were available at 16 locations. Initial model simulations indicated that the application of traditional finite difference-based methods of calibration and uncertainty analysis would be complicated by low magnitude numerical instabilities and require excessive computational effort due to multi-point derivatives or highly refined model grids and long simulation times.

The IES calibration successfully produced 150 model parameter realizations that acceptably reproduced groundwater observations. The flexibility of the IES method allowed for the inclusion of 1,493 adjustable parameters and geostatistical realizations of hydraulic conductivity fields to be included in the analysis. The IES method out-performed finite difference methods when model simulations contained small magnitude numerical instabilities.

Stochastic knowledge integration for groundwater exploration in data scarce areas

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We have developed a systematic probabilistic framework to spatially assess the potential for sustainable groundwater development. The workflow starts by explicitly defining sustainable groundwater extraction, in our case study, a groundwater abstraction that can provide 1ML/d for 10 years with a salinity of less than 2500 mg/L without causing a drawdown of more than 5% of the saturated thickness at 1m from the borehole.

The methodology is applied to groundwater exploration in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands in central Australia. In this arid region, a crystalline basement is covered with regolith and a vast system of palaeovalleys that are filled with sediments. Both the regolith and the palaeovalley systems are known to host aquifer systems. An ensemble of interfaces that define the boundaries between the basement and the overlying weathered rocks and palaeovalley sediments is generated with a Bayesian Data Fusion methodology to ensure they are consistent with the available borehole, airborne electromagnetic and digital terrain information. The surfaces defined by these interfaces are combined with probability distributions of hydraulic conductivity and storage to create ensembles of equivalent transmissivity and storage. A similar procedure is used to generate ensembles of salinity that are consistent with the available knowledge of salinity distribution across the region.

Gridded water balance equations, in combination with the Theis equation, allow the rapid generation of ensembles of sustainable pumping volumes from these stochastic grids of hydraulic properties and salinity. The ensembles provide the probability of locating areas where the requirements of sustainable groundwater extraction are met.

The integration framework not only allows to rapidly identify prospective zones for sustainable groundwater extraction, it is transparent, can be iteratively and locally updated when new information becomes available.

Spatial data mapping for reduction of uncertainty in groundwater modelling

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Unbalanced monitoring distribution is always a big challenge in groundwater modelling for assessing the impact of regional groundwater systems on the local human activities. Pilot points as a tool are often used in such groundwater modelling for enhancing information from limit observations but still restricted to the monitoring data distribution. We propose a novel spatial mapping strategy which combines fuzzy set theory and pilot point approach to form a logic potential from relevant spatial hydrogeological information for reduction of data uncertainty in the model calibration. An effective fuzzy logic approach, which incorporates random probability and fuzzy set theory, is introduced to capture the dispersion of the reliable monitoring information from the relevant regional hydrogeological and monitoring data to produce a map of "intensity" scores which allows the modeller to place "smart pilot points" at locations defined by their probability for producing informative constraints on the statistical distributions of the target variables. The method is demonstrated to be successfully applied for groundwater modelling with limit site monitoring data in a remote mine development project. In summary, the proposed approach intends to reduce the data uncertainty in the groundwater model calibration with the information gleaned from borrowing relevant spatial and historical data associated with hydrogeological mapping while reducing the site monitoring costs.

Climate Change/Variability Impacts and Water Security in Tropical & Arid Climates

Mapping groundwater trends across Australia – visualising the impact of drought

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Objectives: A wealth of groundwater level data is collected across Australia. Across each state and territory, water level data is collected for tens of thousands of bores, sent to the Bureau and published in the Australian Groundwater Explorer. The Bureau has been able to integrate this data with contextual information on climate change, groundwater extraction, rainfall and streamflow to provide insight in those factors impacting groundwater levels across Australia.

Methodology and Results: The Bureau produces estimates of groundwater level trend and status for bores across the nation, where status is defined as a decile rank of current levels. However, groundwater data is notoriously variable, typically having sporadic temporal frequency, highly variable lengths of record, and limited quality control of the historical record. This makes it difficult to sensibly apply a trend method across all groundwater systems in Australia.

Current methods used to estimate trends and status were designed to be applicable to the widest set of bores, thus giving the broadest coverage across Australia. These methods use monthly average groundwater levels to estimate trends and annual average groundwater levels to estimate status. While this approach captures broad trends very well, it can produce undesirable results in some bores, especially where seasonal fluctuations are much greater than long term trend. To address this, the Bureau has developed a methodology which focuses on assessing the trends and status based only on annual recovery peaks. This method automatically identifies recovery peaks during the non-pumping season, and assesses trends and status based on the recent peak against peaks in prior years. However, this method is restrictive in its application as it requires a higher frequency of water level readings for each bore analysed.

Conclusion: By assessing trends and status based only on annual recovery peaks the trends and status are improved, better representing the recovery of the aquifer rather than average values across the year. These improved trends can provide quick, yet accurate, insights into changes in groundwater resources across Australia. An example of how this has been used to assess the impact of drought in the Murray Darling Basin will be presented. This approach delivers an improved visualisation of changes in groundwater resources across Australia.

Rationalisation of the Shepparton irrigation region public groundwater pump network - an adaptive response to a changing climate

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Objectives: During the latter part of last century, rising water tables across the Shepparton Irrigation Region (SIR) in Northern Victoria prompted significant public and private investment to manage and control salinity. This investment assumed shallow water tables, and associated salinity threats, would be a permanent feature of the SIR irrigated landscape. One of the many initiatives implemented to combat the salinity threat was the progressive installation of a Public Groundwater Pump network. The resulting network of 115 Goulburn-Murray Water (GMW) owned and operated groundwater pumps provided capacity for water table protection to about 18,000 hectares of horticulture and pasture.

Since the onset of the Millennium Drought approximately 20 years ago, a combination of changes in climate, water use, irrigation practices, land-use and stakeholder expectations has led to a different understanding of the SIR salinity threat. This changed understanding has seen a shift from previously fixed and prescriptive groundwater and salinity management arrangements to adopting a more adaptive and flexible approach.

Design and Methodology: Consequently, a number of projects, such as rationalising the SIR observation bore network, have already been undertaken by GMW to ensure management of sub-surface drainage assets evolves to meet a more contemporary risk profile and is able to be adapted to foreseeable risk scenarios. GMW's network of public pumps is now being rationalised to around 32 active pump sites. Water table trends are monitored to ensure pumps can be readily reactivated if high water tables and salinity threats return. Ongoing salinity risk surveillance and reporting will continue, primarily through a web-based portal designed to better inform landholders about salinity threat changes.

Original data and results: The public pump rationalisation project, as with other recent initiatives, stems from a need to respond to significant climatic and landscape changes. Importantly, rationalisation of the public pump network is supported by sound science about changing water table behaviour and salinity threats. The project is also responding to significant changes in irrigation and is strongly aligned with community expectations.

Conclusion: There is now a clearer understanding that long-term regional prosperity and resilience requires management responses that adapt to change and address uncertainty. The SIR Public Groundwater Pump Rationalisation project is clear example of recognising the value of important infrastructure and adapting its operation to changing circumstances.

Climate change adaptation: Protecting and expanding freshwater lens resources during land reclamation on low lying islands

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Sea level rise due to anthropogenic climate change is an existential threat to low lying Pacific islands and their inhabitants. The Island of South Tawara is the capital and main hub for the Republic of Kiribati and home to around 50,000 people, half of the Kiribati population. The island is low lying, with a maximum elevation 3 m above mean sea level, meaning most of the 15 km^2 island and its freshwater lens water supply are at risk of ocean overtopping and inundation. A climate change adaptation proposal has recently been funded by the New Zealand government looking to provide around 3 km^2 of reclaimed land at a higher elevation by dredging and pumping lagoon sand onto a tidal flat area. The land reclamation offers secure additional land for habitation and in the long term the possibility to expand the area of freshwater resource. However, during construction pumping of seawater and sand threatens existing freshwater.

An existing variable density groundwater model of the freshwater lens system was adapted to investigate the period during and after construction. Transient 3D simulations of the existing lens and reclamation area were completed using the variable density code Modflow USG-Transport. Risks to existing freshwater resources during construction can be mitigated by phased placement of dredged material and appropriate drainage. The time taken for freshwater resources to develop under reclaimed land depends heavily on future rainfall and groundwater recharge. It is estimated to take multiple decades such that other freshwater sources will be required for new housing in the short and medium term.

Application of MAR technology in Sri Lanka

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Despite Sri Lanka's rich history of water capture and reuse since 414 BC, technological advances and social changes after the 1970s has seen water supply become insufficient to meet the demand. Shortages of water impact all groundwater uses, from irrigation to potable supply.

Managed aquifer recharge (MAR) is a proven technology that stores water in aquifers for reuse. This project, undertaken on behalf of Australian Water Partnerships and funded by DFAT, responds to a request by the Water Resources Board of Sri Lanka (WRB) to identify the preferred locations that might be considered for a MAR trial to prove the application of MAR technology in Sri Lanka.

The methodology to gather sufficient information for a trial began with a national level review of shortage, source water and hydrogeology followed by more detailed reviews in the preferred locations. In partnership with local organisations, the national review identified an abundance of source water and the presence of aquifers of various quality in all ten of the Districts with a shortage, however, the three Districts with the greatest water shortage was identified by the WRB as Puttalam, Moneragala and Vavuniya. Water Technology matched data from source water availability and the presence of suitable aquifers with a MAR technology that could be supported by a future scheme operator. Local partners provided a national stakeholder analysis to assist with this process. Suitable aquifers were characterised by sufficient storage and permeability identified from studies, field investigations and remote sensing.

Analysis of the findings presents estimates of water volumes and qualities that could be provided by a MAR scheme to meet the demand. This includes estimates of the costs for delivery of a trial MAR scheme, the key uncertainties and suggestions for successful management. Positive results from a trial are anticipated to enable wide-scale adoption of the MAR technology in Sri Lanka to address a range of water shortages.

Impact of climate change on the groundwater resources of India: need of an appropriate adaptation strategy

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Availability of reliable groundwater in India is fast decreasing as a result of climate extremes and human impact on the environment. Dependency on groundwater increases with rising water demands and depleting surface water resources. Higher temperatures produce more evaporation from surface water bodies and also make the soil dry, reducing the recharging of underground resources. Increasing rainfall seasonality allows wasteful runoff and reduces the duration of groundwater recharge. High intensity rainfall erodes topsoil, reducing the water holding and recharging capacity of the surface. Trends in rainfall in the dry zones increase dependency of groundwater for irrigation where there is no balance between extraction and recharge. Changing frequency and intensity of cyclones increasingly salinates coastal aquifers. Predicted change in sea level may add to this in future. Changes in the course of rivers as a result of flooding and sedimentation may lower the water table in the heavy rainfall regions. Falling water availability leads to social issues such as migration of farmers, conflicts over allocation and pricing. Present study analyses the trends in rainfall, temperature and aridity, proneness to droughts, their impact on groundwater resources, and critically reviews the existing policies, strategies and management practices. Current availability and utilisation of groundwater in different States, and the possible changes under an altered climate have been assessed. Main objective of the study is to assess the present groundwater situation in India and its possible changes in near future to suggest guidelines for appropriate groundwater policy and climate change adaptation strategy in the agriculture and water sectors.

Necessary data have been procured from the India Meteorological Department; Ministry of Water Resources and Ministry of Agriculture. Study reports from various Research Institutes, Universities and NGOs have been used. Study reveals a sharp decline in groundwater availability in almost all parts of India. Groundwater across north-western and south-eastern India drops by 4cm/year and more than 109 Km^3 of groundwater disappeared in 4 years. Quality of groundwater in more than one-third of India is very bad. Urgent measures to cope with changing climate are vital in maintaining food and water securities and poverty alleviation.

Future scenarios for reliability of community groundwater supplies in East Sumba, Indonesia – a karst savanna case study

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Abstract unavailable

Rising water levels in the Burdekin groundwater management area

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The Burdekin Groundwater Management Area (BGMA), is part of an extensive alluvial aquifer associated with the lower Burdekin River. It supports approximately 35,000ha of irrigated agriculture and drains to the Great Barrier Reef. Since the construction of the Burdekin Haughton Water Supply Scheme (WSS) in the late 1980's, groundwater levels have risen by up to 10m. Water-tables within 1m of the land surface have been recorded in some areas, posing a significant threat to agricultural production. The WSS allows water to be pumped from the Burdekin River and delivered to farms via open channels, irrigation runoff is removed by a separate drainage network. Recharge to the aquifer is identified to be by rainfall, irrigation deep drainage, losing streams, and leakage from the channel supply system. Discharge mechanisms from the aquifer include coastal outflow, abstraction, gaining streams and evapotranspiration from groundwater dependent ecosystems (McMahon *et al.,* 2012).

Hydrograph analysis (Ferdowsian & Pannell, 2009) was used to determine whether groundwater levels in the area have reached a new equilibrium. An investigative water balance approach was then used to determine why water levels have stabilised in some areas.

An equilibrium has been reached in the coastal sections of the BGMA, primarily through increased discharge, as the water-table has risen and intersected the surface water drainage. The drains act as either gaining or losing watercourses at times. While groundwater levels have stabilised to a height that may mitigate the risk of waterlogging during years of average rainfall, periods of above average rainfall and flooding would result in an exceptionally high-water table, with major implications for agricultural production. Further, the quality of the groundwater entering the drainage system, and discharging to the Great Barrier Reef lagoon is of major concern (Vardy *et al*., 2015). The risks associated with these two issues suggest that additional management of the groundwater table is needed.

Water levels further inland in less transmissive sections of the aquifer continue to rise with increasing risk to agriculture. There is potential that the drainage network will have less of an impact in stabilising the water-table in this area due to lower transmissivities in the aquifer. Elevated water levels will result in increased salinisation and waterlogging which may have an irreversible impact on agricultural production.

These findings will guide future groundwater management decisions in the BGMA and may be transferrable to other irrigated agricultural areas.

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Climate resilient urban water security by recharge techniques

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As a part of an ongoing PhD work, Climate Resilient Water Security Urban settlements demand climate resilient strategies and action plans to ensure a secured water management for Bengaluru Urban region, India was undertaken.

Comparative analysis was conducted, UN reports that since 1900, natural disasters including intense flooding have quadrupled from 50 per year to 200 per year. A definite climate resilient action plans in cities around the world are available. These initiatives have demonstrated definite vision, agenda and action plans specific to each of the cities. Case Studies of four urban settlements Guarulhos (Brazil), Arequipa and Lima (Peru) and Durban (South Africa) reveal transition, structural changes for delegation of responsibilities on water security and its management. Literature survey was conducted.

Data was collected from the analysis of the relevant case studies and field visits. These global practices are relevant to over 277 Urban Local Bodies in Karnataka of which only 54 towns have Under Ground Drainage and Sewage Treatment Plants. A study of Bengaluru are reported in this paper.

Conclusively, Studies using Survey Maps and Satellite Imageries during 1900 to 1985 reveal a trend of lowered ecological planning in development plans. In the recent past over 300 urban water bodies are of focus for conservation strategies at Bengaluru Urban Region. Hydrogeological investigations reveal that the ground water resources are contaminated. Dynamic Ground Water Resources investigations emphasis appropriate attention as there is a decline of ground water resources. In this presentation hydrogeological conditions of Bengaluru Urban Region climate and rainfall, Geological Succession, soil and ground water condition, seasonal, ground water levels and Quality, Estimation methodology are reported. Non-Monsoon recharge from rainfall computed by RIP method is discussed. Water Chemistry interpretation Techniques are introduced. Climate resilient structural changes for Bengaluru Urban water security are identified and reported. Comparison between four global urban regions and Bengaluru case are compared and found that the inadequacy in planning and urban design need to be addressed. State of the art remote sensing techniques in assessing ground water at Bengaluru urban and action plan reveal an endangered ground water security.

Stygofauna & Microbiology

What happens to groundwater ecosystems when you take out the groundwater?

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The removal of groundwater results in the lowering of water tables, which, for groundwater organisms, translates to reduced habitat availability and changed environmental conditions in the habitat that remains. While changes in groundwater levels may be well modelled and predicted, the impacts on groundwater ecosystems remain poorly known.

There are three key processes associated with groundwater drawdown in shallow alluvial aquifers that may threaten groundwater ecosystems. These processes are 1. the physical decline of water levels, from which fauna can be stranded in isolated or unsaturated sediments; 2. the loss of or change to habitat, particularly as water levels move through different geological strata and 3. changes in hydrological connectivity, that may influence water quality as a result of increasing distance or disconnection from the surface and other water sources.

Results from laboratory studies show the variable capacity for stygobiotic invertebrates to move with declining water tables, dependent on both drawdown rate and sediment attributes. Once isolated in unsaturated habitats, our tests show that survival of fauna is limited beyond 48 h. Invertebrates are constrained by sediment size and unable to use those with relatively small pore spaces and may not be able to use all available saturated habitats.

This talk will present a framework that identifies the key threats of groundwater drawdown to groundwater ecosystems and will highlight the current state of knowledge of each of these threatening processes. We present the results of empirical studies on the response of stygobiotic invertebrates to specific elements of the framework.

What's going on down (under) there? Unravelling biochemical flows under differential rainfall periods in a Western Australian calcrete

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Groundwater is a vital resource. It contains 97% of unfrozen water on the planet, playing a key role in present and future water needs for humanity. However, our knowledge about the ecosystem functioning is very poor, and groundwater environments are increasingly exposed to anthropic impacts and climate change-related processes. Novel biochemical (e.g. isotopic ecology) and genetic (e.g. eDNA) techniques, widely employed in fresh surface water studies, have the potential to unravel the complex dynamics shaping subsurface ecosystems, providing new insights to the small but quickly growing field of groundwater ecology. Stygofauna, together with microbes, are crucial actors in shaping and maintaining the organic matter (OM) cycles in environments characterized by low energy and scarce carbon availability. In order to understand groundwater ecological patterns, we investigate calcrete stygofaunal shifts linked with contrasting rainfall periods (low rainfall (LR), dry season; high rainfall (HR), wet season), through an interdisciplinary design composed of hydrology, isotopic ecology and genetics. Our results indicate that the inflow of rainfall under HR is responsible for increased nutrient concentrations in the system and dissolved organic carbon (DOC) pulses from the surface. Both the meiofaunal and stygofaunal communities' benefit from these organic inflows, with gamma and proteobacteria the biota that fuels carbon and nutrients to the higher levels of the trophic web. The HR regime - and its subsequent terrestrial carbon incorporation - triggers a cascade effect driven by microbes (OM processors) and amphipods (biofilm grazers), which is finally transferred to the aquatic beetles (top predators). Overall, and in line with other work in the same research area, the inflow of rainfall triggered shifts towards more deterministic dynamics, revealing a complex web of interactions in a seemingly simple environmental setting. This study provides a preliminary untangling of the biochemical flows driven by rainfall in a calcrete aquifer. More investigations involving multidisciplinary approaches on other subsurface ecosystems, i.e. alluvial aquifers, will help to understand present ecological patterns and predict future scenarios in groundwaters.

Can metabarcoding provide insights into trophic web interactions underground: a case study from the Yilgarn region of Western Australia.

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Objective: Subterranean ecosystems host a vital and highly adapted invertebrate aquatic biota which play a key role in sustaining groundwater ecological functioning and hydrological dynamics. However, functional biodiversity studies in groundwater environments, the vastest source of unfrozen freshwater on earth, are remarkably scarce.

Design and Methodology: To fill this gap, we propose to dig into the field of groundwater trophic ecology *via* multi-locus metabarcoding analysis to potentially elucidate trophic web interactions (food webs) and the associated gut microbiome. Stygofaunal specimens were collected from a well-known biodiversity hotspot, the Sturt Meadows calcrete in Yilgarn region of WA. Sampling campaigns were carried out during the dry (LR) and the wet (HR) seasons with the goal of comparing ecological trends within different rainfall conditions.

Results: Preliminary results on a small subset of samples support the possibility of opportunistic feeding of beetles on beetles (*Paroster macrosturtensis*, *P. mesosturtensis*, *P. microsturtensis*) and the sharing of bacterial Families within the gut microbiome of these species, which may be associated with microbially-mediated carbon inputs (gamma and proteobacteria). Further work to expand on these findings is currently underway. Metabarcoding results also highlighted scavenging as a driving force shaping beetles' feeding habits.

Conclusion: This study, although in its infancy, may provide untangling of stygofauna food web dynamics and stress the importance of the synergy between microbes and invertebrates in calcretes. This is of importance to understand the groundwater functioning and model future affections linked with climate change such as aridification and loss of biodiversity.

All creatures great and small - a case study of stygofauna from an agricultural field site in Canterbury, New Zealand

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Biologically, groundwater ecosystems remain one of the most understudied systems in New Zealand. As well as the nature of sampling methodologies and accessibility to suitable sampling sites, there are also challenges due to taxonomic capability. However, information and new sampling techniques are rapidly being generated from this emerging area. We present a site-specific study from Canterbury, containing several wells from the same aquifer that have been sampled for biodiversity, including traditional and molecular techniques.

Objectives: To compare the biodiversity of several wells from the same aquifer and compare with environmental and sampling parameters.

Design and Methodology: Groundwater samples from a number of different wells from within the same aquifer were collected using a pump or hand netting method. Samples were all collected on the same day across different seasons. Sub-samples were stored for water chemistry and stygofauna were identified using traditional and molecular techniques.

Original Data and Results: Biodiversity amongst several sites from the same aquifer is variable. There was a relationship between water chemistry and biodiversity.

Sampling technique can bias the animals collected. Smaller animals are difficult to identify.

Conclusion: Our study suggests that several sites are required to sample groundwater biodiversity and careful consideration of environmental parameters should be determined beforehand, to prescribe representative sampling locations. Smaller meio-fauna, require further sampling protocols, and DNA-barcoding may be a more efficient way to measure their biodiversity.

Biological exchanges within the hyporheic zone: the importance of maintaining connectivity between surface and groundwaters

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Groundwater ecosystems are dependent on the input of oxygen, nutrients and organic matter from the surface. The hyporheic zone, the ecotone that connects surface and groundwaters, is a vital conduit for the supply of these nutrients to aquifers. The dynamics of exchange through this zone has a major influence on the biota and the overall health of both surface and groundwater ecosystem, particularly during low flow or drought, when groundwater discharged to streams maintains baseflow. However, surface -groundwater interactions are equally important to the ecosystems within aquifers during losing conditions. This study investigates how variations in surface-groundwater exchanges and connectivity influence the biotic communities in these freshwater ecosystems, using a combination of environmental DNA (eDNA) to characterise microbial and invertebrate communities and water chemistry (including nutrient, carbon and isotope data) to quantify the extent of SW-GW exchange. Samples were collected between 2015-2016 at three locations within the Maules Creek catchment, a sub catchment of the Murray-Darling Basin in NW NSW. At each site, samples were collected along a gradient from the creek through the hyporheic zone and into the adjacent alluvial aquifer. We found a rich diversity of invertebrates and microbes with distinct overlaps in biological communities noted along our gradients. Surface water microbes, distinguished by their ability to photosynthesise, were observed in highly connected aquifers, supporting the direction of water flow indicated by water chemistry data. Our results help characterise biogeochemical processes within the hyporheic zone, highlighting the importance of this hydrological connectivity for surface and groundwater ecosystems. Such findings will lead to a greater understanding of the connectedness of ground- and surface waters resulting in a more holistic view to water management within the Murray-Darling Basin, and elsewhere.

Development of a groundwater health index

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Within groundwater there are a whole range of organisms from micro to macroscopic that live in a complex ecosystem. These ecosystems protect our groundwater by removing contaminants and maintain porosity and flow. The processes that occur in these systems is still largely a black box and there are many potentially vital ecosystem services that occur that we still do not fully understand.

Objectives: Our project is aimed at ultimately establishing a groundwater health index that can be used, similar to the macroinvertebrate community index (MCI) in surface water systems. Our research is not only focused on the macroinvertebrates present but the microbial diversity as well.

Design and Methodology: Groundwater samples, *in-situ* biofilm bag samples have been collected at sites in New Zealand over multiple seasons. The water chemistry is analysed with the 16s rRNA sequence data (targeting bacteria, archaea, fungi, and eukaryotes) to provide the basis of a method to identify the status of a groundwater source.

Original data and results: We have shown there is a complex diversity present in both the groundwater itself and the attached microbial biofilm. We have shown this variation between the attached and groundwater occurs across all sites studied and significant differences in the Shannon richness indicator seen in Canterbury (Wilcoxon rank, $p = 4.6 \times 10^{-7}$). We also find there are differences occurring in groundwater and attached microbial populations depending on the lithology and water chemistry present.

Conclusion: Our research is identifying key species (micro and/or macro) present that can potentially act as a tool for predicting the health of a groundwater. An additional benefit of understanding the biological processes that are occurring in our groundwater is that beneficial organisms capable of remediation could be discovered.

Novel Bioremediation strategies for nitrogen contaminated groundwater

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Objectives: This study examined several lines of evidence to determine effective strategies for the remediation of the nitrogen-contaminated groundwater surrounding a water treatment plant. Understanding the hydrogeology, chemistry and ecology and how they interact is essential to selecting an appropriate bioremediation strategy.

Design and methodology: To determine the most effective bioremediation strategy, statistical analysis was conducted on sampling data collected over >10 years in and around the water treatment plant. This allowed for further understanding of the hydrogeochemical site characteristics, to help inform the experimental phase. As a result, seven triplicate microcosms using the native groundwater ecosystem were established. The microcosms were used to test how inorganic electron donors at different concentrations affect the natural attenuation of nitrogen. Simultaneously, the effects of the different treatments on the microbial ecosystem were explored to determine any detrimental effects nitrogen plumes and the accompanying remediation efforts may have on the groundwater ecosystems.

Original data and results: Multivariate statistical analysis of sampling data showed that iron concentrations were significantly correlated with total N and NH_4^+ but not NO_3^- (P-values of $2.54*10^{-14}$, $1.65*10^{-4}$ and 0.283 respectively) and sulphur was significantly correlated with NH_4^+ but not total N and NO_3^- (P-values of $6.54*10^{-7}$, 0.18, 0.05627 respectively). These correlations are consistent with an important role for redox in the behaviour of N contamination in the groundwater.

Conclusions: The findings of the statistical analysis of the sampling data show correlations between iron and sulphur concentrations and total nitrogen, NH_4^+ and NO_3^- concentrations. By combining these data with microcosm experimental results, we hope to delineate how different concentrations of these ions affect the natural attenuation of nitrogen-contaminated groundwater. This in turn can be used to design bioremediation strategies based upon biostimulation of the native ecosystem.

Intermittent/Ephemeral Drainage Systems

Are all rivers equal? Attitudes towards intermittent and ephemeral rivers in Australia, the UK and USA

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Objectives*:* Intermittent and ephemeral rivers and streams (IRES) are prevalent yet often overlooked and underprotected. This may be because inadequate understanding of their ecosystem services leaves them undervalued by society. However, evidence of negative attitudes towards IRES is scant.

Design and methodology: We investigated the strength and extent of negative attitudes to IRES by surveying undergraduate students from Australia, UK and USA on their agreement (positive attitude) or disagreement (negative attitude) with statements about the ecosystem services, moral consideration and protection of both perennial rivers and IRES. Students were surveyed at the start and end of teaching units covering environmental topics.

Original data and results*:* Disagreement with statements was uncommon (17% across all statements and surveys) and attitudes towards tIRESs were mostly

positive. However, attitudes towards perennial rivers were more positive, particularly in comparison attitudes towards IRES when they were not flowing and in regard to their aesthetic value and recreational amenity. There were no significant differences in attitudes towards perennial rivers and IRES in one teaching unit in Australia, and responses were more often more positive at the end of teaching units in the UK.

Conclusion: Our study indicates education can change attitudes. The overall positive response to statements may reflect underlying environmental awareness and pre-existing interest of participants enrolled in environmental and biology degrees, but not necessarily specific knowledge of IRES. General environmental education across the wider community could improve attitudes towards IRES, particularly when they are not flowing or in regions where they are uncommon or inconspicuous, and could support positive protection measures and innovative, inclusive management of surface and groundwaters alike.

Identification and systematic prioritisation of surface water refuges to sustain freshwater biodiversity in eastern Australian intermittent stream networks

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Objectives: The hydrological variability of intermittent streams means that the spatial distribution of aquatic refuges within river networks and the temporal dynamics of hydrological connectivity between them are critical for the persistence of aquatic biodiversity. We demonstrate a new approach to identify surface waterbodies as potential refuges for freshwater biodiversity in river networks and efficiently prioritise them for on-ground conservation management.

Design and Methodology: We developed models of surface water extent and of daily streamflow to represent spatio-temporal variation in surface water extent and hydrological connectivity within river networks of eastern Australia over a 107-year period. We also assembled spatially explicit freshwater fish species distribution data as targets for refugia prioritisation and elicited estimates of their relative mobility potential within river networks. We then applied a systematic prioritisation algorithm to identify areas that provide all resident fish species with access to a minimum number of aquatic refuges while maximizing the length of stream potentially accessible for recolonisation after dry periods.

Original data and results: Simulated long-term variations in streamflow intermittency and surface water extent were highly dynamic through space and time over the past century. A subset of highly irreplaceable aquatic refuges for freshwater fish were identified that were widely distributed throughout the river networks, encompassing main stems to headwater streams. A set of on-ground conservation management actions to maintain the refugial-values of these areas is recommended to minimize disturbance from livestock and feral animals, pollution, water extraction, local aquifer drawdown, and other threats.

Conclusion: Our study presents a novel and practical approach to identify priority aquatic refuges for targeted conservation management to enhance the resistance and resilience of freshwater biodiversity in intermittent stream ecosystems.

Use of multiple methods for studying recharge/discharge processes in regulated and unregulated reaches of the Dumaresq River

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Rivers of arid and semi-arid regions of Australia are among the most variable in terms of discharge of any rivers worldwide and are characterised by extended periods of no flow regimes. During extended dry spells, aquatic habitat are able to survive in billabongs.

Since the onset of the current drought, there has been several environmental flow releases from the Glenlyon Dam, located on Pikes Creek, a tributary of the Dumaresq River. The environmental flows mitigated dry conditions to maintain aquatic ecosystem health and services, by filling and connecting waterholes.

In this paper, hydrogeological processes (recharge/discharge) of the Dumaresq River are studied, at different spatial and time scales, using multiple methods. The study area extends from Glenlyon Dam to Keetah Bridge, representing unregulated and regulated reaches. The methods used are:

- Conjunctive analysis of surface water gauging stations and groundwater monitoring networks in QLD and NSW
- Heat as a groundwater tracer
- EC routing, and
- Normalised Difference Water Index (NDWI).

Understanding of hydro(geo)logical processes at a reach scale will lead to better informed surface and groundwater management in the upper parts of the Border Rivers basin.

The canary or the coalmine? Isotopic evidence of drying climate versus groundwater outflow as the cause for recent losses from Thirlmere Lakes, NSW

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The Thirlmere Lakes Research Program (TLRP) is a collaboration investigating water loss mechanisms in recent drying of five adjacent lakes, located 75 km south-west of

Sydney. Some stakeholders and previous studies have perceived a correlation with local longwall coal mining history and suspect deep fracture outflow. Others suggest the lakes are simply responding to a drier climate, serving as the canary in the broader climate-change 'coal mine'.

ANSTO has applied recurrent isotopic and chemical monitoring of the lakes and adjacent groundwater over two years to unravel some of the mystery of their recent water losses. Each lake behaved uniquely, but they shared some common trends. Steady enrichment of stable water isotopes, ^{2}H and ^{18}O, indicates the dominance of evaporation, with minimal losses to groundwater or through transpiration. Lake Cl/Br ratios were very low and clustered in three groups, two trending away from initial ratios indicative of groundwater input. ^{3}H and ^{14}C show recent rainfall and/or runoff as the main contributors to lake waters, with apparent ages in the adjacent shallow groundwater up to several decades. High levels of ^{222}Rn from shallow bores suggest a close association between the peats enclosing the lakes and ^{238}U from ancient erosion, or proximity of an underlying shale lens. The only deep piezometer (72-84 m) near the lakes showed negligible contributions from the lakes or recent surface water.

The trends in isotopic and chemical parameters infer that evaporation is sufficient to explain recent water losses from most of these perched lakes. Trends in some lakes hint that these had previous inputs from groundwater. While the historical variability of groundwater input to the lakes remains unknown, there is no current evidence of major losses to groundwater. Thirlmere Lakes will exist only intermittently under dry climate conditions.

Streamflow generation mechanisms for an intermittent-ephemeral catchment in South Australia: a modelling approach

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In Australia, Intermittent Rivers and Ephemeral Streams (IRES) are the common features that dominate the landscape. Contributing with roughly 70% of the stream network, IRES are key for ecosystems health, are important for farming and agriculture and represent a main source of groundwater recharge. However, the understanding of streamflow generation mechanisms for IRES remains a challenge. This study examines an intermittent-ephemeral catchment in South Australia where little is scientifically known about the processes leading to streamflow generation and the contributing mechanisms, although there are many well-developed hypotheses among the local vineyard owners. Previous research in the catchment has shown complex spatiotemporal interactions between the creek and the shallow aquifer, outlining changes in losing and gaining conditions along the creek during the intermittent flow season. We used a fully integrated surface-subsurface hydrological model coupled with the hydraulic mixing-cell method to investigate the processes leading to the onset of flow for the intermittent season and to determine the spatiotemporal variability of the streamflow generation mechanisms. For this, we analyzed the development of flow generating areas and the dominant contributing flow generation mechanisms at different locations along the catchment at the onset of flow, and during the transition from ephemeral to intermittent flow. The expected results from this study will allow us to better understand streamflow generation at the threshold of flow and at the transition from ephemeral to intermittent flow for an intermittent-ephemeral creek in South Australia. This will be useful to aid IRES management decisions such as those pertaining to ecosystems health monitoring,

the vulnerability of the catchment to the effects of droughts, and potential impacts of declines to the shallow groundwater system.

Geological controls on the spatial variability of ephemeral flow regimes

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As global population increases and climates shift, intermittent rivers and ephemeral streams (IRES) are receiving increased attention from researchers and water resource managers. These types of systems are commonly associated with arid regions of the world but are also present in temperate Mediterranean-type climates. While the distinction between IRES and perennial systems can be useful, not all streams or rivers neatly into one of these categories. Here we present two examples of streams in different climates that have both ephemeral and perennial flow regimes along their length. Longitudinal stream surveys, groundwater monitoring and geophysical mapping identified that in both cases the underlying geology is the key control on the surface water flow regime. The first site is the Donnelly River in south-west Western Australia (WA). The Donnelly River flows across the deeply weathered granite of the Yilgarn Craton and onto the unconsolidated alluvial sediments of the Scott Coastal Plain (SCP). Decreasing rainfall has resulted in a change from perennial to ephemeral flow over the Yilgarn Craton, but our data demonstrate that groundwater discharge across the geological transition to the SCP still maintains perennial flow along the lower reaches of the river. The second site, Spring Creek, is located on the Dampier Peninsula in the Kimberley region of northern WA. The headwaters coincide with perennial groundwater springs, below which we identified a sequence of perennial and ephemeral reaches on the order of 10 km in length. Geophysical surveys identified a previously un-mapped confining layer that results in the "pinching out" of the upper Broome Sandstone aquifer. This geological transition causes groundwater discharge that maintains stream flow along the perennial reaches of the stream. These two examples from varying climates highlight the importance of geological controls on stream flow generation in intermittent and ephemeral stream systems. This type of process-based understanding of stream flow generation is critical to ensure appropriate monitoring and management of IRES under threat from changing climate or increased water use.

Directly measured soil evaporative losses in the semiarid Pilbara

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Soil evaporative loss is an important but usually only coarsely estimated component of the catchment water budget of dryland streams. Most estimates reflect a potential maximal evaporative (reference) loss as they are based on the energy budget (Penman-Monteith) or weather parameters (Hargreaves-Samani) but rarely account for the actual soil moisture content. While these estimates are credible in wet climates with evenly distributed precipitation throughout the year, they are less

accurate in more arid regions where rainfall can be strongly seasonal and potential pan evaporation can exceed precipitation ten-fold.

In this study, we used an RTG weighing lysimeter (Umwelt-Geräte-Technik, Germany) to quantify soil evaporative loss in situ and to assess how evaporative loss varied between wet and dry cycles. Our experimental site was in the semiarid and subtropical Hamersley Basin of the Pilbara region of northwest Australia. Measured mean daily evaporative losses during dry cycles were 0.33 mm day^{-1} (2016, over 86 days) and 0.25 mm day^{-1} (2017, over 73 days). These rates were three (0.95 mm day^{-1} in 2016) to five (1.21 mm day^{-1} in 2017) times lower than estimated potential reference evaporative losses using common theoretical calculations. During the wet cycle (2018 over 81 days), the measured evaporative loss rates were significantly higher (3.64 mm day^{-1} 81 days) and similar to the potential reference evaporative loss (3.61 mm day^{-1}); however, rates varied greatly from 0 to 13.04 mm day^{-1} and increased significantly in the days following rainfall events occurring during hot summers. The difference between the calculated theoretical potential reference evaporation and the actual measured evaporation at the scale of our study catchment (4,000 km^2) lead to the daily overestimation of ~ 5 GL during dry cycles. A new proposed correction factor applied to the Hargreaves-Samani method significantly improved the accuracy of soil evaporative estimations based on weather parameters.

Water velocity and groundwater upwelling control benthic algal biomass in an intermittent tropical river: implications for water resource development

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Benthic algae are a major source of carbon supporting aquatic food webs in tropical northern Australia, but little is known about the factors that regulate algal production particularly over small scales. We surveyed benthic algal biomass in mainstem habitats in an unregulated sand-bed tropical river during a base-flow period. Physicochemical parameters (e.g. water velocity, substrate, water quality) were measured at each sampling point and groundwater upwelling (as indicated by radon) and nutrients were measured at a sub-set of points. We used predictive models to reveal the factors controlling algal biomass in mainstem habitats. We found that water velocity was an important driver - algal biomass was lower at higher water velocities. Sub-surface flow was also influential - algal biomass increased in locations where upwelling occurred, as evident by a positive relationship between algal biomass and elevated radon and ammonium concentrations. Micro-algal constituents (diatoms, green algae, cyanobacteria) displayed the same pattern as total algal biomass. In this sand-bed river, it is likely that high flow velocity destabilises the sandy substrate preventing the establishment of algal biofilms. However, where flow velocity is low enough for algal establishment, groundwater upwelling promotes algal growth by delivering limiting resources (e.g. nutrients) and/or creating stable physicochemical conditions that promote algal production. The importance of surface and sub-surface flow conditions to benthic algae biomass means that any modification to the Fitzroy River catchment that alters dry-season longitudinal flows (via river regulation) and/or groundwater levels (via groundwater extraction) may directly influence river algal production.

Tracers & Isotopes

Multi-tracer characterisation of the Cambrian Limestone Aquifer in the Beetaloo Sub-Basin

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The Cambrian Limestone Aquifer (CLA) in the Beetaloo Sub-Basin is the main water supply for domestic use and pastoral agriculture and provides baseflow to unique environmental assets at headwaters of local rivers. In competition, it is a potential resource for fluids to be used in unconventional gas extraction as well as a potential receptor of contamination. The CLA, whose recharge has not been quantified to date, is a complex and highly vulnerable system because it is karstic and only partially confined.

Multiple campaigns have been undertaken, targeting 500 km transects from Mataranka (NT) southwards, collecting samples from 33 bores. The measured tracers include major and minor ions, stable isotopes (^{18}O&^{2}H of H_2O, ^{18}O&^{34}S of SO_4, ^{13}C, $^{87}Sr/^{86}Sr$), tritium, SF_6, halon-1301, radiocarbon, and noble gases. Cluster analysis on hydrochemical data were used to identify different hydrogeological groups.

Radiocarbon activity increased along the flow path, contrary to expectations from the northward flow direction. Modern water was also evident across the sampling area from halon-1301 and SF_6. A two-component mixing model indicated "old" water at the beginning of the investigated flow path with only 2% in radiocarbon and increasingly modern recharge with >100% in radiocarbon further along the flow path. Some samples show elevated ^{4}He, which may be indicative of older water from layers below the CLA.

Noble Gas inferred temperatures were 37-41°C for samples from the Gum Ridge Formation and 32-37°C for the Tindall Limestone. These differences likely result from different recharge characteristics in the North and South. Strontium isotopes differentiate the Gum Ridge Formation and Anthony Lagoon Beds from the Tindall Limestone.

Tracer analysis indicates an increased rate of recharge northwards, consistent with the rainfall gradient.

Characterising changes in isotope hydrochemistry through time in a high use, arid-zone aquifer

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Alice Springs is an important centre for regional industry, tourism and transport in the Northern Territory. The town has approximately 29,000 inhabitants and 400,000+ visitors are wholly reliant on groundwater from aquifers in the Amadeus Basin. Current groundwater use in the Roe Creek Management Zone borefield is ~8,500 ML/yr, far in excess of the ~750 ML/yr of groundwater recharge to the area. As a result, groundwater levels in the Roe Creek borefield have fallen by ~1 m/yr since 1964.

As part of the Exploring for the Future program, Geoscience Australia flew ~2375 line km of AEM, drilled 3 boreholes, took 34 SNMR readings and collected 21 groundwater samples for hydrogeochemical analysis in the Alice Springs project area. Hydrochemistry samples were analysed for major and minor chemistry, stable isotopes, carbon-14, chlorine-36, tritium, CFCs and SF6. In addition, DENR NT have drilled a number of deep (500m) groundwater bores to analyse hydrogeochemistry and to monitor groundwater levels.

Over the last 40 years, there have been at least 4 generations of groundwater sampling for chemistry, stable isotopes and radioisotopes in the Amadeus Basin. The earliest samples were collected by Calf in 1978, followed by Jacobson in 1989, BRS in 1999-2000 and Geoscience Australia in 2017-18.

During this period there have been at least 12 large rainfall events (> 150mm), although only the anomalously wet year of 1974 showed significant groundwater recharge in the Amadeus Basin, the water table has fallen by over 40 metres and many additional bores have been drilled or deepened. In addition, many older bores were indifferently constructed while modern bores are targeted to specific aquifers and intervals. This paper looks at how these changes are reflected in groundwater hydrochemistry and isotopic values and what these changes may mean to the management of groundwater in Alice Springs.

Understanding the sources and transit times of water sustaining streamflow in upland catchments

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Headwater catchments are important sources of water in many rivers. While headwater catchments are commonly developed on indurated rocks without extensive groundwater systems, the observation that many headwater streams are perennial implies that they are sustained by water in fractures, soils, or the regolith.

Understanding the sources and transit times of water in headwater streams is important for understanding catchment functioning and predicting the impacts of changing climate or land use. This study uses major ion geochemistry and tritium (^3H) to determine water sources and transit times in first-order streams in the Otway Ranges, southeast Australia.

Comparison of the geochemistry of soil water, water from soil pipes (macropores), and riparian groundwater indicates that macropore flow is the major contributor to streamflow. The streams are gaining, and the lack of riparian zone groundwater inputs may be due to the presence of low hydraulic-conductivity organic-rich streambed sediments or compartmentalisation of shallow groundwater by clays in the weathered rocks. Similarly, much of the soil water exists in isolated pockets of isolated water that are not connected to the soil pipes. The stream water has tritium (^3H) activities of 1.80 to 2.06 TU. These are significantly lower than the ^3H activities of modern rainfall (2.6 to 3.0 TU), even during the higher winter flows. The water from the soil pipes has ^3H activities of 1.80 to 2.25 TU, the riparian zone groundwater has ^3H activities of 1.35 to 2.39 TU, and one sample of soil water has a ^3H activity of 2.22 TU. Mean transit times calculated using a range of lumped parameter models are between 3 and 57 years. Relatively long mean transit times are consistent with the major ion geochemistry that implies that waters are resident for sufficient time for weathering reactions and evapotranspiration to have occurred.

While the discharge from the soil pipes increases following periods of high rainfall, the long mean transit times implies that this water is stored for several years within the regolith before discharge, with storage volumes estimated as $>10^8$ m^3. Thus the increase in streamflow is not the simple transmission of recent rainfall through the macropores but mobilisation of existing catchment stores. The streams will be buffered against year-on-year variations in rainfall but are vulnerable to longer-term variations in rainfall or land use. Management of these catchments needs to consider the impacts on the macropores, and the delayed responses caused by the large storage volumes.

Use of environmental tracers in environmental impact assessments for coal seam gas and large coal mining developments

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In updating its Information Guidelines (2018) the *Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development* (IESC) identified the lack of use of environmental tracers in developing conceptual and numerical models and how they can be used in a risk context to reduce uncertainty.

Confidently identifying and evaluating causal pathways to impacts on water-assets is key to an efficient environmental assessment process. Environmental water tracers can often complement other techniques and offer an important means of gaining multiple lines of evidence to support conceptual models. Importantly, in some situations tracers may be the only feasible way of gaining information about systems at appropriate spatial and temporal scales. This presentation will provide an overview of the IESC's environmental tracers factsheet, by explaining how tracers can be used in environmental impact assessments by:

1. outlining how tracers can fit into a risk-based framework; and
2. discussing five case studies where tracers have investigated:

1. surface and groundwater connectivity: estimation of groundwater discharge into a section of the Gellibrand River, VIC;
2. recharge sources: the relationship between surface water in a marsh (asset), alluvial groundwater and deep groundwater in the Hamersley Basin, WA;
3. connectivity between different aquifers: groundwater movement between the coal seam and the alluvial aquifer in the Condamine River Catchment, Qld;
4. using tracers to constrain a water balance: evaporation from temperate highland peat swamps on sandstone in the Sydney Basin, NSW; and
5. improving groundwater modelling with tracer evidence: aquifers intersected by dewatering bores at a mine-site in the Pilbara, WA.

References to further reading materials are provided for more detailed technical explanations.

Using environmental tracers to quantify recharge mechanisms and variation in the semi-arid Pilbara region

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Recharge processes in arid and semi-arid environments are characterised by their high variability both temporally and spatially, making it difficult to determine appropriate components of water balances. However, quantifying recharge and understanding how recharge volume responds to changes in climate and hydrological regimes underpins accurate prediction of long-term water supply and water level recovery. We used environmental tracer techniques (including stable isotopes, radioisotopes, and anthropogenic compounds) to estimate ephemeral stream recharge processes in the Pilbara region of northwest Australia. We interpreted soil water profiles (> 6 m depth) of stable isotopes with a model of groundwater flow to assess recharge mechanisms and evapotranspiration in the riparian corridor of an ephemeral stream. We also used CFC-12 and ^{14}C data coupled with a simple flow and groundwater-age model to investigate the change in groundwater recharge over time, with an emphasis on how the modified stream flow regime due to mining water discharge over the previous 10 years had altered groundwater recharge. The model applied an approach of correcting groundwater ages proportional to the flow rate in the system. We were able to identify that in upstream areas with (now) perennial surface flows, groundwater recharge was up to 200% greater than pre-mining conditions. At sites downstream where event-driven stream flow remains dominant, groundwater recharge was consistent with pre-mining conditions. Our results indicate that the spatial variation of groundwater ages is indicative of temporal variation in groundwater recharge. The scales of variability identified in our study, corresponded to the time scales of variability in recharge concentrations of the measured tracers. However, applying a similar methodology with tracers of "old" groundwater could give insight into variability of longer-term recharge.

A golden age for environmental tracers in Australia

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Environmental tracers have been an integral component of hydrogeological studies in Australia for decades. However, the stage is now set for an unprecedented level of activity driven by the increased need for water resource assessments, new fields of investigation, and the recent availability of new tracer techniques. In water resource assessments, there is a need for more detailed groundwater system characterisation due to increased scrutiny of existing water allocation plans, resource development proposals, the proposed expansion of irrigation in Northern Australia, and a dwindling resource under climate change. The planned trillion-dollar expansion of the unconventional gas industry in the coming decades will bring an increased focus on the connectivity between deep and shallower geological units and the slower movement of fluids at depth – areas where tracers have many applications. Other national challenges where tracers could see broader use include groundwater contamination, mine site remediation, underground disposal of CO_2 and nuclear waste, as well as rising sea levels and its effects on coastal cities and aquifers. The development of a new suite of analytical facilities in Australia to measure stable and radioactive noble gases opens many possibilities for new applications. These tracers have simple input functions, have no chemical reactions and are ideally suited to the evaluation of hydrological connectivity, recharge environments, or addressing the parts of the groundwater-age distribution invisible to other tracers. Despite a recognition of their usefulness, the cost, lack of expertise, and delays in obtaining results are current hurdles for a more effective uptake of tracer techniques by industry. Advanced training tailored to students, policy makers, and industry, coupled with a more robust infrastructure for the timely delivery of tracer analyses are the key ingredients required to enable a golden age for environmental tracers in Australia to blossom.

Partitioned mantle degassing through the Australian plate delineated by noble gas data

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Objectives: A compilation of new and published $^{3}He/^{4}He$ data in Australia reveals a surprisingly pervasive yet partitioned ongoing process of transfer of mantle-derived volatiles to the near surface groundwater system and into oil and gas reservoirs.

Design and Methodology: Comparison of helium isotope data with mantle tomographic images show that high $^{3}He/^{4}He$ values in groundwater correlate with domains of low velocity mantle and with sharp mantle velocity contrasts.

Original data and results: Deep lithospheric boundaries (150-200 km) between high velocity mantle in western Australia and lower velocity mantle in eastern Australia, provide the first order control of mantle degassing and are interpreted to represent Precambrian structures that are currently being neotectonically reactivated (e.g. Tasman line and Torrens hinge zone). Mid-lithospheric (75- 100 km) low velocity domains underlie zones of mantle degassing in central and western Australia. Rather

than uniform upward flux of mantle volatiles into the lithosphere, our data delineate variably fertile mantle source regions and lithospheric conduit zones. Understanding the conduit systems for the deeply derived fluids require holistic geologic models, but we envision asthenospheric (MORB) sources in eastern Australia related to transfer of basaltic magma and accompanying volatiles from asthenosphere to lithosphere over the last several Ma. Helium leakage in non-volcanic areas is likely sourced from metasomatized lithospheric mantle. Helium and CO2 volatile transport through the crust takes place by (and facilitates) microseismicity, and water-rock interactions of deep geothermal fluids with hydrocarbons and deep basin brines introduce Cl, metals, and radiogenic Sr into aquifers. This continental scale fluid convection system is driven by small scale sublithospheric convection induced by plate reorganization events related to initiation of transpression in New Zealand ~ 5 Ma and accompanied reactivation of lithospheric zones of weakness.

Hydrogeology: Implications involve a new paradigm for the Great Artesian Basin (GAB) which underlies 22% of the Australian continent and is one of the largest groundwater basins in the world. This new paradigm involves endogenic fluid inputs into the J-K aquifer system that leak up faults from below the aquifer, partition the GAB into hydrogeologic subbasins, and cause variable degradation of water quality.

Use of stable and radiogenic isotopes in characterising wastewater derived impacts in Urban and Peri-Urban areas

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Objectives: This study focuses on one of South East Water's Water Recycling Plants (WRPs), located adjacent to an area of significant agricultural activity (market gardens), where multiple potential sources of groundwater contamination (nutrients) have been identified. The primary objective was to examine the use of stable and radiogenic isotopes in conjunction with contaminants of emerging concern (e.g. pharmaceuticals) to gain a greater understanding of the underlying hydrogeochemical processes and separate wastewater-derived contamination from other potential sources e.g., agriculture.

Design and methodology: This project combined long term groundwater monitoring data (collected since 1997) with in-situ isotopic tracers sampled in 2018-2019 including: $\delta^{2}H_{H2O}$ and $\delta^{18}O_{H2O}$, $\delta^{13}C_{DIC}$, ^{3}H and ^{14}C, analysed at ANTSO's Lucas Heights facility, and $\delta^{18}O_{NO3}$ and $\delta^{15}N_{NO3}$, analysed at China's Key Laboratory of Agricultural Water Resources. The isotopic data were combined with other lines of evidence, including contaminants of emerging concern (e.g. pharmaceuticals) analysed at RMIT, as an additional metric to better delineate wastewater impacts in a mixed source environment.

Original data and results: Groundwater residence time indicators from groundwater wells located adjacent to or upgradient of the treatment plant, contain ^{14}C and ^{3}H activities (>73 pMC and >0.68 TU) which indicate a large component of modern recharge (i.e. <50 years old). Groundwater near suspected leaky infrastructure contains elevated levels of these radiogenic isotopes compared to those considered more indicative of background conditions (>97 pMC and >1.4 TU compared to 72-85 pMC and 0.68-1.03 TU, respectively), indicating potential anthropogenic inputs. Water stable isotopes, plot along a mixing line between regional groundwater (e.g. outside the known plume) and evaporated groundwater (e.g. recharge from former and current sludge lagoons). End-member mixing calculations indicate a significant proportion of effluent in groundwater downgradient of treatment infrastructure. Elevated nutrient concentrations in groundwater occur throughout the region (e.g., 0.6 to 160 mg/L nitrogen (total)). Nitrate isotopes show clear differences between nutrients derived from agriculture (values between 5 and 29‰, median = 12.0‰), and those impacted by the treatment plant (values between 2.9 and 41.2 ‰, median = 18.0‰), with effluent values between 20.2‰ and 39.1‰). Further work is being undertaken to quantify pharmaceuticals as an additional metric to better delineate wastewater impacts.

Conclusions: The findings show how isotopic tracers can assist in overcoming the difficulties associated with delineating multiple similar contamination sources. This will enable wastewater treatment plant operators to more accurately assess and manage their impacts on groundwater.

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^{14}C-dating model for groundwater affected by CO_2 inputs from deep underground formations

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Groundwater age, defined as the time since the groundwater was recharged, is useful for estimating the groundwater renewal. The radiocarbon (^{14}C) activity has been widely applied for groundwater age dating since 1950s. However, the application can be complicated by other ^{14}C-free carbon sources, which will dilute the initial ^{14}C content at groundwater recharge. Several modifications/corrections models have been introduced to obtain the dilution factor, on the basis of carbon isotope and water chemistry mass balance. However, these models do not entirely account for the influence of deeply derived (endogenic) carbon source and are hence not applicable for dating groundwater over endogenic CO_2 degassing areas. We developed a modified ^{14}C groundwater dating model to include three carbon end members of biogenically derived sedimentary carbon, carbonate carbon and deep crust and/or mantle carbon, combining the principles of water chemistry with carbon isotope mass balance to quantify the dilution factor. The new model, applied to aquifers in California, predicted younger groundwater age and less mass fraction of fossil groundwater by 15~25% and 5%~10%, respectively, compared with the predictions of the traditional method without endogenic CO_2 considered. In principle, the proposed method here can be applied for groundwater age estimating over other regions globally, where the aquifers are affected by endogenic CO_2. However, its application requires local geological, hydrogeological and geochemical situation to be identified in advance.

1D groundwater elevation prediction model

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Predicting groundwater elevations based on limited data is often required as part of informing design and impact assessments and represents an ongoing challenge for groundwater specialists. As part of understanding the potential for impacted groundwater levels rising and intersecting a stormwater drain flowing into surface water a 1D groundwater elevation model was developed. The groundwater level model was developed in excel and based on a simple box model with groundwater level in the box increasing with rainfall and net storage decreasing with no rainfall. The representative equation inputs where varied to simulate a two-month groundwater elevation dataset that had a number of significant rainfall events. There was a high degree of fit between simulated and actual groundwater elevations. Due to the high degree of fit, the model was then able to be used to predict groundwater changes over a long-term rainfall dataset. Uncertainty analysis was completed by stressing the recharge component to higher and lower levels and then re-calibrating the model while maintaining a high degree of fit. The model relied on simulating response rather than a rigid set of hydrogeological input parameters (storage and hydraulic conductivity) providing more freedom in the variability of input parameters

to achieve a fit. Its certainty therefore relies entirely on the goodness of fit. This model was based on groundwater response in a shallow unconfined and unconsolidated aquifer. Further testing is required to validate the model for use on other lithologies and aquifer types, however, it would have direct applicability for a range of assessments where understanding reasonable worst-case groundwater elevations using short-term high frequency groundwater elevations is required.

A comparison of methods for the numerical simulation of the unsaturated zone in the SA River Murray floodplain

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The mechanisms of transient groundwater recharge are often not well understood or quantified but can be explored through numerical simulations. There are numerous ways to simulate recharge for groundwater models, with varying levels of complexity. In this study, we compare simulations of groundwater recharge in the floodplains of the lower River Murray, where recharge from rainfall and flooding is a critical part of the water balance. The complexity of conceptualising the timing and amount of groundwater recharge triggered this research.

The selected codes for comparison are: RCH with EVT in MODFLOW, UZF in MODFLOW, HYDRUS, and LEACHM. Each is used to simulate a dynamic scenario of twenty years of rainfall, evapotranspiration, changes in river level, and flooding within a thin unsaturated zone of 0.5-3 m. Loxton weather station data was used to simulate seasonal changes from 1992 to 2011. The soil parameters of the Coonambidgal and Monoman Formation are derived from field measurements and pedotransfer functions.

The RCH-EVT and UZF methods generated similar volumes of recharge, but the difference in timing of recharge between two approaches can be significant, with two to five weeks of lag-time between applied water and net recharge. In some cases, the wetting front from rainfall overtook and mixed with a flood. The higher recharge chiefly happens during the cold seasons, from March to August, due to lower evapotranspiration rates. The lags in infiltration depend on the thickness of the unsaturated zone. To understand the salt movement in the vadose zone and magnitude of recharge, the LEACHM and HYDRUS model were developed as benchmarks, which investigated the salinity and water stress on vegetation health as well. A long-term simulation revealed that HYDRUS delivered a significant recharge, 42% above UZF, and ET removed by LEACHM was 61% larger than UZF. It is instructive to compare results for a significant climate event, as observed during the 2002 drought where the groundwater recharge was hampered.

This research contributes to understanding hydrological features, surface water-groundwater interaction, within the MDB floodplain in SA. The developed method in this research can be employed in models within the study area, which can be used in simulating solute transport. This research contributes to modelling tools for managing ecosystem health in the MDB floodplain.

A different approach to characterising aquifer properties using pressure transducers in privately owned bores in South East Queensland

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The findings presented in this study relate to an area with a distinct lack of information regarding aquifer hydraulic parameters and volumetric water use. This study classifies the response of a basalt aquifer in South East Queensland, Australia, based on water level information from pressure transducers and rainfall data. Based on the data from the pressure transducers, it is possible to identify pumping events. This information is combined with water use data from water meters, to produce the data normally obtained from a pumping test, without having to disrupt the daily use of the pump and/or the supply of water to the residents or business. The response to rainfall in each bore is also classified using the same dataset, therefore providing valuable additional information for understanding recharge processes in the area. The challenges associated with the use of private bores for assessment of aquifer properties were found to include limited options for the transducer installation depth and gaps in the available bore construction and pump installation information.

A novel hydrogeochemical investigation utilising Pb and Sr isotopes in the vicinity of the Century Pb-Zn Mine, NW Queensland, Australia

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The closure of the Century Pb-Zn mine open-pit workings brings with it the need for an understanding of the environmental impact of the mine and also an opportunity for renewed mineral exploration in the surrounding tenements. A novel combined approach to these questions is presented here using high-resolution Pb and Sr isotopic analyses of groundwaters surrounding the mine. A study of this nature has never been attempted before.

Pb isotopic signatures obtained from the 21 accessible groundwater bores in 2014, when compared to the Century ($^{206}Pb/^{204}Pb$ = 16.441) (and nearby Silver King, $^{206}Pb/^{204}Pb$ = 16.337) ore bodies, show lower Pb isotope ratios proximal to the pit and higher Pb isotope ratios with increasing distance from the pit (A_GW05 $^{206}Pb/^{204}Pb$ = 18.322). Mixing calculations, however, indicate only very small contributions from the bulk Century ore to the groundwater even in those samples measured closest to the pit. Sr isotope ratios are relatively uniform across the region. The mixing calculations comparing the contribution of both Pb and Sr from the two aquifers (Thorntonia Limestone Aquifer and Lawn Hill Formation (shale) Aquifer) to the groundwater geochemistry indicate that the groundwater receives a greater contribution from the Thorntonia Limestone than the Lawn Hill Formation. Overall, the mixing calculations indicate there is no significant Pb contamination from the mining operation to the surrounding groundwater, likely as a result of the low solubility of Pb complexes in this setting.

Despite the very low Pb concentrations in the groundwater, Pb isotopic compositions appear to faithfully mirror the compositions of local sources, thus signatures adjacent to known prospects reflect those of the prospects, demonstrating the potential of the groundwater to reveal mineralisation signatures. The results of this study show promise in the use of Pb isotopes as tracers of environmental contamination as well as vectors for identifying potential mineralisation, although the sensitivity of the method in specific settings will depend upon groundwater chemistry.

A simplified methodology for uncertainty quantification in dewatering modelling of an operational mine

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Groundwater modelling is a data-driven decision-making process. To support Rio Tinto's Pilbara iron ore mines, groundwater models are constructed to inform regulatory approvals, environmental assessment and dewatering planning. In many cases, a groundwater model is required long before the commencement of mining. Models built in the early stages of mine development, therefore, can generally be hydrogeologically data poor, specifically in and around the immediate area of a proposed pit. Construction of the groundwater model is reliant on the only information available, the geological drilling designed primarily to inform ore grade. A case study, using an existing, six-year-old numerical model constructed largely on the geological 'block' model was revisited. Validation of the model was attempted using four years of post-original model information but subsequently showed a poor match between observed and the original prediction. The model was simplified to include only a fraction of information from the original geological stratification. Parameterisation was also significantly reduced to reflect current hydrogeological conceptual understanding. Simplification of the original complex multilayer model and subsequent re-calibration were constrained to a predictive envelope bound by two conceptual end members that effectively define the upper and lower boundaries of the model uncertainty. It is concluded that groundwater models should not be built to replicate complicated geological geometry due to the fundamental difference between geology and hydrogeology characterisations. Moreover, simple models with less defined aquifer units have advantage over complex models with regarding to quantifying model uncertainty.

An overview of the geological and bioregional assessments program

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The Australian Government has committed AU$30.4 million to undertake the Geological and Bioregional Assessments Program. The program aims to promote sustainable gas development through independent, scientific studies into the potential environmental impacts of shale and tight gas exploration and production. These studies will be undertaken by CSIRO and Geoscience Australia and managed by the Department of the Environment and Energy.

The program began in July 2017 and will be delivered in three stages over four years. Stage 1 narrowed the focus of the assessments to three regions, the Cooper Basin, the Isa Superbasin, and the Beetaloo Sub-basin. Stage 2 will establish a

geological and environmental baseline for the regions. Data from disciplines such as geology, hydrology, hydrogeology and ecology are collected, analysed and synthesised to conceptualise the petroleum, groundwater and surface water systems to establish whether shale and tight gas activities in the subsurface could potentially result in any interaction between gas plays, productive aquifers and/or surface water resources. This work is then used to conceptualise links and potential impacts to matters of national or state environmental significance in the region. The collection of baseline data in Stage 2 also identifies information and/or data gaps to inform the potential collection of additional data during Stage 3.

Stage 3 will analyse the potential impacts of shale and tight gas development. From these analyses methodologies for monitoring and managing these activities will be developed and made available for any future Commonwealth and state assessments.

On completion, the Program will deliver geological and environmental data and tools that will assist regulators and the oil and gas industry with planning, assessment and reporting. It will provide regulators and industry with a common information base to help inform decision-making and enhance the coordinated management of cumulative impacts.

Aquifer and aquitard permeability changes following earthquakes: insight from the water level response to earth tides and atmospheric pressure

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Changes in the permeability of aquifers may have a significant impact on groundwater flow and thus on groundwater supplies and solute transport, while vertical permeability changes in aquitard may have an impact on the safety of underground waste repositories, aquifer vulnerability and may trigger seismicity. In a highly destructive tectonic activity, large earthquakes will cause different degrees of damage to the structure of well-aquifer system both in near and far filed, one of the most common phenomena is changes in permeability. Thus, quantitative evaluation of earthquake-induced permeability changes is important for understanding key geological processes. Many studies have independently documented permeability changes in either an aquifer or an aquitard, but the effects of an earthquake on both the aquifer and aquitard of the same well-aquifer system are still poorly understood. Analyzes show that well water level can be sensitive to response periodic loadings, especially to response earth tides and barometric pressures. And such response characteristics are closely related to hydraulic properties of the well-aquifer system. We investigated changes in aquifer and aquitard properties based on the water level response in a well in Zuojiazhuang (ZJZ), Beijing following the March 11, 2011, Tohoku earthquake. We employed a wavelet transform to capture the changes of the water level response in time-frequency space and combined tidal analysis and barometric response function to calculate earthquake-induced changes in the hydraulic properties of the well-aquifer system. Our results show that permeability increased both in the aquifer and aquitard after the earthquake. The horizontal transmissivity of the aquifer increased by a factor of six, and the vertical diffusivity of the aquitard doubled. This novel study highlights that large earthquake may threaten the groundwater flow system both in aquifer and aquitard.

Assessing seawater intrusion vulnerability to sea level rise in Christchurch, New Zealand using GIS-based methods

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The Christchurch coastal aquifer system provides one of the highest quality drinking water sources in the world, which local residents completely rely on for critical needs. Coastal aquifers are vulnerable to sea-level rise (SLR) through seawater intrusion (SWI), which is the landward movement of the saltwater-freshwater interface. In this study, we carry out a first-pass assessment of SWI vulnerability to SLR in the Christchurch coastal aquifer system using two GIS-based methods.

The assessment of SWI vulnerability using GIS is a useful first-pass approximation to highlight areas of highest possible risk to SLR. Here, the qualitative GIS-based GALDIT method (Lobo-Ferreira et al., 2007) was used to assess SWI vulnerability in the shallow confined Riccarton Gravel aquifer under various SLR scenarios. To overcome limitations of the GALDIT method, the analytic solutions of Werner et al. (2012), which predict the change in the saltwater-freshwater interface position under SLR, were applied within a GIS framework. These analytic solutions predict the change in the saltwater-freshwater interface position under SLR and are, arguably, more physically justifiable than GALDIT.

As expected, both methods showed greater SWI under increasing sea level. Interestingly, both methods highlighted similar areas of greatest SWI vulnerability to SLR, which occurred in areas of low groundwater heads. Brooklands (a suburb built on low-lying swampland), Woolston (where SWI has occurred previously) and Ferrymead (adjacent to the Avon-Heathcote estuary) had maximum SWI vulnerability under the simulated SLR scenarios.

Analytic solutions, such as those developed by Werner et al. (2012) can be incorporated into a GIS framework to quantitatively assess SWI vulnerability to SLR and are a useful addition to traditional qualitative approaches such as GALDIT.

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Can you have an in-pit tailings storage with a permanent water cover in Australia?

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In Australia, once an open cut coal mine closes, the final mine voids are often left to fill with water and become lakes. Mine voids can be used to store tailings; following mining, the tailings can be capped, however another option is a water cover, which is a method for controlling the oxidation of sulphides in tailings.

A miner in NSW is currently investigating the option of storing tailings in pit(s) and utilising a permanent water cover. In the initial stages of this work, various options are being considered, including tailings to differing elevations in the pit(s).

There are many factors that need to be considered and investigated to prove the concept is viable for this mine at its location, including whether the rainfall will be sufficiently high to maintain the cover, including during periods of drought.

To determine the minimum thickness of the water cover, an extensive literature review was undertaken, including identifying the critical aspects for defining a water cover thickness, methods for estimating the thickness, and collating what thicknesses have been utilised around the world and whether the water cover can be considered successful. For water covers to be effective, there should be no stirring or resuspension of the bed tailings. Resuspension would increase suspended solids and turbidity, and increase the possibility of oxidation, acid generation and the release of metals and sulphates, as well as increase salinity. This will occur if the water cover is too shallow, roughly below about 2-3 m. Australian examples were also found, such as in Victoria and Tasmania.

Numerical groundwater modelling was undertaken to predict the void inflows/outflows under differing scenarios. Water balance modelling is now being undertaken, utilising the inflows/outflows from the numerical groundwater modelling, rainfall, evaporation and rainfall runoff. The water elevation in the in-pit tailings storages for each of the scenarios will be predicted, and an assessment undertaken on whether a water cover of sufficient thickness (identified during the literature review) will develop for any of the scenarios.

Should the water cover in this NSW example be deemed feasible following these initial works, further work to prove this concept will be undertaken, which may include refining the minimum water cover thickness through the application of various methods, such as the use of a lake water balance and stratification model coupled with a water quality model, field measurements, laboratory tests and pilot studies.

Given permanent water covers for in-pit tailings storages are not well-known in Australia, and not previously used in NSW, scientific rigour is imperative to obtain regulatory approval. Should regulatory approval be obtained, it is expected in-pit tailings storages with a permanent water cover will become more common in Australia.

Case study of the application of EM34 geophysical surveys in assessing fresh groundwater potential in Onotoa atoll – Republic of Kiribati

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Climate change has been attributed to an increase in frequency and intensity of extreme hydro-meteorological conditions, including droughts and overtopping experienced in the Pacific. Low-lying atolls, with elevations less than 5m and communities with a historical dependence on shallow fresh groundwater lenses, are highly susceptible to the impacts of drought and seawater inundation. Onotoa atoll, located in the southern Gilbert Islands of Kiribati, with population of 1,519), receives relatively less rainfall than other parts of Kiribati, and 85% of all households is reliant on groundwater from shallow wells (Census 2015).

In collaboration with the Kiribati Government, The Pacific Community undertook groundwater investigations using EM34 for 7 villages of Onotoa. Water quality sampling for E.Coli from household wells, installation of an automatic rain gauge, and well survey data used to supplement the geophysics. The assessments helped to identify thickest parts of freshwater lens and advise the community on water resource development opportunities aimed at improving the supply of potable water during extended dry periods.

EM34 geophysics is rapid and cost-effective assessment technique, indicating lateral and vertical variation in bulk conductivity. The surveys are relatively easy to undertake, with results that are indicative of the presence and relative thickness of fresh groundwater. The confidence in interpretation of EM34 measurements is greatly improved as results can be calibrated against known freshwater lens thicknesses from monitoring bores in similar hydrogeological settings, such as found in Bonriki, South Tarawa, Kiribati.

Support was provided to the Government of Kiribati's water resources staff to develop their capacity to plan and undertake water resource assessments. The Onotoa assessment included 48 EM-34 survey lines across width of the islets, at a separation of 200m, with measurements taken every 20m along each traverse using the horizontal dipole.

Resulting information was processed and GIS-based maps generated indicating the variability in thickness and extent of fresh groundwater lens. These were shared with the community to assist them with their planning for future water supply needs, especially during extended dry periods. Two of the villages demonstrated poor groundwater potential and are vulnerable to groundwater salinisation during droughts, which may require investigation of alternative options, including desalinisation. Survey information for the remaining villages identified areas of thicker fresh groundwater potential that could guide future water supply investments, such as infiltration galleries and communal well systems.

This case study highlights application of EM34 geophysics as a tool to identify fresh groundwater potential in atolls across the Pacific.

Co-transport of the F-RNA coliphage MS2 and graphene oxide nanoparticles (GONPs) in saturated limestone-packed columns: role of biofilm

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Objectives: Colloidal particles such as microorganisms, minerals and engineered nanoparticles are ubiquitous in subsurface environment. The knowledge about transport behaviour of colloidal particles would be critical for prediction of groundwater contamination in managed aquifer recharge (MAR) sites. The main objective of this study was understanding the effect of MS2 on graphene oxide nanoparticle (GONP) transport and retention in porous media.

Design and methodology: The GONPs transport experiments were conducted in saturated limestone aquifer columns in either the presence or absence of MS2 at low (10 mM NaCl) or high (5 mM $CaCl_2$) ionic strength. Furthermore, some other experiments were conducted in biofilm-conditioned columns with treated wastewater to determine the effect of biofilm on retention of GONPs. The breakthrough curves and retention profiles of GONPs were also obtained to identify the dominant mechanisms effecting GONP retention.

Original data and results: The results showed there was no difference in the transport and retention behaviour of GONPs in the presence of MS2 at high ionic strength. At 5 mM $CaCl_2$, the retention of GONPs in the presence and absence of MS2 were 7.09 and 5.96 %, respectively. However, in low ionic strength conditions, enhanced transport and decreased retention of GONPs was observed. The co-presence of MS2 led to an increasing percentage of the eluted mass of GONPs from 45.0% in the absence of MS2 to 60.08 % when MS2 was present. Moreover, the pre-conditioning of limestone with biofilm enhanced GONPs retention, while no significant changes in GONPs transport were observed affected by MS2 co-presence.

Conclusion: Ultimately, it is obvious that at low ionic strength, which is similar to that of typical aquifers, the risk of groundwater contamination by engineered nanoparticles co-transported with virus is higher than at high ionic strength. Furthermore, biofilm acts as a bio-filter against discharging engineered nanoparticles into the groundwater.

Design of a simple tool for automated groundwater level forecasting

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Objectives: Knowledge of the likely variation in groundwater levels over an upcoming season is desirable for water resource managers and users to plan more efficiently for the near future. The objective of this project was to test the technical feasibility of a simple automated groundwater level forecast product.

Design and Methodology: Groundwater level eigenmodels (Bidwell and Burbery, 2011) are a logical approach for rapid implementation of a forecasting system (e.g. Bidwell 2005). The input to an eigenmodel may be simply generated using a soil-moisture balance model (e.g. Aqualinc's IrriCalc model), driven by weather, land-

use, irrigation and soil properties. Assuming the irrigated area and land-use remains constant, only weather variability is required to generate forecasted land surface recharge and groundwater levels.

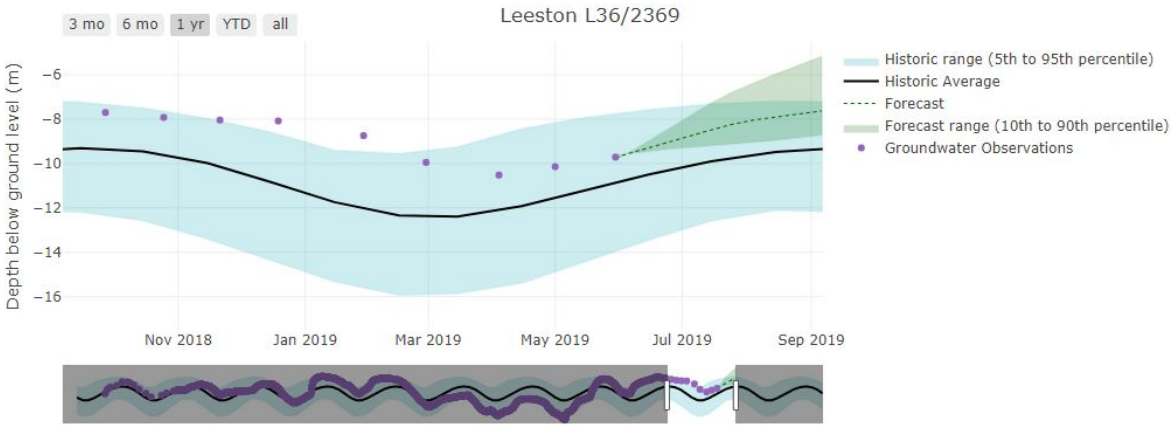
To overcome the limitations of seasonal weather forecasting, the groundwater forecast model is driven with an ensemble of past weather observed for the forecast season. This assumes that the future weather is likely to fall within the range of historical weather. Using past weather greatly simplifies the overall forecast system as the data are already available. The forecasting method then simplifies down to five steps:

1. Obtain current weather variables;
2. Update the modelled soil moisture state;
3. Update the modelled groundwater state;
4. Apply historic weather to the forecast period to generate land-surface recharge and groundwater level forecasts and
5. Present the range of forecast groundwater levels.

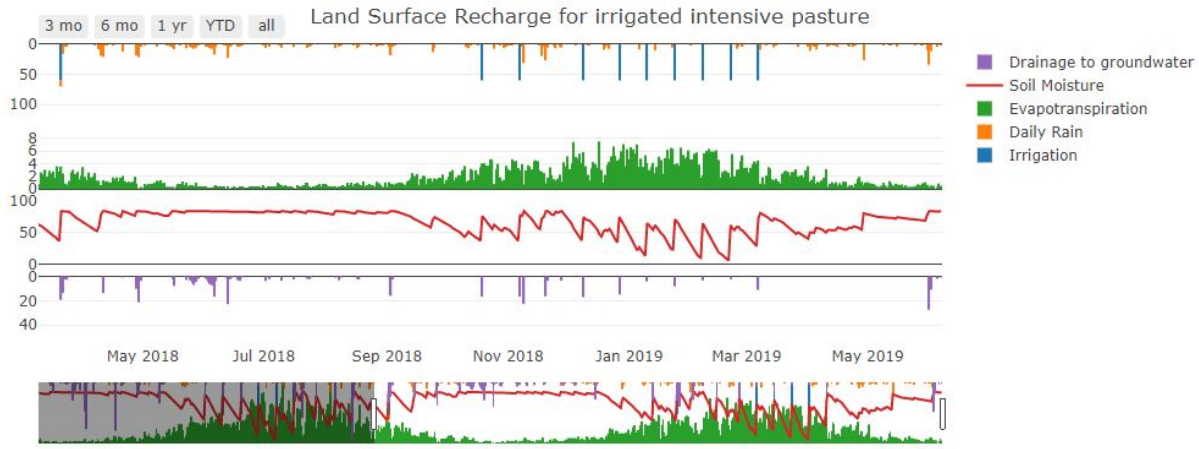
This approach requires judgement from the user on the likely outcome within the forecast range.

The system can be implemented in R on a standard personal computer with the resulting forecast uploaded to a web site.

Data and Results: The following figure shows outputs from the forecast tool, including recent observed water levels, the historic range of water levels, and the forecast range based on the ensemble of historic climate data.



A useful by-product of the forecast process is a semi-realtime update of modelled soil moisture and land-surface recharge, as shown below:



This project has enabled discussions on the utility of groundwater forecasting and the direction of further development. Possible next steps include developing the ability to run scenarios (e.g. changing irrigation demand), and assimilation of soil moisture and water-use measurements.

Conclusions: Simple automatic groundwater level forecasts for New Zealand (or elsewhere) are technologically possible using currently available tools. Key advantages are the low cost and rapid implementation, compared to numerical groundwater models. Feedback from potential users will determine the path of future development.

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Diurnal water level fluctuation in pressure logger data: an evapotranspiration response or a pressure transducer artefact?

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Publish consent withheld

Environmental watering requirements in the context of groundwater under the Murray-Darling Basin Plan

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Environmental water in a groundwater context is the water that supports groundwater dependent ecosystems (GDEs). GDEs can be either partially or fully dependent on groundwater at some point in their lifecycle. These ecosystems can include large areas such as rivers, creeks and wetlands where groundwater discharges to the surface as baseflow. They may also be smaller ecosystems such as springs or certain types of terrestrial vegetation such as River Red Gums where the

root systems can access groundwater. Other GDEs are subterranean and are located within the aquifer itself, including cave ecosystems and stygofauna communities.

Groundwater environmental water can therefore take the form of the water left in an aquifer outside of the volume permitted for extraction; it may also be a part of surface water flow that groundwater contributes as baseflow to maintaining instream ecological values, or part of surface water environmental flows that becomes groundwater recharge. Protecting environmental water in the groundwater context then requires protection of the water in the aquifer and to those surface and groundwater resources connected to that aquifer. Protection may take the form of ensuring water quality is maintained or improved, that a groundwater level is maintained, or that a connection is maintained.

The Murray–Darling Basin Plan sets out requirements to ensure the protection of GDEs. Each state must then develop their Water Resource Plans (WRPs) to meet Basin Plan requirements. These requirements for groundwater environmental water include the protection of environmental watering in relation to GDEs, surface to groundwater connectivity, water quality and the structure and hydraulic relationships of aquifers.

Evaluating the presence of chemotaxic microbes at a hydrocarbon contaminated site undergoing remediation

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Groundwater is a vital source of drinking water for many communities worldwide, however the resource is vulnerable to contamination. In order to evaluate remediation practices, biologically driven processes such as natural attenuation (NA) need to be studied in detail. One aspect of this remediation technique which is not fully understood is microbial chemotaxis. This biological phenomenon allows certain microorganisms to direct their motion in accordance with a chemical gradient. In this study we investigated the various groupings of indigenous microbial genera present at a petroleum contaminated legacy site near Perth, Western Australia, based on their chemotactic and hydrocarbon degrading abilities. The site is around 60 years old and has been subjected to sporadic episodes of contamination, with the contamination been linked with leaking storage tanks and accidental spillages. The overall complex is comprised of multiple zones of contamination associated with differing ranges of petroleum hydrocarbon; crude, diesel and jet fuel. A total of 108 samples from 9 cores; including a representative background control core, were chosen for 16S rRNA Amplicon sequencing. The relationships between the detected microbes, core section, moisture content, contaminant type, and total petroleum hydrocarbon (TPH) concentration (g/kg); including concentrations for several non-aqueous phase liquids (NAPLs) (mg/kg) were investigated. The microbial genera detected were split into five groups; chemotactic (towards hydrocarbons) and hydrocarbon degrading (CD), chemotactic (towards other compounds) and non-hydrocarbon degrading (C), non-chemotactic (towards hydrocarbons) and hydrocarbon degrading (D) and non-chemotactic (towards all compounds) and non-hydrocarbon degrading (NCND); with unclassified taxa at a genus level also being represented (Genus N/A). Microbial community analysis undertaken utilising multiple

ecological techniques, such as ordination and network analysis, revealed that the CD grouping is dissimilar in nature to the other groupings and it occupies a slightly different ecological niche. The keystone taxa within the CD grouping are *Pseudomonas* and *Achromobacter*, these genera are principally located in the bottom section of jet fuel zone, with their prevalence being governed by the NAPLs; such as naphthalene. These results are, to the best of our knowledge, the first to demonstrate the different distributions of genera based on their chemotactic and hydrocarbon degrading abilities at a legacy site, as well as providing vital knowledge of the genera within the CD group potentially capable of influencing the rate of NA.

Field to desktop integrated water data management solution

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Coal seam gas (CSG) is produced by abstracting (depressurizing) groundwater from coal seams. The produced water is often of poor quality, and therefore it goes through a filtration treatment system before it is discharged back to the environment. The depressurization of the coal seams has the potential to alter fluid pressures and qualities of groundwater in aquifers above and below the coal seams. These activities, and others associated with CSG production, are subject to regulation, which requires the measurement of physical and chemical conditions throughout the lifecycle of the CSG project. Compliance with these government regulations is a significant and costly task that requires a solution to ease the management, analysis, and reporting of large volumes of water-related data.

A major water management solution was delivered to one the main CSG operators in Queensland. This solution is an end-to-end process from field data captured using a cloud-based technology all the way to automated analytical and regulatory reports reducing the operational cost and uncertainties caused by manual data handling. Also embedded within this solution is the automation of data quality metrics including telemetry data (temperature and pressure), quality tagging, and analyte value classification on laboratory analysis results. This solution also provides a complete business coverage including baseline assessment, environment, hydrogeology, field operations, and water operations with successful results.

The latest assessment indicates this solution provides up to 50% efficiency gain over the legacy process, thus allowing teams to focus on the business intelligence these data provide. The combination of the deep science technology with quality, consistent, and timely data gathering has enabled the CSG operator to be more efficient in maintaining compliance obligations while focusing on running the business. The solution will considerably decrease monitoring and make-good costs, reduce risk exposure, and deliver quality data regarding the water operations in the field.

Groundwater chemistry and microbiology in a wet tropics agricultural catchment

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The analysis of microorganisms is often not included in environmental groundwater chemistry studies, but an interest in the ecological significance of these organisms is starting to emerge. This is particularly relevant where the transport of excess agricultural contaminants poses a significant risk to the sustainability of important bioregions like the Great Barrier Reef. This study shows how broad scale agriculture can affect groundwater chemistry and the diversity of groundwater microbiota in the wet tropics of north Queensland, Australia. Eight groundwater monitoring bores were regularly sampled in a sugarcane-dominated catchment for analysis of microbiology and major ion chemistry. Soil samples were also collected from a sugarcane plantation paddock specifically for microbiological analysis. Metagenomic analysis of 16S ribosomal RNA sequences was conducted on extracted biological material from the samples. The results revealed a consortium of abundant bacteria that have associations with a variety of soil, water and plant processes, dominated by Proteobacteria, Firmicutes, Actinobacteria and Bacteroidetes. These were present in both shallow (<10 m depth) and deep (>35 m depth) groundwater aquifers, suggesting a connectivity between soil and groundwater environments. This shows that, in tropical catchments characterised by high rainfall and heterogeneous alluvium, biological indicators of broad-scale agriculture are not restricted to the upper soil environment. The implications are that anthropogenic activities can exert great control on the biological diversity of aquifer ecosystems.

Groundwater monitoring programs in mining– adaptive management considerations

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Defining long term groundwater monitoring programs for mining operations is a major challenge. Understanding groundwater patterns over long periods of time, at all stages of mine life, and during hydrologically important events is critical to effectively monitor, identify, and manage environmental impacts.

As per standard risk-based management practices, groundwater monitoring programs are informed by a source-pathway-receptor (SPR) framework. However, changing weather and climate variables such as seasonality and longer-term temporal trends may alter recharge and discharge areas, groundwater levels, hydraulic gradients and ultimately the contaminant flux that would have informed the monitoring program design. These changes in hydrodynamics on site may alter the SPR linkages over short or longer time periods.

Climate variations need to be reflected in the selection and flexibility of groundwater monitoring locations as well as the timing and frequency of monitoring events. Where appropriate, the monitoring program may need to be amended to ensure that data critical to evaluating environmental impact are captured. Variability in climate impacts such as long-term drought and extreme weather events also needs to be considered in the design of the monitoring program and reviewed throughout its

execution. In most cases, the site will require conceptual and, sometimes, numerical hydrogeological and geological models that consider the groundwater system under a range of climate conditions.

Climate change presents further challenges to the closure of mining operations. Regional-scale changes in groundwater systems may alter the background conditions of a site, changing the applicability of the baseline assessment data that informs closure management.

Developing and implementing a groundwater monitoring program that is responsive to climate variables and climate change issues can build confidence in mine performance under a range of conditions, particularly during and after closure. This paper presents key considerations for future-proofing groundwater monitoring programs to provide this flexibility. Examples are provided to illustrate the importance of these considerations when constructing a program.

Guidelines for the application of adaptive management to groundwater contexts

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Adaptive management (AM) is an approach that uses new information on the efficacy of management practices to improve future practices in a structured and iterative way. AM is frequently used to label groundwater management plans that face issues of significant uncertainty about the impacts of proposed projects. AM is proposed as a solution to avoid potential negative impacts that are unclear at the outset of a project. Despite this, there is limited guidance on the use of AM for specific problems involving impacts to groundwater systems. Moreover, previous commentary on AM states that it is not appropriate for all situations. We provide guidance for application of AM to groundwater contexts through an interpretation of AM theory, and by evaluating practical examples of AM, thereby defining adaptive groundwater management (AGM). Two forms of AGM are identified, being broadly consistent with pre-existing AM forms, namely: active AGM and passive AGM. In active AGM, uncertainty reduction regarding predictions of future impacts is integral to management decision-making, whereas in passive AGM, explicit reduction of uncertainty does not feature as a component of decision-making. Furthermore, we comment on characteristics of groundwater management problems that contribute to the applicability of AGM, thereby defining adaptive groundwater management capacity. This work aspires to more effective AGM application, greater transparency in groundwater-related environmental planning, and clearer expectations of AGM for groundwater stakeholders.

Handpump borehole functionality in rural Africa: using environmental tracers to evaluate groundwater residence times, water quality risk and supply in Shallow Unconfined Aquifers

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Poor performance of water supply has been a persistent problem in rural Africa. The UPGro Hidden Crisis project (2015 – 2020) has brought together an interdisciplinary research team to investigate and identify different factors affecting the functionality status of boreholes equipped with hand pumps (HPs). A three-tiered survey approach to define and measure functionality was applied to 600 hand pumped boreholes across Ethiopia, Uganda and Malawi. The results, in agreement with national surveys, show that c.80% of hand pumped boreholes produce some water. However, <50% can deliver HP design yield reliably for more than 11 months of the year and far fewer provide water that meet WHO guidelines on chemical parameters and total thermo-tolerant coliforms (TTC). To determine the major contributing factors to functionality outcomes, detailed hydrogeological and engineering investigations, combined with social, institutional and economic factors, were conducted on a subset of 150 HPBs. Within this second survey a full range of HPB functionality outcomes (e.g. aquifer properties, borehole construction and the condition of HP components) were generated. In all three countries water level, aquifer yield, borehole construction and materials, and pump cylinder placement interact to produce conditions that are sub-optimal for HPs to meet design capacity (pumping head and yield). In many instances, the apparent groundwater age from the shallow HPs was at odds with the measured positive counts of e-coli, suggesting a mixture of different age waters and/or contamination issues related to well construction and completion. Improving our knowledge and understanding of handpump borehole functionality in rural Africa will provide the necessary hydrogeological and social frameworks (e.g. functionality monitoring and asset mapping and assessment) that are necessary in evaluating groundwater as a safe and secure water supply to meet the local demands and regional development pressures with the larger external changing climatic conditions.

Helium-4 as a tool to assess sequences of hydrogeochemical reactions

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Evolution of groundwater can be described based on hydrogeochemical reactions such as mineral dissolution and precipitation. These reactions can take place on timescales of days to thousands of years. Confirmation of the sequence in which they occur often relies on complex hydrochemical modelling. Alternatively, estimates of the mean residence time of groundwater samples based e.g. on environmental tracers such as tritium or ^{14}C can provide a timeline, especially in cases where it is unclear whether the samples all fall along the same flow path. One potentially very useful tracer for this is ^{4}He because of its chemical inertness and the wide time range (millennia to a million years) covered in comparison to other tracers.

Data sets of existing groundwater studies in Australia (Peel (WA), Beetaloo Sub-Basin (NT), Surat Basin (QLD), Pilliga (NSW)) were used to evaluate the usefulness of combining ^{4}He with hydrochemistry records (major and minor ions). Mineral saturation indices (SI) of minerals related to the specific geochemical environment of the aquifer were calculated with PHREEQC. To increase the sensitivity of ^{4}He as a time indicator in younger groundwater, excess air models were applied to separate the atmospheric and terrigenic ^{4}He components.

Simple scatter plots of the SI as a function of ^{4}He reveal the order in which minerals reach saturation either because of dissolution or once they start to precipitate. This method is thus useful to infer the sequence of hydrogeochemical reactions without the need for a kinetic reaction model or it can inform the building of such a kinetic model. ^{4}He is currently not a very widely utilized tracer, partly because of the high cost, e.g. compared to hydrochemical analyses. However, the advent of new field-going mass spectrometers (MIMS = membrane-inlet mass spectrometers) will allow the measurement of ^{4}He directly in the field at significantly lower costs.

Hydrogeochemistry of basalt aquifers: Multi-isotope analysis for better understanding of groundwater recharge, flow-paths and surface water interactions of the McBride and Nulla Basalt Provinces - northern Queensland, Australia.

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Basalt aquifers of the Upper Burdekin region are utilised for stock and domestic purposes and farming as well as contributing to springs, wetlands and rivers. However, the underlying dynamics of the groundwater system are poorly understood. In this study, as part of the Australian Government *'Exploring for the Future'* Program, targeted hydrogeochemical sampling was undertaken to identify aquifer system processes controlling groundwater recharge, flowpaths and surface water interactions in the McBride and Nulla Basalt Provinces.

Groundwater was sampled from existing and new monitoring bores, and surface water and springs were sampled from selected sites for a wide suite of hydrogeochemical parameters to fingerprint and trace groundwater dynamics. Analytes included: physicochemical parameters (EC, pH, Eh, DO and T); major anions and cations; and isotopes of water ($\delta^{18}O$ and δD), DIC ($\delta^{13}C$), and dissolved strontium ($^{87}Sr/^{86}Sr$) as a tool.

Hydrogeochemical signatures identified in this study support groundwater recharge and groundwater flowpaths being largely restricted to within the basalt provinces. Groundwater typically occurs in a main basal groundwater system and multiple shallow groundwater systems. Groundwater flowpaths of the main basal system were traced from higher elevations in the mountains through to the Burdekin River, showing interaction between the basal and shallow systems. Groundwater recharge to the basal system is indicated from $\delta^{18}O$ and δD as being largely from higher elevation and higher rain-out in the mountains. In contrast groundwater recharge to the shallow systems is indicated as being from localised rainfall, as well as local input from rivers and the basal aquifer. Springs across the study area are largely sourced from the main basal groundwater system and form the tributaries that discharge into the Burdekin River. Likewise, some springs contribute to tributary rivers along flowpath. Groundwater signatures also suggest the basalt aquifers discharge directly to the Burdekin River linking groundwater to surface waters in places.

This study demonstrates how hydrogeochemistry, including isotope analysis, can be used as a tool to reveal fundamental controls on groundwater system processes. The results of this study identify the principal processes of groundwater recharge processes, flowpaths and surface water interactions, which can be used to better understand the basalt aquifer systems in the Upper Burdekin region.

Hydrogeological Bayesian hypothesis testing through trans-dimensional sampling of a stochastic water balance model

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Conceptual uncertainty is considered one of the major sources of uncertainty in groundwater flow modelling. In this regard, hypothesis testing is essential to increase system understanding by refuting alternative conceptual models. Often a stepwise approach, with respect to complexity, is promoted but hypothesis testing of simple groundwater models is rarely applied.

We present an approach to model Bayesian hypothesis testing in a simple groundwater balance model, which involves optimization of a model in function of both parameter values and conceptual model through trans-dimensional sampling. We apply the methodology to the Wildman River Area, Northern Territory, Australia, where we set up 32 different conceptual models. A factorial approach to conceptual model development allows for direct attribution of differences in performance to individual uncertain components of the conceptual model.

The method provides a screening tool for prioritizing research efforts while also giving more confidence to the predicted water balance compared to a deterministic water balance solution. We show that the testing of alternative conceptual models can be done efficiently with simplified water balance models early in the groundwater modelling workflow.

Landscape patterning of riparian vegetation across a novel gradient of surface water persistence and groundwater proximity

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For streams of intermittent or irregular flows, the structure and composition of riparian vegetation is usually related to water availability and flood disturbance. The hydrological recruitment niche, in which strong variability in water availability through flooding provides the foremost opportunity for germination and establishment of tree seedlings in riparian and floodplain areas. In the Pilbara region of north Western Australia large-scale iron ore mining activities such as the pumping of groundwater have large impacts on ephemeral streams and may affect the water balance by elevating groundwater levels and increasing water availability to riparian trees. We sought to quantify changes in the structure and composition of riparian and floodplain woodlands across a gradient of stream persistence and groundwater depth. Our results show that increased water availability in this dry semi-arid stream environment can create significant increases in the abundance, size and composition of the riparian tree community. However, we found that the relationship between depth to groundwater and tree density and size across our study sites was not strong. This is most likely due to the important effects of landscape position and other edaphic factors such as soil nutrients and soil moisture variability. The hydrological recruitment niche has been somewhat disrupted at sites where stream flow is continuous due to mine water discharge upstream. Maintaining riparian communities in semi-arid regions requires specific management priorities, particularly in the face of anthropogenic disturbances such as mining operations. Therefore, we need to better understand the relationship between the dynamics of groundwater and key riparian species. This requires a greater understanding of when, where and how riparian species are accessing groundwater on streams in semi-arid regions.

Lessons learnt in shallow groundwater monitoring in urban areas: the Christchurch experience

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Following the 2010/2011 Canterbury Earthquake Sequence, EQC needed to quantify the impact of ground surface subsidence on residential property. Thousands of holes were installed, and subsequently, ~1000 were dipped on a monthly basis, to monitor shallow groundwater.

In 2016, the groundwater network was rationalised to ~250 sites and instrumented with transducers, logging water level every 10 minutes, resulting in more accurate and much more detailed monitoring. The new high-resolution dataset is probably a world first and is a game changer. It provides insight into the short-term groundwater response to rainfall, tides and river flows, and has been used to generate tens of thousands of surfaces to characterise, spatially, the variability of groundwater levels and flow. It sets a new standard of monitoring for urban areas

constructed on shallow groundwater, where hazards such as liquefaction and flooding are driven by changes in groundwater level that can occur over hours or days. The data show the extreme variability of the groundwater level response to different drivers: at one end of the scale there is a streamflow-type response to every rainfall event, but a rapid return to a 'baseflow' level in between events (see Figure 1). At the other end of the scale is a longer-term groundwater-type response, where levels do not respond to summer rainfall, but show a persistent rise in winter due to the onset of recharge (see Figure 2). The differences are crucial in understanding the:

- impacts of rainfall on groundwater levels,
- subsequent impacts on groundwater and surface water flooding,
- consequent impacts on the community.

For example, summer rainfall might only affect areas that have a response such as in Figure 1. Areas with a groundwater-type response might be immune from groundwater flooding in summer but will have prolonged periods in winter when groundwater levels are at, or close to, the ground surface.

There are many current and future needs that are being, or will be, informed by the data. A key use will be real-time integration of groundwater data into flood modelling, to take into account the groundwater contribution to surface water flooding. There are numerous other uses, including contributing to liquefaction susceptibility assessments, timing infrastructure works to minimise dewatering requirements, understanding the contribution of shallow groundwater to sewer infiltration. This rich dataset is also being used to inform the assessment of sea level rise impacts.

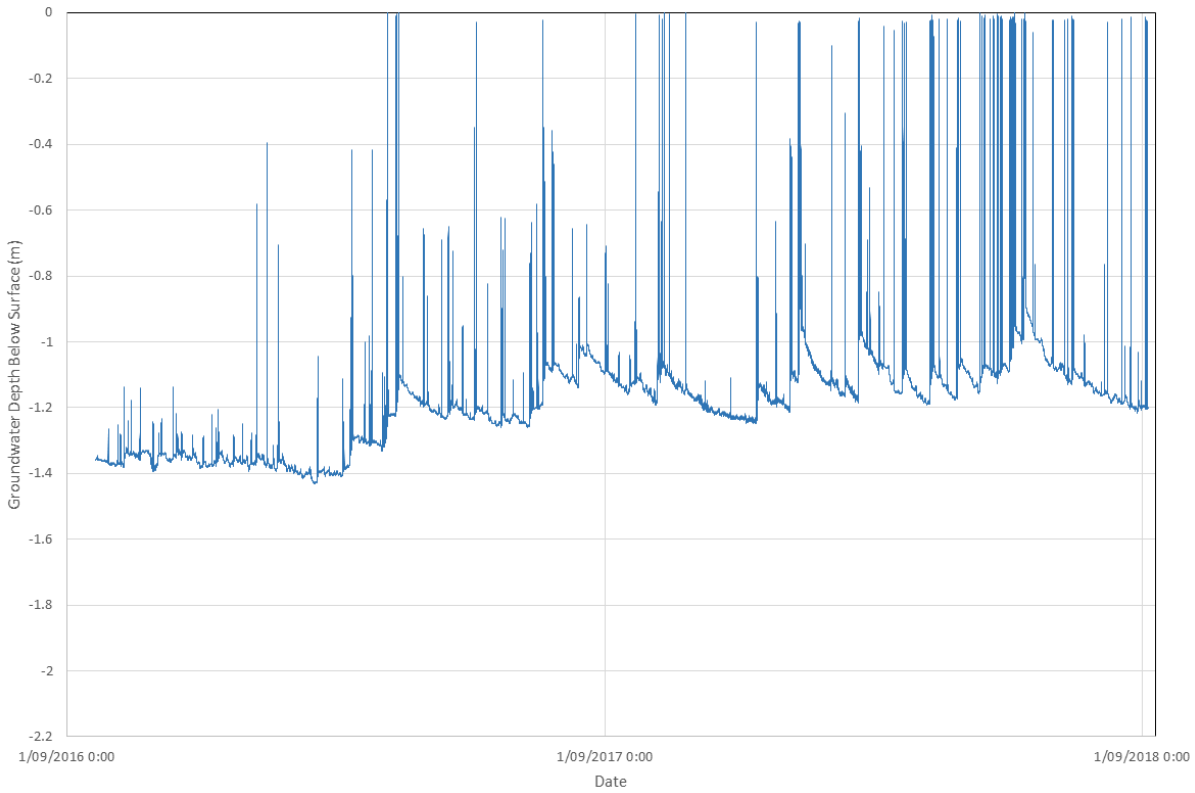

Figure 1: Streamflow-type response to recharge

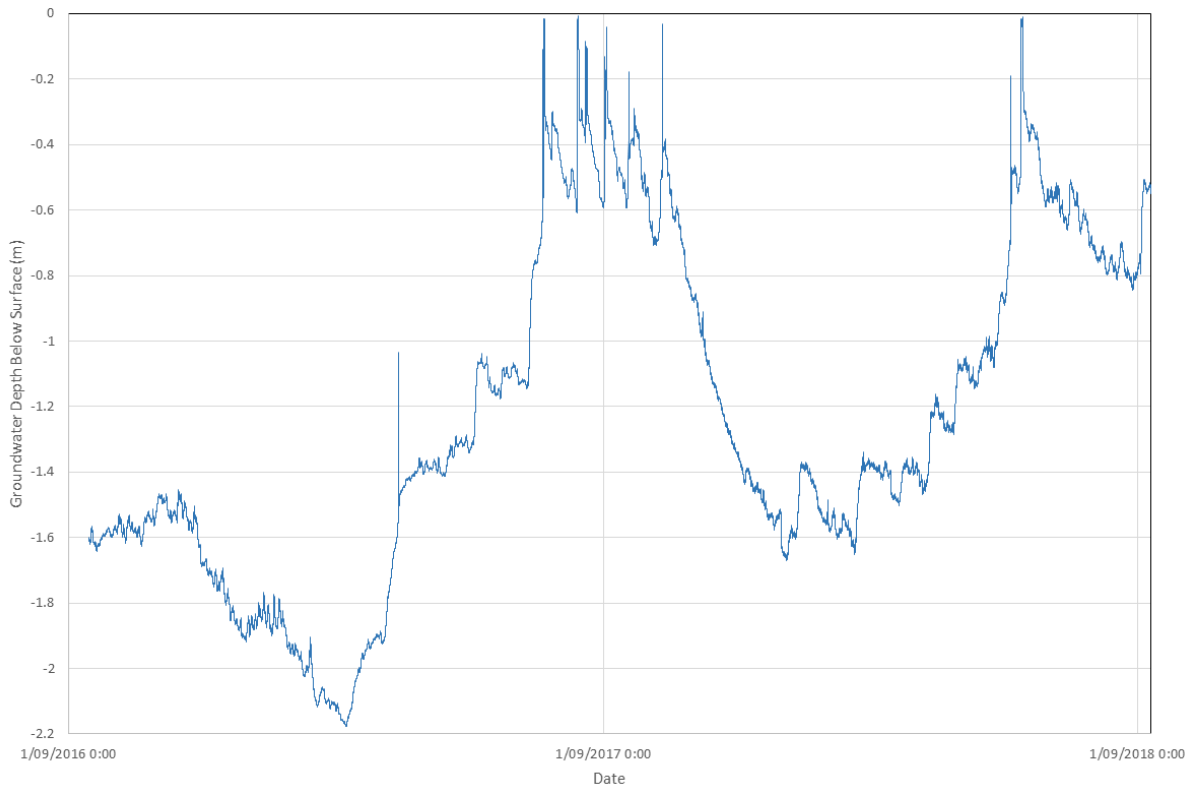

Figure 2: "Groundwater" type response to recharge

Mining and the role of NSW Water Legislation in managing impact change

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NSW has the largest economy in Australia valued at over half a trillion dollars in 2016-17 or about 33% of Australia's GDP. The NSW mining industry is a very significant component of NSW GDP and spends approximately $11 billion per annum of which nearly half of this is contributed to the Hunter Region economy. With such concentrated coal mine development comes not only the demand for large quantities of water for operational uses but also potential for catchment scale changes in water flow and water quality. Large scale land use changes impact on water dependent assets including both registered water users and water dependent ecosystems. In addition, a number of these mining induced impact changes will not be realized for many decades post mining due to long recovery times in groundwater levels.

The mining industry continues to grow and has a social and legal responsibility to limit impacts in line with the 'Objects' and 'Principles' of the *Water Management Act 2000*. This abstract explores the role of the NSW Government in managing water impacts. It includes the process of defining acceptable limits of change and the regulations permitting certain trade-offs for the broader economic benefit of NSW. An overview of shifting trends in registered use of water driven from the introduction of NSW Water Sharing Plans and the implementation of a water trading market is presented, concluding with where new policy is needed to facilitate challenging legal compliance issues unique to the mining industry and the NSW Government commitment to independent monitoring.

New South Wales Great Artesian Basin bore survey projects

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In 2018 the NSW Government initiated a Great Artesian Basin Bore Survey Project which aimed at providing in-situ data towards management of the Great Artesian Basin, renewal of the Water Sharing Plan and scientifically informing future infrastructure and water management strategies of the NSW GAB.

Over 8,500 bores have been drilled in the NSW-GAB since 1879. More than 1,300 were flowing uncontrolled into open bore drains. About 400 bores ceased to flow at some stage due to general pressure decline.

Implementation of the NSW Cap & Pipe Programs resulted in pressure increases in the last decade, of up to 10m in some areas, potentially causing several bores to start to flow again. Some of the bores are very old and have the potential to fail. The GAB Bore Survey Project was initiated to provide evidence-based information to prioritise future GAB infrastructure and water management strategies that includes the current and predicted renewed flowing bores.

The project objectives are to identify number of bores under artesian condition; assign bore integrity risks; measure/estimate total extractions/discharge; quantify uncontrolled discharges/leakages; Estimate current and future BLR requirements; and to assess water quality status of GAB.

In 2018, 220 bores were visited. In 2019, the NSW government extended the survey. The 2019 survey aims at 600 bores.
Each bore survey included landholder interviews, bore headworks inspection, gas emissions, water distribution infrastructure, geo-tagged photos, electronic logging of pressure, flow and water levels, and water quality sampling.
Individualised bore integrity status reports together with water quality analyses were sent to all participating landholders.

The outcome of the 2018 survey fed into a pressure recovery assessment. Upon completion, the full dataset will inform the scoping of the GABSI funding, inform aquifer geochemistry, total extractions/discharge, uncontrolled discharges/leakages and BLR requirements.

Northern Australia Hydrogeochemical Survey: groundwater as a tool for mineral and hydrocarbon prospectivity and environmental baselines

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With the majority (80%) of the Australian's solid geology overlain by regolith, groundwater is increasingly being investigated as an exploration tool to see through cover material, though few investigations have surveyed for regional hydrogeochemical trends and environmental baselines. In this study, as part of the Australian Government '*Exploring for the Future'* Program and in collaboration with the Northern Territory Geological Survey, groundwater chemistry was utilised as a

tool for passive sampling of underlying geology to detect hidden mineralisation and hydrocarbons as well as to build a regional baseline to inform environmental monitoring and decision making.

Groundwater samples were collected from private bores in the Lake Woods (Caritat et al., 2019), Tennant Creek and McArthur River regions of the Northern Territory for a comprehensive suite of hydrogeochemical analyses and fingerprinting including: field physicochemical parameters (EC, pH, Eh, DO and T); major and trace elements; isotopes of $\delta^{18}O$ and δD, DIC ($\delta^{13}C$) and dissolved strontium ($^{87}Sr/^{86}Sr$); dissolved hydrocarbon VFAs, BTEX, methane concentrations and methane isotopes ($\delta^{13}C$ and δD).

Results of the current study show groundwater chemistry matches regional geological trends, demonstrating the capacity of hydrogeochemistry to reveal the chemistry of rocks under cover. Anomalous trace element concentrations from different regions are associated with different physicochemical parameter groupings indicating predictable patterns of trace element mobility related to the geological environment. Additionally, elevated Cu concentrations in groundwater are associated with elevated Cu concentrations in independent datasets of soil geochemistry (Bastrakov et al., 2018) and in machine learning Cu concentration predictions (Wilford et al., 2018).

These initial results show regional hydrogeochemical sampling surveys can highlight trace element anomalies as well as provide an environmental background. By identifying the underlying chemical reactions, the results of this survey allow an interpretation of groundwater processes that can inform decision making with respect to groundwater use, mineralisation, hydrocarbons and the environment.

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Offshore fresh groundwater in New Zealand: a review

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Objectives: Fresh groundwater occurs within submerged fringes of continents globally. These offshore fresh groundwater reserves can form via connections to modern day onshore hydrological systems. Offshore fresh groundwater may also be paleo-groundwater emplaced during previous glacial periods when lower sea levels drove fresh water into exposed continental shelves. Offshore aquifer research is an emerging field that is becoming increasingly important as population growth and climate change put pressure on coastal water resources. The objective of this study is to document evidence for New Zealand aquifer systems that extend offshore and that likely contain significant volumes of low salinity groundwater.

Design and methodology: The study involves a review of previous work on coastal aquifers and adjacent continental shelf geology in New Zealand. Onshore and offshore geological and hydrogeological data, marine geophysical data and seafloor fluid seepage indicators are combined to develop conceptual models for onshore-offshore aquifers. Analytic and numerical modelling is used to provide a preliminary estimate of offshore fresh groundwater extent at selected locations.

Original data and results: There is evidence for offshore fresh groundwater systems in South Canterbury and Wellington. Preliminary analysis suggests there is potential for offshore fresh groundwater systems at many locations along the east coast of the South and North Islands, including but not limited to Dunedin, North Canterbury and Hawkes Bay.

Conclusions: Our review documents multiple lines of evidence for offshore fresh groundwater systems at several locations in New Zealand. Some of this is direct evidence for fresh or low salinity submarine groundwater, some is indirect via geophysical imaging of the offshore continuation of aquifers where freshwater occurs up to the coastline. In the longer term, offshore drilling will be required to prove freshwater resources however this regional scoping study is a first step towards that goal.

Planning water resilience, by using an MAR approach in South Africa

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The need to build resilience into current available water resources is required for sustained living. Adopting a Managed Aquifer Recharge (MAR) approach for conjunctive water use might be one of many options available to obtain a sustained potable water supply and requires detailed planning to be successfully integrated with current water supply system(s). This presentation highlights some of the planning challenges faced in a South African context, based on a strategy to diversify and augment potable water resources, to be informed by policy; and be designed to include reclamation of storm water and treated effluent.

Recommendation for groundwater management for lower Indus basin: a case study of Sukkur barrage left bank command

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3. Ecoseal Water Resources Management, Sydney, NSW, Australia
4. Sindh Irrigation Department, Hyderabad, Sindh, Pakistan

Objectives: In Pakistan, where agriculture production is of prime importance for its economic development, the increasing dependence on groundwater for irrigation and drinking purposes makes it vitally important to assess underground water balance to recommend policy measures for its sustainable management. The key objectives of this study are to enhance groundwater management and to develop sub-regional groundwater model for informed decision making.

Design and Methodology: First objective was achieved by developing a geo-database for the groundwater information available with departments. Historical data sets were digitized, and additional data sets for groundwater level and quality were acquired by installation of data loggers in newly established observation wells in the command area. With the available data, a physical process-based groundwater model was developed for achieving second objective. Calibrated model of sub-regional level was used to assess the policy scenario for sustainable water use and protection against water logging and salinization. The assessment of the scenarios were performed by aquifer stress analysis, water level threshold assessment, and water balance impact assessment.

Original data and results: Lithologically, the area consists of sands of various grades with silt and clay down to several hundred feet. Sand is predominant and is highly transmissive and constitutes the potential aquifer in the area. The groundwater flow in the region is divided into two directions, with the hydrological divide seen near the Rohri canal-constituting world largest single canal area for irrigated agriculture. There are zones of shallow to deep water tables in the area. Depth to water table increases near the river Indus and decreases near the main canals. The Indus River and the canals are the main sources of groundwater recharge in the area. The area has recently seen an increase in groundwater pumping, especially at the tail reaches of canals. Reasons for this growth include less availability of water at these tail reaches, and subsidized cost of tube well installation.

Conclusion: Tail reach of canal commands are highly dependent on groundwater, and long-term trends shows that water balance will become negative if high pumping continue in regions near the Indus River. There will be positive impact on waterlogged area with water levels going below root zones, which will ultimately bring good crop yields. Government has to cap the groundwater in regions near the river and should allow pumping of groundwater in waterlogged area where the groundwater quality is suitable for irrigation.

Reporting and compliance of groundwater use under the Murray-Darling Basin Plan

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As a first in groundwater management within the Murray-Darling Basin (MDB), the *Basin Plan (2012)* has introduced Basin wide limits on groundwater take. This is part of a new water accounting and compliance framework based on sustainable diversion limits (SDLs). Groundwater take is governed by local management plans set and managed by Basin State Governments across 80 SDL resource units within the MDB. Basin states report the annual permitted and annual actual take to the MDBA by 31 October each year, as required by section 71 of the *Water Act (2007)*. This data is then used in a SDL compliance assessment which will be enforceable from 1 July 2019.

In preparation for 1 July 2019, the MDBA have developed a set of trial accounts which apply the compliance assessment process set out in the Basin Plan over the past 6 years of section 71 reported data. This has allowed the development of a wider understanding of the operation of the accounts and provided an opportunity to prepare for their formal application from 2019. Under the SDL accounting arrangements, if a potential non-compliance with the SDL is identified, the MDBA will follow the process outlined in the *SDL Reporting and Compliance Framework* (MDBA,

2018) to determine whether the relevant Basin State has a reasonable excuse and what any appropriate actions in response to the situation may be.

The trial groundwater accounts have been published in the annual Water Take Report (MDBA, 2019). Groundwater SDLs ensure the long-term sustainable management of groundwater at a Basin-scale, providing protection for the groundwater dependent communities and ecosystems of the Murray-Darling Basin.

Review of methodologies to extract and measure noble gases in rock fluid inclusions

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Noble gas measurements in groundwater are an established tool to investigate groundwater systems including magnitude and timescales of fluid exchanges. In formations with very slow to no advective groundwater flow (e.g., aquitards and shales), noble gases, especially helium, are excellent tracers for confirming diffusion-dominated transport. In "dry" formations of extremely low porosity and permeability, such as igneous rocks, studying noble gases within fluid inclusions is the only means to assess fluid migration in the matrix. Fluid inclusions in mineral grains evolve mainly during crystallization or are enclosed during rock deformation. However, fluid inclusions are not necessarily completely isolated from surrounding pore water. For example, in the case of quartz grains in sedimentary rock, helium can diffuse from pore water into the fluid inclusions which may influence total helium concentration in the porous quartz grains, and hence add uncertainty to the derivation of aquitard permeability based on the quartz-helium method. Information on these very slow fluid migration time scales is paramount to confirm the effectiveness of the sealing capacity of deep formations for carbon sequestration, nuclear waste disposal, and as a potential natural gas resource

The Environmental Tracer Laboratory (ETL) at the Waite Campus, SA, operates one of only a few High-Resolution Noble Gas Mass Spectrometers in Australia. This device can purify noble gases and measure rare isotope ratios like $^{136}Xe/^{132}Xe$, $^{21}Ne/^{20}Ne$ and $^{3}He/^{4}He$ in groundwater and pore fluids. In fluid inclusions, these noble gas isotopes are the only means to evaluate how long fluids were isolated from the water cycle, due to the small amount of fluid and the large time scales.

The presentation will review and compare methods reported in literature to extract fluid inclusions for noble gas measurement and is further informed by laboratory visits in Australia, Germany, the UK, and the USA. The most common approach is to crush mineral grains in vacuum to release noble gases from the fluid inclusions. The findings will underpin the design for a new crushing system at CSIRO.

Reviewing three years of measurements of all stable Noble Gases in groundwater

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2. Stantec Consulting Services, Salt Lake City, Utah, USA

The Environmental Tracer Laboratory (ETL) of CSIRO hosts the only mass spectrometric system in the southern hemisphere that can measure all stable noble gases dissolved in groundwater. This significantly improved system (the previous system was only able to measure the light noble gases) has been operating routinely since January 2017. The aim of this presentation is to provide an overview of the successes and challenges we have faced in applying and interpreting noble gases in groundwater in Australia.

Concentrations of ^{4}He have been used to improve our understanding of groundwater flow patterns in various hydrogeological systems in most Australian States/Territories. These studies (622 samples) provide data to quantify the variability of ^{4}He accumulation rates in groundwater systems across Australia by cross-calibrating ^{4}He with other tracers such as ^{14}C, ^{36}Cl, and ^{81}Kr. In addition, measurement of the heavier noble gases (Ne, Ar, Kr, Xe) allowed us to derive excess air (EA) estimates and noble gas temperatures (NGT), which reflect soil temperature during recharge for approximately 244 samples in 22 different studies around Australia.

There were two major challenges in the interpretation of these data. First, models to correct for excess air often inferred unreasonably high NGT (>40^{0}C), with the exception of the very simple "unfractionated excess air" model. Second, when plotted against a "water-age" scale, the timing of changes in NGT and EA often does not coincide with changes in the stable hydrogen and oxygen isotopes. Because some of the observed changes were dated to the last glacial maximum (based on ^{14}C), NGT and/or ^{18}O and ^{2}H may not be reliable indicators to identify groundwater from the last glacial maximum in Australian aquifers due to a lack of historical data to understand how other processes might also have affected either soil temperatures or ^{18}O and ^{2}H.

Spatial and temporal stable isotope variability within Alpine Streams of the Snowy Mountains

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2. Australian Nuclear Science and Technology Organisation, Sydney, NSW, Australia
3. Institute for Applied Ecology, University of Canberra, Canberra, ACT, Australia

As an alpine region, the Snowy Mountains are identified as susceptible to the impacts of climate change. This is projected to influence annual variability in rainfall and snowfall amounts which will change availability of runoff water. The Snowy Mountains Hydro-electric Scheme has also altered natural flows in the area since the 1970s, changing behaviours of water resources in the Murrumbidgee and Snowy River catchments. Understanding processes that affect and have affected these surface waters can therefore improve the scientific basis for future water resource management decisions of the region.

Historical physiochemical data of streams in the Snowy Mountains region has been monitored by NSW government and Snowy Hydro over the past half century. However, little stable water isotope data in alpine streams and rivers currently exists. As stable water isotopes (δ2H and δ18O) are excellent tracers of water through the hydrologic cycle, their use can better current understanding of the regions surface waters.

Rapid stream surveys in 2019 have collected stable isotope and physiochemical data of streams within the Snowy Mountains, as well as Murray and Murrumbidgee systems downstream. Analyses of both these and archived samples from 2004-2017 were undertaken for this project. The data was then used with precipitation isotope data from parallel ANSTO studies, and historical records on regional streams for interpretation.

Results showed that stable isotopes in streams varied spatially amongst sites with elevation, temperature difference, and location in the reservoir network, with distinct variance over smaller distances with steeper elevation. Temporal affects were seen with the appearance of seasonal snowmelt contributions into streams and climate. Physiochemical data saw trends similar to historical reports, with significant climate and geographic influence.

This data will specifically contribute to further research into groundwater sustainability, isotope forensics and agricultural water use led by ANSTO and ANU for future betterment of the catchment.

Stable isotopic and water quality characteristics of groundwater systems associated with methane pathways in the Surat/Bowen Basins

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Target coal seams are depressurised during the CSG extraction process to release methane gas. CSG wells do not capture all of the methane released from the coal seams and as a result of depressurisation some methane has the potential to escape the capture zone of a production well. This fugitive gas has the potential to migrate up-dip and rise through porous saturated aquifer media towards overlying water resource aquifers. When investigating increased gas occurrences in water resource aquifers, it is important to establish if methane levels in aquifers/water bores have actually increased, and whether any increase in gas levels is related to the CSG industry. Since methane gas naturally occurs in geological formations in the Bowen Basin distinguishing between the methane from shallow Jurassic aquifers and deeper Permian CSG formations is a critical issue in determining its source.

In light of this a pilot study was conducted in the Surat\Bowen Basin involving sampling selected water bores and CSG production wells for stable isotopes, standard hydrochemical parameters, dissolved inorganic carbon (DIC) and dissolved C1-C6 hydrocarbon gasses. This study focussed on characterising the methane pathways in the groundwater systems in the study area in order to inform GIAT during gassy bore investigations.

The δ2H and δ18O compositions showed three distinguishable groundwater categories namely 1. Deep CSG water 2. Precipice Sandstone water with low

dissolved methane levels and 3. Precipice Sandstone water with high dissolved methane levels.

Towards a consistent approach to groundwater resource assessments in Victoria

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The Victorian government oversees many assessments of groundwater resources. These assessments vary greatly in the scope of the assessment, the availability of supporting data and the range of organisations conducting the assessment. To assist the comparability of the range of assessments performed and to encourage consistency of use of assessments a framework and guideline for undertaking resource assessments has been developed. This framework addresses the following elements of groundwater assessments for management:

- Problem statement - management decision(s) that is/are required to be assessed, and the technical questions that are required to be addressed by the assessment and evidence supporting the decision(s)
- Conceptualisation - Development of a conceptual model that provides an appropriate level of understanding.
- Data adequacy assessment - Scrutinizes the available knowledge including the conceptual model to identify major knowledge gaps and uncertainties
- Preliminary risk assessment - Establish early insight into the likely risk to values to inform application of an "effort commensurate with risk" principle
- Assessment method selection - Selection of an assessment method that is consistent with framework principles and provides outputs aligned with technical questions set out in the problem statement
- Application & predictions - Undertake the technical assessment to provide evidence to support a response to the problem statement management question.
- Final risk assessment - Use the assessment application and predictions to provide the decision maker within an understanding of the risks inherent in the management decision.
- Documentation - Provide a summary response to the problem statement providing the information/evidence necessary to inform and justify the management decision.
- Risk and Uncertainty – integrates risk and uncertainty assessment throughout the assessment chain.

Through the process of developing the framework a few key aspects have emerged that will form important parts of future assessment undertaken by and for the Victorian Government. Explicit statement of the purpose and scope of the assessment is required to be able to determine if the resulting assessment is fit for purpose. Analysis of uncertainty of any assessment and resulting findings is essential. Development of an analysis method that is supported by both the overall need and the available data.

The assessment framework is being trialled on current assessments in Victoria.

Using $^{87}Sr/^{86}Sr$ ratios in groundwater to assess inter-aquifer connectivity

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The Keep River area in the East Kimberley, northern Australia, is underlain by aquifers hosted in both unconsolidated Cenozoic sediments, and Permo-Carboniferous sandstone bedrock. The Permo-Carboniferous sandstone aquifer is in places overlain by the Cenozoic aquifer, and in other areas is exposed at surface, with hydraulic gradients between the aquifers indicating vertical flow from the Permo-Carboniferous sandstone into the Cenozoic. Connectivity between these two aquifers is important to proposals to increase development of irrigated agriculture.

Water quality in both aquifers appears to be controlled by the same processes, with extremely fresh (TDS < 100 mg/L) water occurring close to recharge areas, and saline (TDS > 30,000 mg/L) water in both aquifers close to the coast. This makes the identification of connectivity from major ion chemistry difficult. We present new groundwater chemistry and monitoring data for the Keep River area and describe the use of $^{87}Sr/^{86}Sr$ ratios in groundwater to identify areas of possible inter-aquifer connectivity.

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) provide an additional method of characterising groundwater. Production of ^{87}Sr occurs through radioactive decay of ^{87}Rb which has a half-life of ~ 4.7 Ga. On the timescales typical of groundwater residence times, $^{87}Sr/^{86}Sr$ of aquifer material can be treated as constant. The $^{87}Sr/^{86}Sr$ ratio of groundwater changes over time as a result of equilibration between groundwater and the aquifer matrix. In sedimentary rocks and sediments $^{87}Sr/^{86}Sr$ will be controlled by the provenance of sediments and is usually dominated by feldspars in siliciclastic lithologies.

Highly evolved groundwater samples, identified by elevated Si in solution, show distinctly different $^{87}Sr/^{86}Sr$ ratios between the Cenozoic and Permo-Carboniferous aquifers, which may indicate limited vertical flow between the aquifers. Further work will focus on the spatial distribution of variations in $^{87}Sr/^{86}Sr$ ratios.

Rapid national hydrogeology assessment framework for groundwater prospectivity and vulnerability: Timor-Leste case study

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1. Geoscience Australia, Symonston, ACT, Australia

Timor-Leste's economy and the livelihood of its people are dependent on groundwater. In Timor-Leste these groundwater resources are replenished by rainfall in the wet season providing storage for use throughout the year. Greater demand for groundwater in Timor-Leste from increases in population, industry and agriculture has caused a strain on this resource and its current prospectivity and sustainability is largely unknown. This study has developed a rapid national hydrogeology

assessment framework for consistent groundwater system understanding that can inform future development of the resource.

This study has brought together national datasets as well as collected new data in three cases study sites. Case study locations are representative of the three principal aquifer types identified in the hydrogeology mapping. Fieldwork at each of the case study sites involved: 1) ground-truthing of aquifer characteristics, 2) ground-based electromagnetic geophysical (TEM) surveys to delineate aquifer architecture and groundwater conductivity, and 3) direct measurement of groundwater levels and hydrogeochemistry.

The hydrogeology framework was designed to simply and clearly demonstrate how existing and new datasets can be rapidly combined to produce consistent information and maps for groundwater prospectivity and vulnerability. The framework allows for limited groundwater information by using surrogate datasets for initial assessments through a system based (knowledge) approach. The framework also allows for incorporation of detailed site-specific groundwater measurements and information to the national scale (data approach). The method and datasets are transparent to permit the user to define data inputs and weightings. The framework has been applied to Timor-Leste to produce a national hydrogeological map that in turn informed an assessment of groundwater vulnerability.

Through the development of a rapid national hydrogeology assessment framework, Timor-Leste now has a consistent national hydrogeology map. This framework enables the incorporation of new knowledge and data, as it becomes available over time, and can be applied to multiple scales including continents such as Australia.

Hidden water in remote areas - using innovative exploration to uncover the past

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Reliable water availability is critical to sustaining community water supplies and determining economic development opportunities. In many cases, particularly in remote and arid areas such as in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands in the far northwest of South Australia, groundwater is the only viable source of water. However, there is limited knowledge of the groundwater resources in these remote regions and the Musgrave Province, where the APY Lands is located, is no exception. Consequently, there is a need to identify and determine the potential of groundwater resources in regions – such as the APY Lands – to supplement their community water supplies and to provide water for sustainable economic development which leads to employment opportunities.

The Goyder Institute for Water Research's Facilitating Long-term Outback Water Solutions (G-FLOWS) suite of research projects has developed new techniques to interpret airborne electromagnetic (AEM) geophysical data, coupled with hydrogeological techniques, to identify groundwater resources buried by deep sedimentary cover which is a major constraint to identifying water sources in the northern parts of South Australia.

In its third stage, G-FLOWS is utilising AEM data collected in 2016 to undertake a targeted program of data acquisition, interpretation and mapping of groundwater resources in the Musgrave Province. The research, a partnership between Department for Environment and Water, CSIRO, Flinders University and the Geological Survey of South Australia, is applying new and innovative geophysical and hydrogeological techniques developed in the previous G-FLOWS projects, combined with a variety of field evaluation techniques, to map the groundwater resources in the APY Lands.

The discovery of a new fresh groundwater resource (<1,000 mg/L) in the APY Lands has enormous potential for the future development of this remote region in outback South Australia. Availability of a high yielding groundwater resource within the Lindsay East Palaeovalley could unlock the potential for economic development in the region.

Data Assimilation & Metrics for Models in Decision Support Roles

PEST and management models – the highs and lows of automated calibration for groundwater management

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Groundwater management is often supported by numerical groundwater modelling. In the Murray-Darling Basin, groundwater models support an accounting framework that manages how the States and Commonwealth manage River Murray salinity. Historically these models have been manually calibrated, using a process informed by expert knowledge where judgement calls can be difficult to document comprehensively. In contrast, automated calibration methods should enable greater transparency.

To improve transparency, a trial of the automated calibration Parameter Estimation Tool (PEST) was undertaken for the Border to Lock 3 groundwater model, which is maintained by South Australia's Department for Environment and Water. The model estimates the salt moving from groundwater into the River Murray.

During the trial, numerous PEST options were tested for their impact on the calibration. Both pilot point and zone approaches were tested. The calibration was constrained using combinations of: Tikhonov regularization, prior information, SVD, SVD assist, and lower and upper bounds. Different numbers of pilot points were used. Steady-state and transient runs were considered. Calibrated parameters included aquifer properties, irrigation recharge rates, and boundary condition parameters. The objective function evaluated the match between observed and modelled potentiometric heads, weighted by data quality and relevance. Other data sources were used as a check on model outputs but were not included in the objective function.

The trial highlights a number of considerations when using PEST for more complex management models. Calibration results can be very sensitive to PEST options, sometimes in unanticipated ways. Model run times become extremely important, as

PEST calibration may take weeks or months to generate. Iterations of PEST runs are also needed as initial results inform further constraints or changes in both the model and PEST setup. This process can be challenging to undertake within the timeframes associated with model development. Policy and management constraints also need to be explicitly brought into the calibration process, which can prove challenging. Most importantly, an automatic procedure must be tempered by actual physical knowledge of the regional area.

Putting the geo back into hydrogeology. Geological uncertainty propagation impact on groundwater modelling

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Groundwater simulations are generally intended to characterise the hydrogeological/hydrological flow in the subsurface or to constrain the physical properties of the medium itself.

As for all modelling situations, external input parameters are required to initiate the modelling process. These parameters can be roughly divided in the three groups, namely the physical parameters such as permeability or, hydric parameters such as recharge characteristics and geometrical parameters such as aquitard/aquifer extent and location. The presented work will focus on that last aspect and more importantly on the impact of the quality and reliability of the prior information used to derive aforementioned geometries in complex geological settings.

When the geological structures are too complex to be appropriately modelled using the layered earth hypothesis, hydrogeologists rely on structural measurements, drill holes, maps and geophysical data to build geological models meant to represent the subsurface as accurately as possible. Therefore, hydrogeological simulations are heavily reliant on the quality of geological information and the reliability of the modelling engine selected. That is, the global uncertainty of the geological modelling process propagates and compounds with that of the hydrogeological modelling process.

Implicit geological modelling engines such as GeoModeller are considered fairly reliable and their behaviour under uncertainty has been extensively studied in the recent year by the geological modelling community. An important concept which developed from these studies is that what appears like minor changes in the structure of a geological model may alter its lithological topology significantly. This, in turn, massively impacts the end results of a groundwater simulation because of unforeseen topology shifts resulting, for example, in aquitard breaches. The relationship between geological uncertainty and hydrogeological uncertainty is non-linear.

The presented work explores the consequences of accurate geological uncertainty propagation on the quality and reliability of hydrogeological simulations using the Saxony geological model developed jointly by Intrepid Geophysics and DHI as a case study.

Does geophysics really reduce groundwater model uncertainty? Insights from a synthetic study on the benefits of including EM and SNMR in groundwater modelling

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Numerical modelling is a useful tool for groundwater resource management. However, many groundwater models are subject to large uncertainty. This is partly due to an inadequate understanding of the subsurface, as traditional hydrogeological techniques generally can only provide point-scale information, while groundwater models require spatially continuous data.

Electromagnetics (EM), a geophysical technique that estimates electrical conductivity (EC), is commonly used to compliment groundwater modelling due to its relatively large spatial coverage. EC can be related to hydraulic conductivity (K) through a petrophysical relationship as they are mutually dependent on pore surface area and volume. Petrophysical relationship often contains empirical constants that require calibration. In practice this is often achieved by comparing with aquifer tests, which may be suboptimal due to the scale difference between EM and aquifer tests.

Surface Nuclear Magnetic Resonance (SNMR) is a geophysical technique that is gaining traction in hydrogeology due to its ability to estimate K, water content and porosity. However, in practice SNMR data are more difficult and expensive to obtain than EM, hence they are generally not as spatially continuous. Nevertheless, SNMR can provide an additional set of K estimates at a similar scale to EM, which can constrain the petrophysical relationship between EC and K.

The objective of this research is to evaluate the benefits of including EM and SNMR in groundwater modelling using a synthetic approach. The methodology includes developing a range of reference models, representing the synthetic truths, to cover various hydrogeological conditions that may affect the effectiveness of EM and SNMR, including clay condition, groundwater salinity and level of hydrogeological heterogeneity. Synthetic data are sampled from the reference models and used to create ensembles of groundwater models using a Markov-Chain Monte Carlo (MCMC) approach. The performance of the model ensembles is evaluated by comparing their predictions with the reference models. The results show that including EM and SNMR in a homogeneous, conductive ground environment may have the potential to distort the model predictions due to the geophysical inversion uncertainty and noise. In contrast, model predictions in a heterogeneous environment can be improved by the spatial pattern information from EM and the additional K constraints from SNMR, where the amount of improvement depends on the ground conductivity. In addition to demonstrating the benefits of EM and SNMR to groundwater modelling, this work also presents a workflow that couples EM, SNMR and MODFLOW in a MCMC framework.

Assimilating remote sensing evapotranspiration into coupled groundwater - unsaturated zone model

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Modelling groundwater systems often involves high uncertainty in the conceptual assumptions made and the forcing inputs or parameterization used. This greatly affects the spatial and quantitative accuracy of model products, particularly for remote areas. In shallow water table systems, the groundwater dynamics are influenced by soil evapotranspiration (ET) and recharge to the water table (WT). The assimilation of remotely sensed evapotranspiration values has the potential to reduce the spatial uncertainty related to the groundwater dynamics.

We present a framework for assimilating ET data into a coupled unsaturated-saturated model through the Ensemble Kalman Filter. The model coupling, realized through the net-recharge variable, allows for the direct update of the state variables of heads and soil moisture from the assimilation of the diagnostic variable ET. The method is applied to a losing stream system in the south-east of South-Australia. The improvements are evaluated for different conditions of WT - vegetation interaction in areas of recharge (deep WT) and areas with high root extraction (shallow WT).

The filter showed improvements of the model states over all the domain when the ensemble spread was adequately generated. As hypothesised, best results for the states variables were found for the extraction area. However, the greatest error reduction was seen for the recharge areas, suggesting that the benefits of the assimilation are not reduced only to shallow water table areas. Consistent improvements were also obtained in the calculation of modelled fluxes of actual ET and net-recharge. Because net-recharge is the linking variable between the two models, the error reduction of it translates into improved modelling of the entire groundwater system.

This indicates that the assimilation of ET is suitable for reducing uncertainty in large scale groundwater simulation.

Water Quality Management

Groundwater hydrochemistry data delivery in Australian Groundwater Explorer—the value of multi-agency collaboration for nationally consistent data

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Objectives: Groundwater hydrochemistry is a key input to many investigations and resource management decisions. It informs the suitability of groundwater for different uses and provides insights into groundwater processes. In Australia groundwater chemistry including isotope data is collected and held by numerous agencies in a variety of formats and databases, which makes it difficult to discover the existing data. Providing access to existing chemistry data can deliver savings to anyone seeking this information and facilitate the creation of value-added products.

The Bureau of Meteorology has collaborated with Geoscience Australia (GA) and CSIRO to deliver a national groundwater chemistry dataset in the Australian Groundwater Explorer, the web mapping application for Australian groundwater data.

Methodology and results: In 2016, the Bureau first partnered with GA to publish their groundwater chemistry data in the Explorer. GA data is accessed from their web services by the Bureau twice a year. Currently available for numerous project areas across Australia, the dataset is growing every time new investigations are completed.

A recent collaboration with CSIRO is delivering even more chemistry data through the Explorer. CSIRO has collated, standardised and quality-controlled groundwater chemistry data from State/Territory agencies across Australia; CSIRO also has chemistry data from its own investigations. The Bureau has standardised this data to the GA data model, integrated it with the GA data and published it in the Explorer to make a national groundwater chemistry dataset publicly available for the first time.

Conclusion: The Explorer now provides groundwater chemistry data for more than 140,000 bores and over 50 parameters such as major, minor and trace elements, and isotopes. In the Explorer, chemistry data can be viewed alongside other complementary data such as bore details, water levels, salinity and bore logs, delivering a nationally consistent and comprehensive suite of data to support decision-making on Australia's groundwater resources. Case studies on how to use this data will be presented.

Retrospective on 10 years of risk-based guidelines for managed aquifer recharge

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The Australian Managed Aquifer Recharge Guidelines, published in 2009, were the world's first MAR Guidelines based on risk-management principles that also underpin the World Health Organisation's Water Safety Plans. In 2015 a survey of Australian MAR project proponents, consultants and regulators revealed that in those states advancing MAR, the guidelines were lauded for giving certainty on approval processes. They were also considered to be pragmatic to use, but there were also

comments on onerous data requirements. The rate of uptake of MAR has varied widely among Australian state jurisdictions, for reasons that are not explained by the drivers for and feasibility of MAR. The states where MAR has progressed are those that have adopted the Guidelines into state regulations. It was originally intended that these guidelines would be revised after five years, informed by experience with any hazards not considered in the guidelines, and by new scientific developments, and advances in monitoring and control methods. As such revision has not yet occurred, this paper was prepared to review ten years of experience, identify issues and suggest improvements for consideration in their revision by Australian water regulators, and for information of regulators in other countries considering adopting or developing their own guidelines. The paper also discusses the value to Australian jurisdictions of having MAR guidelines and factors affecting their international applicability, including on capabilities required for implementation.

Using aquifers for natural treatment: nutrient removal from urban stormwater during ASR

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Managed aquifer recharge (MAR) can enhance the use of urban stormwater and treated wastewater. In addition to providing storage, aquifers can provide water quality treatment and therefore can be used as a treatment barrier within a multiple barrier approach to recycle urban waste waters. However, the treatment performance of a MAR scheme can vary considerably due to the heterogeneity of aquifers, the type of MAR scheme used and how it is operated. It is essential to improve the understanding of water quality treatment in aquifers, firstly to ensure the water quality recovered from a MAR scheme is fit for its intended use, and secondly to ensure the groundwater quality beyond the 'treatment zone' is protected from contamination. This study utilises a probabilistic method to evaluate aquifer treatment performance based on the removal of total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) from urban stormwater, during aquifer storage and recovery (ASR) in a confined, limestone aquifer. Four long-term stormwater ASR schemes were used to assess nutrient removal. Operational water quality data from several injection and recovery events were combined and fitted to lognormal probability density function (PDFs) to represent the 'injectant' and 'recovery'; these injectant and recovery PDFs were then used to derive a theoretical ASR removal efficiency (RE) PDF. TOC and TN removal was dominated by redox processes. Median removal of TOC was 50 to 60% at all four sites, while for TN removal was 40 to 50% at three sites with no change at the fourth. Median TP removal of 29 to 53% was attributed to filtration and sorption. It was concluded that the probabilistic method was able to quantify TOC, TN and TP removal capacity of the anoxic carbonate aquifer treatment barrier, which demonstrates that aquifers can provide effective natural treatment of urban stormwater.

Interaction between groundwater salinity and hydraulic head at an underground storage cavern, Port Botany, New South Wales

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The Sydney LPG Cavern is located at Port Botany, New South Wales. The cavern is an unlined rock storage cavern mined out of the Hawkesbury Sandstone and located at a depth of approximately 124 metres below ground for storing Liquefied Petroleum Gas (LPG). A 'water curtain' was constructed approximately 15 metres above the top of the storage galleries to maintain saturation and to ensure permanent groundwater flow towards the mined cavern, which is particularly important when considering impacts of climate change on long-term groundwater levels.

The LPG cavern has been operational for 19 years. During the early years of operation, seepage inflows to the cavern were becoming more saline. This trend was mostly reversed with the injection of large volumes of fresh water into the water curtain above the cavern (>2,000 kL/month). However, since early 2018, water curtain injection volumes have been low (<250 kL/month), and the net contribution of higher salinity groundwater to cavern seepage has increased.

Groundwater and process water chemistry and water level data has been collected every three months since 2000. Hydrogeological and hydrogeochemical factors were examined to better understand the salinity trends in the deep groundwater and cavern seepage waters. Groundwater levels remain lower than pre-construction levels, however data from piezometers down-gradient of the cavern suggests seawater intrusion from Botany Bay, the result of a reversal of hydraulic gradients, is no longer occurring. The large difference in hydraulic head between the upper and lower aquifers causes a downward flux of saline groundwater from the Botany Sands aquifer, from the upper to the lower sandstone aquifers.

Chloride/bromide ratios and d18O data showed that the lower Hawkesbury Sandstone remained fresh on the seaward side of the cavern.

Regulation, Policies & Management

Groundwater management at the localised scale in the Murray-Darling Basin

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Groundwater systems which are subject to extraction require careful management to maintain resource sustainability at both the groundwater resource unit and local scale. To facilitate this process the Murray-Darling Basin Plan requires Basin state governments to develop Water Resource Plans (WRPs). WRPs must address a number of Basin Plan requirements to demonstrate that risks associated with groundwater extraction are minimised. However, because WRPs provide for water resource management at relatively large spatial scales, local scale issues may still

occur within WRP areas. The nature of groundwater resources means that intense extraction in a localised area, while still within the Sustainable Diversion Limit volume, may result in unacceptable impacts. Therefore, there may be a need for additional management actions to be put in place to address specific issues at smaller scales, such as localised groundwater drawdown.

Rules to manage a groundwater system based on resource condition limits (RCLs) allow specific needs of a groundwater system to be managed effectively and adaptively on a local scale to protect the environment, aquifer integrity, or hydraulic relationships between surface and groundwater resources. The Basin Plan ensures these rules will be brought forward into WRPs, and that a consistent, risk-based approach is applied.

RCLs used in rules vary depending on the local needs, and may include volumetric limits on extraction, buffer distances around an environmental asset, aquifer drawdown limits or trigger levels, seasonal limits of water extraction, creating zones to limit entitlement or allocation, cease to pump rules and restrictions on water trading and bore density. Monitoring and adaptive management allow effective response to risks posed. Basin Plan requirements for a rule to be established is based on risk assessment, which requires analysis and interpretation of best available data and information for an area, and an adaptive management framework including monitoring, evaluation and reporting.

NSW groundwater team is on the move and looking ahead, getting ready for upcoming needs

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The team of hydrogeologists of the Department of Industry (DoI) is responsible for providing support to planners and policy makers, for providing the technical advice on projects which have a potential to impact groundwater (mining, gas, land development, infrastructures, quarries) and for supporting the implementation of the water sharing plan essentially through the approval or not of all groundwater trades. The team also support other agencies (EPA, NSW Health, DPE, councils, water utility agencies) and support specific program such as GABSI, regional water utilities water security 'Safe and Secure' project, Regional Strategies.

Our world is changing rapidly, not only through climate change but also through the changing needs and expectations of the community on groundwater management. At DoI Water, the groundwater team and the surface water science team form together the "Water Science" unit. To ensure we are getting ready, the Water Science team has identified where the needs of knowledge acquisition are and what policy challenges lay ahead. A Water Science Strategy has been developed in line with agency strategies and vision. A number of platforms and activities are being implemented to respond to the challenges. To cite a few: groundwater and surface water science prospectus, efficiency tools, delivery of analytical products, guidelines, science day symposiums.

This is an ambitious vision and it will require engagement with the broader hydrogeological community.

This presentation will explore the knowledge gaps and the policy challenges that the DoI Water groundwater team has identified. The presentation will provide an overview of work done in the last two years towards that goal. Finally, it will provide

insights on how DoI Water will engage through different platforms with internal teams, other agencies, research agencies, the hydrogeology community and quite importantly with the public.

Murray-Darling Basin groundwater strategic planning beyond 2019

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The Murray-Darling Basin Plan sets out rules to sustainably manage surface and ground-water resources across four States and the ACT. To implement these rules, States are developing water resource plans (WRPs), which set out the accounting arrangements for managing to sustainable diversion limits (SDLs) and the rules or management arrangements which mitigate risks to groundwater. To date, finalising these WRPs has been a key focus of the Murray-Darling Basin Authority to ensure they are robust and meet requirements. However, with WRPs to be finalised in 2019, it is timely to consider the next steps for groundwater planning across the Murray-Darling Basin.

These 'next steps' are being identified through a review of the issues identified during the WRP assessment process, and the content of recent reviews of the Basin Plan – including the recent Productivity Commission five-year assessment. For example, while WRPs detail rules to manage risks, they are set at a relatively large spatial scale and don't prescribe detailed management at the local scale. This means there are some groundwater risks which may not be fully managed by WRPs.

Based on preliminary reviews, key priorities into the future include understanding the impacts of climate change on groundwater resources, managing local groundwater issues, communicating more effectively with the public, reviewing recharge estimates and better understanding surface water–groundwater connectivity. Much of this work involves working with Basin states and industry partners to address key knowledge gaps and build an evidence base for the full Basin Plan review which will take place in 2026. The 2026 review will provide an opportunity to review groundwater SDLs and consider whether provisions in the Basin Plan are sufficient to sustainably manage groundwater systems, based on best available information. This work ensures the Basin Plan is adaptive and fit-for-purpose, optimising long-term outcomes for communities and the environment.

The costs and benefits of managed aquifer recharge

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Managed aquifer recharge (MAR) is an important technique for improving groundwater recharge and maintaining aquifer levels. MAR has a number of advantages compared to other forms of water storage, including the wide distribution and accessibility of aquifers, relatively cheap storage and minimal evaporative loss. Managed aquifer recharge can restore over used or brackish aquifers, protect groundwater dependent ecosystems, enhance urban and rural water supplies and water quality and improve water supply security. Despite the numerous benefits and demonstrated advantages of MAR, uptake has been lower than expected. The

financial and economic performance of MAR is a key determinant of its global uptake but there are very few studies that analyse of the economic performance of multiple MAR schemes. MAR schemes show a great diversity which is reflected in the wide range of costs and benefits. A standardised conceptual approach and methodology is needed to compare and assess financial and economic aspects of MAR. This study builds on previous work on the financial costs of MAR and presents a conceptual approach and methodology for assessing the benefits of MAR. This study analyses financial costs of MAR in up to 40 schemes and 10 countries. The study also reports benefits and benefit cost ratios for up to 30 schemes. The analysis shows that schemes recharging unconfined aquifers using infiltration basins with untreated water, and riverbank filtration are relatively cheap and have good benefit cost ratios. Although schemes requiring wells with substantial drilling infrastructure and or water treatment, including stormwater and wastewater recycling, have relatively low albeit positive benefit cost ratios, these schemes can offer substantial benefits. Further research is needed to include a wider range of MAR types and technologies, including a greater number of schemes from developing countries, with further consideration of the impact of different biophysical, socio-economic, legal and institutional settings.

Irrigation & Groundwater Protection

Targeted field investigations are fundamental to underpin future water planning and investment in northern Australia: insights from the Northern Australia Water Resource Assessment

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Sustainable regional development is a priority for Australian governments (Federal, State or Territory) and requires appropriate information at a range of scales to guide investment. CSIRO in collaboration with three State/Territory governments and local experts have completed the Northern Australia Water Resource Assessment to underpin future water planning and investment in three priority regions. A critical component of the Assessment was the evaluation of opportunities for future groundwater development, a task requiring significant investment in field investigations in what are data sparse regions.

Field investigations including drilling, hydraulic head observations, and groundwater and surface water environmental tracer sampling were used to improve aquifer mapping, characterise and quantify groundwater recharge and flow, and to constrain inputs and boundary conditions for water balance and risk assessment models. Models incorporating land suitability, flood inundation, depth of drilling and groundwater dependent assets were used to evaluate the potential scale of future development from several aquifers. In addition, shallow drilling, sediment sampling and analytical modelling were used to evaluate the risk of irrigation-induced salinity and water table rise.

The Assessment demonstrates the fundamental need for integrating new knowledge from field investigations to constrain models that evaluate the potential scale and impact of future irrigation development in data sparse regions. In addition, it highlights the huge variability in hydrogeology across northern Australia, the approaches required to provide new information at desired scales, and the need for a holistic approach incorporating factors beyond groundwater. A key factor in the project's success was the packaging of project outputs and outcomes in a way that was easily understood by all stakeholders.

Lower Burdekin Water – management challenges of a large aquifer replenishment scheme

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Objectives: The North and South Burdekin Water Boards, now Lower Burdekin Water (LBW), were formed in the mid 1960's to acquire land, construct and operate water infrastructure to sustainably manage the large unconfined coastal aquifer in the Burdekin River Delta. The costs of constructing and operating the scheme has been fully funded by the growers and sugar millers. The scheme was initially operated as an aquifer recharge scheme capturing local rainfall runoff as well as diverting large volumes of water, from the Burdekin River, to percolate into the aquifer via a series of constructed channels, recharge pits and natural watercourses. The design of the replenishment scheme was based on historical climatic data and a geological investigation of the aquifer to ensure there was sufficient water to support industry and irrigated agriculture through long dry periods between natural recharge events.

Design and Methodology: The scheme has been successfully operating for over 50 years and now consists of 18 pump stations and over 320 kilometres of channels, pipelines and natural lagoons. The scheme is operated on a conjunctive use approach with approximately 650 metered surface water pumps taking water from the distribution system and approximately 1800 groundwater production bores accessing the aquifer.

LBW on average pumps approximately 210,000 ML per annum from the Burdekin River and utilises rainfall and irrigation runoff, which is captured across the 76,000 hectares, for aquifer recharge and water delivery. In a dry year, the volume pumped from the Burdekin River by LBW can be as high as 290,000 ML.

LBW has successfully maintained aquifer levels over the years by adjusting its pumping and recharge operations according to water levels within the aquifer and general water demand as opposed to a strict monitoring of the volumetric usage within the area.

Original Data and Results: Measurements taken from monitoring bores within the Burdekin Delta document the changes in groundwater levels and water quality over time.

Conclusion: While the strategies deployed to manage the aquifer quality and level have been successful across the last 50 years, a large dependence on frequent periodic natural recharge events remains critical to the sustainability of the scheme. A change in the severity and/or duration of dry periods and natural river flow events would require a rethink on how the scheme is managed into the future. Impacts associated with sea level rises also need to be understood and factored into future management strategies.

Management and optimisation of agricultural irrigation systems by using digital twins in the framework of a digital physical system (DPS)

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Industry 4.0 is an idea towards using digital twins in a framework of digital-physical systems. The idea is transferable to agricultural irrigation systems and generate ecological and economic additional values. Under the condition that water is conditionally sufficiently available, it must be used optimally. Networks of sensors record the actual situation on the field. Holistic models as the core of the digital twin can determine, predict, and optimise irrigation, regardless of the regional climate in which the system is used. In the further development, the basics of networked models, are already integrated into the system. This allows the targeted prediction of heavy rainfall and the resulting soil losses.

This research focuses on the development and application of an off grid supported digital physical systems (DPS) for irrigation. A configuration based on solar pumps and optimised irrigation systems was developed for this purpose. Soil moisture sensors, a climate station, and settings of the irrigation system are continuously logged and automatically pre-processed in a database. The hydrological model MKE SHE is used as a forecasted digital twin. It determines current soil evaporation and transpiration and soil moisture for different irrigation techniques. An optimisation delivers the actual control settings for the irrigation system. In addition, numerical modelling allows the integration of individual soil and irrigation strategies. Via an OPC (Open Platform Communication) interface the irrigation system is directly controlled by the digital twin. The applicability was tested on research plots in Saxony-Anhalt (middle Germany). A further goal is to reduce the damage and influence of salination by means of needs-based irrigation adapted to the soil. The fact that this is possible has been proven within the research project SuMaRiO.

From investigation to legislation - lakeland groundwater management, Cape York Peninsula, Australia case study

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Localised aquifers in areas where irrigation requirements exceed or nearly exceed surface water availability are often at threat of overuse unless strategic management rules are in place. Lakeland, a small basalt plateau in southern Cape York Peninsula, has expanding high water demand agriculture. The majority of the watercourses are ephemeral with 80 per cent of annual rainfall occurring during the wet season. New applications to source the groundwater resource triggered an investigation of the condition of the aquifer in 2012. The underlying geological structure was differentiated through use of existing bore log stratigraphy and data. Transmissivity testing data was examined, and storage capacity and sustainable yield analysed. This study indicated a significant drawdown of the major basalt aquifer from existing groundwater entitlements (DNRM 2013a). A groundwater management strategy (DNRM 2013b) was developed to account for existing groundwater entitlements and allow for minimal expansion of usage in certain areas. Rules were developed based

on sustainable yield capacity of the resource with the division of the area into two zones. The Water Plan (Cape York) 2019 (Queensland Government 2019) subordinate legislation enhanced the sustainable management of the water, providing a mechanism for the monitoring and reporting of the condition of the aquifers and the ability to further refine the management rules over time.

1. DNRM, 2013a, Lakeland Groundwater Review, State of Queensland, Department of Natural Resources and Mines, 2013.
2. DNRM, 2013b, Lakeland Groundwater Management Policy, State of Queensland, Department of Natural Resources and Mines.
3. Queensland Government 2019, Water Plan (Cape York) 2019. Available from https://www.legislation.qld.gov.au/view/whole/html/asmade/sl-2019-0090

Fractured Rock Hydrogeology Systems

To connect or not to connect: the importance of hydrogeological conceptualisation for groundwater impact assessments

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The groundwater regulatory environment for Queensland is moving from a reference site approach towards a site-specific approach. Complex dual-porosity groundwater flow systems are often hosted in mineralised rocks, causing naturally elevated solute levels. Water-rock interaction in fractured rock terrains can result in highly variable groundwater quality. Thus, a site-specific approach to groundwater compliance lends itself well to such systems. This approach detects a departure from background water quality. However, it is then crucial to determine the cause of that departure, which requires a robust conceptual model of the hydrogeology. This presentation interrogates the influence of conceptual interpretation on such assessments.

Interpretation of hydraulic connectivity forms an important basis of the conceptual hydrogeological model, influencing the outcome of assessments and predictions. Conceptual models, like numerical models, are non-unique solutions, designed to best fit the available data. However, the possible solutions are narrowed during the concept development, as assumptions drive the outcomes of interpretation and constrain predictions. Therefore, careful analysis of primary data to form the conceptual model of connectivity is vital. Using the precautionary principle, connectivity is the most conservative assumption, as a more connected system typically allows pathways to develop more readily between causes and effects. Therefore, the interpretation of a system as "disconnected" should be supported by clear and convincing data trends. However, classical concepts of fracture-hosted groundwater flow often involve disconnected systems, comprising isolated blocks of groundwater, and limited connectivity across faults and contacts. Therefore, assessment of dual porosity systems for beneficial management is hampered by the subjectivity of data interpretation.

Hydraulic head distribution trends, both temporal and spatial, are used to assess the degree of connectivity at a range of metalliferous mine sites with fractured rock settings. Geological structure and hydraulic properties are interpreted to build a framework within which the flow system is analysed. The concept is also deepened through characterisation of groundwater quality, via both primary (sample analysis)

and secondary (conductivity survey) methods. Contrasting conceptual models of both connected and disconnected systems are presented and discussed.

The benefits of understanding connectivity, or lack thereof, are improved efficiency and greater efficacy in managing and protecting groundwater quality. Furthermore, the repercussions for ignoring the conceptual question of connectivity are significant, especially as the approaches to groundwater compliance change. This presentation questions our assumptions and promotes the case that one size does not fit all.

Making sense of hydraulic tests in fractured rock

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Abstract not available.

The use of proxy data for hydrogeological site characterisation

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The hydrogeological characterisation of a mineral deposit is often undertaken under significant economic constraints. While the hydrogeological regime is every bit as, or more, complicated than the mineral distribution and characteristics, the resources available to characterise this regime are often meagre by comparison. Given the typically high spatial variability of hydraulic parameters such as hydraulic conductivity, specific yield or various hydrochemical parameters, the development of a conceptual and numerical hydrogeological models to an appropriate level of confidence can be a significant challenge.

There are, however, often opportunities to collect and utilise the typical geological, geophysical, geotechnical, metallurgical and other data which are useful proxies for hydraulic parameters. In most cases, these data already exist or may be collected at a relatively low cost. These can be obtained from an exploration stage onwards and can be used to improve the hydrogeological understanding of the deposit, focus subsequent targeted hydrogeological investigations and reduce the cost of subsequent groundwater exploration or mine dewatering programs.

This paper examines the opportunities to collect and analyse data which may have statistically significant correlations with hydraulic parameters and may be used to extend and improve the hydrogeological characterisation at a moderate cost. Those data sources include geophysical data, basic drilling data, geotechnical parameters, structural geological characterisation, alteration logging and others. Case histories are described which document the development of statistically significant relationships between these data sources and site hydraulic parameters, which were then used to provide greater confidence to the site hydrogeological model.

Hydrogeological characterisation of volcanic-sedimentary rock aquifer within Southern Johor Bahru, Malaysia

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3. Universit Kebangsaan Malaysia, Bangi, Malaysia

The properties of volcanic-sedimentary rock aquifers are definitely forthright, and the results are volatile due to its spatial heterogeneity, especially in the tropical region where higher degree of weathering is a norm. A study on hydrogeological characteristics of volcanic-sedimentary rock aquifer in Southern Johor Bahru was carried out. This region is underlain by Jurong Formation in which the upper member is made up of interbedded sandstone and clay while lower member is made up of primarily tuff. First, the 2D resistivity survey was carried out to identify potential aquifer zone. Upon identifying possible fractured zone, drilling was carried out at one location followed by pumping test. The groundwater samples were collected for quality testing. The preliminary result shows that the depth of fractured rock aquifer was 120-170 m and the resistivity was 70-600 Ohm.m. The air-lift yield indicated that the yield increased from 7.57 m^3/hr at first predicted fractured/jointed (at 136m) to 38 m^3/hr at second predicted fractured zone (at 165m). In addition, pumping test shows that the aquifer acts as double-porosity model. The aquifer characteristics obtained were 7.85 m^2/d for transmissivity, $1.05x10^{-1}$ m/d for hydraulic conductivity and 5.26 x 10^{-1} for storativity. The quality test indicated that the pH and total dissolved solids of groundwater is 7.6-7.8 and 170-180 mg/L respectively. Hence, the preliminary results imply that identifying major fracture system in this region is vital for exploration it controls the quantity of groundwater. Also, the quality of the groundwater was good when compared with international standards.

Abstracts presented on Wednesday 27 November 2019

Large Scale Multidisciplinary Studies to Support Resources Development in Australia: Groundwater Perspective

Deliberating about new gas markets in Australia: exploring potential tight and shale gas industry development with regional stakeholders

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In recent reforms to energy policy, the Australian Government prioritised the development of additional gas resources to meet Australia's current and future demand, including tight and shale gas resources. It is well-established there is a need to respond transparently to community interests and concerns about the potential social and environmental impacts of unconventional gas development, which has been contentious in Australia and around the world. In this context, there is a commitment within the Australian Government's existing $30.4 million Geological and Bioregional Assessment (GBA) program to not only provide independent scientific advice to governments and regulators, landowners, communities, businesses and industries about the potential environmental impacts of developing these resources but to host a long-term dialogue with key stakeholders in three major basins across the country to fully consider the lived impacts of such developments in the landscape. These dialogues engage with key stakeholders and communities about their views and expectations of gas development within their own regions through formal biannual meetings hosted in the three basins across Australia. These forums reflect a deliberate commitment to incorporate targeted stakeholder engagement over the life of the GBA program, improve community understanding of potential tight and shale gas industries, and provide decision-makers with access to an understanding of the needs and expectations of stakeholders and communities that can be considered alongside the scientific and environmental impact assessments. The effectiveness and performance of this engagement is assessed through a formal monitoring and evaluation program that aligns data collection with the intended outcomes of building legitimacy and trust, governing risk, and enabling transparency in the program. This approach also assesses opportunities for learning across the three engagement processes underway in different geographies within Australia to identify implications for designing early stage engagement processes on issues of national importance. This presentation highlights the role of community and public engagement processes in getting new gas resources into Australian markets.

How structural geology and environmental tracers can support groundwater impact assessments in large sedimentary basins

Jorge Martinez [1], Matthias Raiber [1], Tim Evans [2], Sam Buchanan [2], Steven Lewis [2], Prachi Dixon-Jain [2], Éamon Lai [2], Tim Ransley [2], Bruce Radke [3]

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The Australian Government's Geological and Bioregional Assessment (GBA) Program is assessing the potential impacts of shale, tight and deep coal gas development on water and the environment in three regions: the Cooper, Isa and Beetaloo GBA regions.

This presentation will demonstrate how integrating geological structures with hydrochemistry and environmental tracers can greatly support the identification of hydrological connectivity pathways from stressors to environmental assets.

Stressors include the development of prospective unconventional gas plays and groundwater extraction to support development. Environmental assets include groundwater dependent ecosystems (e.g. streams, wetlands, waterholes and springs) and shallow aquifers.

Potential connectivity pathways were identified by assessing multiple independent lines of evidence. Hydraulic pressure data, hydrochemistry from hundreds of bores, surface water and springs, dissolved methane concentrations in groundwater, stable and radioisotopes and noble gases data were interrogated within three-dimensional geological modelling platforms.

The spatial distribution of the data points in relation to geological structures and environmental assets supported the development of alternative conceptualisations of surface water – groundwater connectivity and an indication of aquifer sources to springs.

In addition, six potential connectivity pathways for liquid or gas migration through the route "stressors > aquitards > aquifers > assets" (not always in this order) were proposed to occur via: i. deep seated (reactivated) faults; ii. direct stratigraphic contacts; iii. flow through porous and karstic aquifers, partial aquifers and aquitards; iv. contact between gas plays and overlying aquifers near basin margins; v. catchment constrictions and river diversions; and vi. direct karstic/fractured aquifer discharge into springs.

The conceptual models allowed the identification of data gaps and the design of a data collection program for subsequent stages of the project, including the assessment of potential impacts to water resources and the environment. The proposed approach and lessons learned in this project can be successfully used in other large sedimentary basins.

The Decision Support Groundwater Modelling Project: An industry perspective

Keith Brown [1]

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Global miners such as Rio Tinto (RT) and BHP rely on the utility of groundwater models to inform water related risk in support of mining. However, many of the models that, we use lack flexibility to meet the demands of the dynamic work environment we operate in. We are not alone on this issue. The hydrogeological community has raised similar concerns, about currently accepted practices in groundwater modelling. These 'inconsistencies', while widely recognised across the global groundwater modelling community have to this point largely been ignored.

As joint co-funders in a tripartite consortium RT and BHP and the NCGRT, under the Groundwater Modelling Decision Support Initiative (GMDSI). By entering into this external partnering relationship, it is RT and BHP's intent to help 'lift the bar', with greater emphasis on technical integrity in hydrogeological science particularly in the governance and use of groundwater modelling. By offering its support RT and BHP are utilising its expertise and position to drive development and the application of groundwater models while at the same time build robustness and strengthen its own internal groundwater modelling processes.

The Decision Support Groundwater Modelling Project is a global initiative aimed at advancing mathematical models that will better inform groundwater related business decisions through the development of a framework for decision making and on-going software development.

GMDSI brings together the world's leading model 'thinkers' and developers who will collectively play a key role in spotlighting and addressing the inconsistencies in groundwater modelling on a global platform. The fundamental premise of decision-support modelling is that decision-pertinent predictions are accompanied by estimates of predictive uncertainty. The modelling process is most likely to be successful in quantifying and reducing the uncertainty of a prediction of management interest if the model construction methodology is designed for this purpose.

Inter-disciplinary, multi-physics, multi-scale approaches for groundwater system investigations and hydrogeological assessments in Northern Australia: the exploring for the future groundwater program

Richard Blewett [1], Ken Lawrie [1], Desmond Yin Foo [2], Donna Cathro [1], Christian Seiler [1], Neil Symington [1], Kokpiang Tan [1], Larysa Halas [1], Stephen Hostetler [1], Ross S. Brodie [1], Niels B. Christensen [3], Chris Haris-Pascal [1], Baskaran Sunderam [1], Andrew McPherson [1], Anna Hablein [1], David Gibson [1], Klara Steklova [1], Anandaroop Ray [1], Mike McMillan [4], Titus Murray [5], Jess Northey [1], Jon Clarke [1], John Wischusen [2], Mel Woltmann [2], Brett Harris [6], Mike Sandiford [7], Paul Tregoning [8], Mike Barnes [1], Narelle Neumann [1]

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The development of Northern Australia has been identified as an Australian national priority, with water availability being fundamental to economic development. Surface water options are limited hence identification of new groundwater resources and water banking options is essential. Over the past 4 years, Geoscience Australia, in concert with State and Territory partners, has been involved in groundwater investigations across northern Australia, including 'frontier' sedimentary basins and paleovalleys within priority infrastructure 'fairways', as well as national-scale investigations.

New data acquisition has included multi-scale airborne electromagnetics surveys; LiDAR surveys; drilling; bore testing; ground geophysics (e.g. surface nuclear magnetic resonance, seismic reflection); borehole geophysics; hydrochemical and hydrodynamic analysis; age dating of water and landscape materials; and mapping (geomorphic, morphotectonic, regolith, geological and hydrological). The program also includes assessment of national to catchment scale water balance through use of satellite gravity, InSAR, GPS data and Digital Earth Australia products.

A multi-physics, multi-scale, inter-disciplinary approach has been critical in enabling the rapid identification and assessment of significant new potential fresh groundwater resources and MAR options within tectonically inverted sedimentary basins in the Kimberley Region (Fitzroy Basin (WA)) and Bonaparte Basin (WA and NT); Western Davenport Wiso Basin (NT); and Southern Georgina Basin (NT). The program has also helped define: the extents of groundwater resources near Alice Springs (NT); aquifer compartmentalisation in the Daly Basin and at Howards East (NT); near-surface faults in the Surat and Galilee Basins; groundwater resources in 6 remote communities (NT); and groundwater resources in the Tennant Creek area, Ti Tree Basin; and more broadly across northern Australia in Cenozoic paleovalleys and Proterozoic, Paleozoic, Mesozoic and Tertiary sedimentary basins.

Project data and value-added products inform groundwater numerical modelling and hydrogeological assessments. Program outputs are being used to underpin water allocation planning and investment decisions in agriculture, community water supplies and regional industries.

Determining aquifer properties using Surface Nuclear Magnetic Resonance (SNMR) data: the Paleozoic Bonaparte Basin, East Kimberley, Australia

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Nuclear magnetic resonance (NMR) is an analytical technique used in geophysical investigations where a magnetic field is induced to produce an NMR response from protons in water molecules in the subsurface. Surface nuclear magnetic resonance (SNMR) data are inverted to produce a layered earth model of water content in the uppermost~100 m of the earth's crust. Given the quick and non-invasive nature of data-acquisition and the fact that water content data can be simply transformed to hydraulic conductivity data, SNMR is a promising technique for mapping the distribution and properties of aquifers in the near surface.

Groundwater resources in the Paleozoic Bonaparte basin were mapped using a multidisciplinary, multi-physics approach. This study revealed a multi-layered hydrostratigraphy comprising of a stacked sequence of aquifers and aquitards and significant fresh groundwater resources within the basin. As part of these investigations >100 SNMR soundings were collected, inverted, and integrated with other datasets to estimate hydraulic conductivities and transmissivities for the main aquifers in the basin.

Hydraulic conductivities were estimated by inserting SNMR inversion parameters T2* (decay of magnetisation) and φ (effective porosity) into the Schlumberger-Doll Research (SDR) equation. The 'optimal' formation dependent constant (C) was estimated by minimising the misfit between SNMR estimates of hydraulic conductivity and hydraulic conductivity estimates from co-located slug and pump tests.

The results revealed that the median hydraulic conductivity for the three main aquifers (Keep Inlet, Kuriyippi, and Tanmurra Formations) all fall within a range of three orders of magnitude (10^{-1} to 10^{2} m/day). Of these the Kuriyippi had higher transmissivities (~5 m/day) than the Keep Inlet formation (~0.8 m/day). The deeper Tanmurra formation had the highest hydraulic conductivity distribution (~30 m/day, 50th percentile), however, data were only collected at ten locations for this aquifer and, therefore, these results are unlikely to be representative of the aquifer in general, particularly at depth. This research demonstrates that SNMR is a useful technique for characterising the hydraulic properties of near-surface formations, particularly in areas where boreholes are sparse.

Groundwater system characterisation and baselining- the Isa Geological and Bioregional Assessment region, Queensland Australia

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Prospective shale gas resources are hosted in the Paleoproterozoic rocks of the Isa Superbasin in north-west Queensland. The limited exploration of the region to date has focused on the northern Lawn Hill Platform where extensive organic-rich shales occur, and where shale gas flowed from a hydraulically stimulated well near Burketown. However, further exploration and appraisal remains needed to improve knowledge of the shale gas resources, ahead of any future gas development.

Prior to any potential gas field development, it is critical to adequately understand the regional hydrology and ecology. Future gas development may potentially impact groundwater and surface water, and the natural and human ecosystems that rely on these resources. Consequently, enhancing our baseline knowledge of the region's hydrology is necessary to help assess the availability of groundwater resources, the scale and complexity of surface water-groundwater interactions, and the potential hydrological connections between gas reservoirs and aquifers.

The Australian Government's Geological and Bioregional Assessment (GBA) Program aims to assess potential impacts of shale and tight gas development on water and the environment in three onshore areas (Cooper, Isa and Beetaloo regions). The initial phase of multidisciplinary research for the Isa GBA has improved our baseline hydrological conceptualisation. This area is host to two major groundwater

systems. The deeper system exists within the Proterozoic Isa Superbasin and overlying South Nicholson Basin. A shallower and more widely utilised groundwater system (tapped by over 80% of local bores) is hosted within aquifers of the Jurassic-Cretaceous Carpentaria Basin, and overlying Cenozoic Karumba Basin, collectively part of the Great Artesian Basin (GAB).

The improved baseline knowledge of groundwater and surface water systems has identified a number of knowledge gaps, including the potential for connectivity between the two groundwater systems. It has also informed the development of a future sampling regime that could be used to help address the identified data gaps.

The role of communications in building collaborative inquiry: Reflections from a complex groundwater project

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NOTE: This abstract is part of a series of five connected presentations related to the ACIAR LWR-2015-036 project

In an uncertain environment, collaboration between organisations can increase opportunities for learning. This was our experience in our large and complex research for development project to improve groundwater management in Pakistan. We present key insights gained from building communication across twelve partner organisations, including both researcher and intended research user organisations, whose locations were spread across three provinces in Pakistan.

An approach of co-inquiry was adopted throughout the project. This spanned across the disciplines of social, economic and hydrological sciences, and included academic and implementation partners. Partners were involved from the outset, including in project proposal design. Key inception activities were to validate the research design, have specific individuals across organisations commit to taking on tasks and responsibilities, and an analysis to guide interactions with other stakeholders.

The need to bring professionals from different types of organisations and disciplines together with other stakeholders presented logistic and cultural challenges. For example, arranging times and locations for meetings between academic and implementation partners was a major challenge given differences in organisational cultures. Equity also had to be considered, resulting in a decision to rotate meeting locations between project provinces. When meeting with farming families, different communication strategies were required to guarantee women's input, as, given that local cultural norms dictate women are often not permitted to meet and discuss with men. More examples and details will be provided as part of the presentation.

Focusing attention on enhancing communications led to a positive incidental outcome, with enhanced collaboration capacity among our research user partners. These irrigation departments in Balochistan, Punjab and Sindh have seen their staff collaborate with researchers to develop groundwater models and are also observing how to deliver a collaborative approach to irrigation management with farming families in our project's case study areas.

New approaches using geoscience and satellite data to remotely assess groundwater storage changes in the Great Artesian Basin for improved decision-making

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Increased and competing demands for water to support new or expanding industries, communities and the environment, as well as the complex nature of the Great Artesian Basin (GAB) groundwater systems are key challenges in effective long-term management of the basin's groundwater resources. Quantification of recharge processes, aquifer compartmentalisation and interconnectivity, along with that the influence of geological structures and geodynamics on regional-scale groundwater flow are only broadly understood.

The GAB Groundwater Project (2019-2022) aims to demonstrate how new geoscience data and approaches can improve groundwater system understanding by developing new tools using satellite measurements to remotely map spatial and temporal groundwater storage changes. The project will be conducted by Geoscience Australia in partnership with the Department of Agriculture, State and NT government water agencies and academia.

Two pilot studies will be investigated, one in the complex, data-rich Surat Basin aquifer system, the other in a simple and data-sparse aquifer system. New geoscience data in conjunction with the integration of multidisciplinary science approaches like recharge and discharge studies, groundwater geodynamics and basin analysis aims to advance the regional groundwater systems understanding. Water balance estimations obtained from an updated hydrogeological conceptualisation of the Surat Basin will be evaluated against groundwater storage change estimates obtained using satellite-based Landsat, InSAR and GRACE/GRACE-FO.

Insights obtained in the pilot studies will be used to develop, calibrate and apply new tools to monitor the status of groundwater resources in the entire GAB. The new satellite-based monitoring approach has the potential to provide an ongoing, low-cost, evidence-based decision-making tool that can: i) identify regional-scale changes in groundwater in a timely manner, ii) identify areas of high priority, and iii) provide focus for more detailed studies and management intervention. This information could also be used to support the draft GAB Strategic Management Plan.

Groundwater & Agriculture

The economics of integrating irrigation water sourced from a regional-scale groundwater system into an existing beef enterprise in the semi-arid tropics

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This manuscript presents a multi-disciplinary analysis of the opportunity and economics of double cropping on well-drained loamy soils in the Fitzroy catchment, Western Australia, sourcing water from the undeveloped inter-connected Grant Group and Poole Sandstone regional-scale groundwater system. This study sought to identify those locations in the catchment that are likely to have the lowest cost, lowest risk and soils suitable for double cropping.

A horizontally integrated enterprise was examined using the APSIM agricultural production and NABSA beef systems models, where cotton seed and an irrigated forage are used on station to increase the weight and reproductive rates of an existing beef enterprise. Assuming the existence of a cotton gin at Fitzroy Crossing the 'effective' gross margin for a cotton – mungbean - forage rotation would be about $3205/ha, Under a more likely potential development scenario of a cotton gin at Kununurra the effective combined crop-forage gross margin is estimated to be about $2580/ha. These gross margins are about 25% higher than potential returns from a single crop and highlights the opportunity for a more diverse investment strategy in double cropping, which in most years is more likely to better meet the capital costs of development.

Interpolated surfaces of depth to the inter-connected Grant Group and Poole Sandstone aquifers and hydraulic head were used to calculate the capital costs of irrigation infrastructure and the annual operational costs of groundwater pumping respectively.

Under the scenario of the nearest cotton gin at Kununurra, approximately 280,000 and 660,000 ha of suitable land (i.e. 'lighter' soils and Class 3 or better) is underlain by the Grant and Poole Sandstone such that it may be possible to achieve an IRR of more than 3% for average yields of 25 and 50 L/s respectively, and 0 and 42,000 ha of suitable land is underlain by the Grant and Poole Sandstone such that it may be possible to achieve an internal rate of return of at least 7% for average yields of 25 and 50 L/s respectively.

Although it may be challenging to find a set of circumstances where it is possible to achieve a high commercial return on an irrigation development (e.g. 7% or greater), the horizontally integrated scenario examined in this study may enable a station to

grow out young cattle and provide alternative markets to the live export trade, thereby reducing risk.

The role of Managed Aquifer Recharge (MAR) in developing Northern Territory agriculture

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The Top End of the NT has significant potential for MAR to support medium scale irrigation. MAR can help overcome the seasonal water balance challenges to increase water availability during the dry season with negligible environmental impacts, and even provide environmental benefits. The Daly River catchment is flagged as a key area for agricultural development due to its proximity to Darwin, soil suitability and water availability. The river is also one of a handful of perennial rivers in the NT, where dry season flows are fed by groundwater from the Oolloo Dolostone and Tindall Limestone aquifers. Environmental flow objectives have led to groundwater extraction being capped and agricultural development is currently limited by the availability of water.

The fundamental advantages of MAR based developments over conventional water sources are explained including the cost of transporting water, lack of evaporative losses, scalability of MAR projects and the variability of the magnitude of the wet season. Conversely the impediments to irrigation-based MAR schemes in northern Australia are also discussed. The primary issue is not the technical feasibility, rather it is the economic feasibility of the total irrigation development, which includes a MAR component.

The technical and economic feasibility of MAR are assessed at three sites in the Daly River catchment based on a range of artificial recharge methods and a range of crop types. The concept of using wet season flow for MAR and recovery during the dry season was found to be both technically feasible and economically viable in some areas in the catchment and for some crop types. Outside the Daly River catchment, the potential for MAR to support irrigation exists where there is a suitable source water, target aquifer and arable soils. The potential for MAR in other areas in the Top End is also considered.

Water bore siting using farm-scale electrical resistivity mapping

David A. Allen [1]

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Soil has a remarkable ability to mask geologic features relevant to bore siting that might otherwise outcrop. A person trying to site a bore typically has just existing nearby bore records, soil variation and the lay of the land as clues. Without a knowledge of what is beneath a farm it is not possible to tell if nearby bores have any relevance, soils commonly are spread horizontally from their source and mask what is beneath and lay of land often supplies insufficient clues.

Electromagnetic mapping reveals bulk electrical resistivity which is (apart from in deep mineral exploration) always related in some way to groundwater and the ions within it. Electromagnetic mapping at various depths gets past the masking soil and

other shallow strata and usually reveals a bewildering complexity of hydrogeology that can be difficult to interpret. This typically is found to be far more complicated than any conceptual models envisioned in relative ignorance beforehand.

Around ten thousand line kilometres of multi-depth electromagnetic data have been collected across farmland using the AgTEM towed time domain electromagnetic system and experience gained from interpreting this data is summarized into a set of steps in this presentation. The interpretation procedure is relevant also to other systems including airborne systems, but the scale of investigation must be different.

In this presentation, a series of logical steps is presented, for planning, executing and interpreting electromagnetic surveys for shallow bore siting. At the end of the process it is important to be able to separate out the new knowledge gained from the ambiguities that remain. Only then can recommendations on siting of bores be logically made. There is an excellent case for encouraging farmers to make their electromagnetic mapping data public and for mosaicking of those maps to be conducted so that neighbours and regulators can see a bigger picture.

Understanding risk in order to manage it

Diana D. Mathers [1]

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The objective of this work is to collect a robust dataset of nitrogen and phosphorus losses from drainage water in New Zealand cropping rotations. An important part of the project is to examine the environmental risks indicated by the data and to identify on-farm management practices that could reduce losses.

In 2014, passive wick drainage fluxmeters were installed at sites on twelve New Zealand cropping farms with mixed arable and vegetable rotations. The installation depth is 1.2m, below the active rootzone for many crops. Since then, drainage water has been collected and measured and the concentration of nitrogen and phosphorus in the drainage sample has been analysed. After 4 ½ years of data collection we are able to see where and when the risks for nitrogen and phosphorus losses occur.

Annual Cumulative Nitrogen Losses in the last three years

Annual Nitrogen losses in Kg/ha for 2016-2017 and 2017-2018 and the spring and summer drainage volume for 2018-2019 in mm. *estimated from water balance model because of flooding in the fluxmeter units. N/A because units have been re installed at a new site.

Site #	1	2	3	4	5	6	7	9	10	11	12
Sep 16-Aug 17	18	24	86	1	20	11	43	31	52	35	17
Sep 17-Aug 18	21	23	16	13	28	12	31	4	26	60	31
Sep 18-Feb 19	13	1	3	17	8	11	<1	N/A	9	28	37

The data set has revealed the size and dynamic nature of N losses from mixed cropping systems. The challenge is tease out farm management effects from the biophysical characteristics of the farm which influence nutrient losses and to develop farm management strategies to mitigate these losses.

Transforming agriculture in the Pilbara through river and groundwater-fed irrigation

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The need for economic diversification in northern Western Australia has been recognised in multiple national and state policy documents. Irrigated agriculture has been identified as a key growth industry in northern WA, with the state government aiming to double the value of agricultural output in the Pilbara by 2025.

The first challenge for irrigation is the provision of a reliable water supply. Most rivers in the Pilbara only flow for a few weeks each year, and annual evaporation is 10 times the volume of rainfall. To overcome the severe water deficit, this study examined the conjunctive use of river flows and groundwater with augmentation through managed aquifer recharge to provide a viable water supply for irrigation.

River flows, aquifer parameters, and the connection between the river and groundwater availability were assessed through fieldwork and modelling. We found that the river was strongly connected to the aquifer and recharged a large volume of water into the aquifer each year. To leverage off this recharge process, an irrigation concept was developed which utilised water table drawdown to maximise the volume of water captured from river flows.

Modelling of conceptual irrigation schemes showed that with groundwater extraction that lowered water tables, the river flows could contribute up to 140 GL/ year to aquifer recharge and provide a long-term sustainable irrigation supply. Further, low-level weirs can be used to increase the volume of river flow captured by another 20%.

This presentation illustrates the use of river flows and groundwater in providing a sustainable water supply for irrigation. We show the economic benefits of such an irrigation scheme for different crop types in the Pilbara, demonstrating how conjunctively harnessing these water sources provides an opportunity to transform agriculture in the Pilbara.

Estimation of water balance of Lower Bari Doab Canal (LBDC) Command Area, Pakistan: A modelling approach

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Water scarcity has been identified as a global issue. Poor management of available water resources contributes to this shortage. An extensive network of canals supply water to small landholdings in the Lower Bari Doab, in eastern Punjab, Pakistan. Quantifying the water balance of intensively irrigated canal and groundwater irrigated regions is critical for improving management of surface and groundwater resources.

Seepage losses from canals and watercourses significantly reduce water availability and efficiency at the farm level. However, seepage from the extensive canal network

are a major contribution to groundwater that allows extensive use of groundwater for irrigation. The present study assessed the water balance for the command area of the Lower Bari Doab Canal (LBDC) Punjab, Pakistan. Recharge and discharge was assessed from October 2009 to September 2015 to quantify the water balance for the area. The water balance components estimated are seepage losses from canals and distributaries, recharge from rainfall, surface water irrigation and groundwater irrigation, and discharge from groundwater pumping in the area and evapotranspiration losses.

Data are available for average water supply to LBDC and groundwater pumping within the LDBC. Seepage losses and irrigation return flows, and groundwater conveyance and field losses can also be estimated from the available data sources. These data are currently being modelled to determine the extent of depletion from the alluvial aquifer system. We will present results from this modelling and what implications can be drawn for policy and improved groundwater management practices.

Note: This abstract is part of a series of presentations related to the ACIAR LWR-2015-036 project. Authors acknowledge financial support of the Australian Centre for International Agricultural Research (ACIAR).

Climate resilient and sustainable water resources management in north-west region of Bangladesh

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North-West region spreads over the 16 districts of Bangladesh which is bounded by the Brahmaputra river in the east and the Ganges in the west. About 35% of Boro rice and more than 60% of the wheat and maize of the whole country's production is from this area. Declining of groundwater levels, is a major concern for Barind area of Northwest region which have resulted in a lack of access to water for drinking and irrigation. Under different projects, we have estimated water demand for current and future cropping scenarios, and the sustainable limit of water use in the region by water balance and groundwater modelling. With limited opportunities for surface water (SW) irrigation, at present there are about 9,531 DTWs and 107,707 STWs (BADC, 2016) in Barind area. Study results shows some upazilas as resource constraint and declining groundwater table. In the next 25 years, food demand of the country is expected to be increased by 29% which will require increased cropping intensity. Without increasing the SW irrigation, added pressure on groundwater will lead to further depletion of the sources. Reduction of SW flows and lowering of groundwater table combined with impact of climate change will aggravate the existing water scarcity problem. All these have compounded the sustainable management of water in this area.

To overcome these complex issues, will require a proper management of surface water and groundwater in an integrated approach. Increasing use of SW, rainwater harvesting, enhancing artificial groundwater recharge, crop diversification for introducing less water consuming crops and optimize use of groundwater for irrigation can minimize the impact of drought and climate change. Regional cooperation can guarantee a sustainable future in terms of water availability since the basin areas of the river systems is dissected by international boundaries. A

strong political commitment supported by adequate institutional arrangement is required. This paper will describe the technology for climate resilient water resources management as well as impact on groundwater table, in this region.

Impact and causes of groundwater depletion with its remedial measures in irrigated area of Bari Doab

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Bari Doab: It is a piece of land between two rivers i.e. Ravi and Sutlej. It is the most rapidly groundwater depleting area of Pakistan. The causes of rapidly depleting groundwater is due to the stoppage of surface water supplies in both rivers after Indus Water Treaty (IWT) in 1960 between Pakistan and India. It created acute shortage of surface water supplies in this area. It generated maximum stress on groundwater to meet the crop water requirement.

This study was carried out with an objective to predict the future groundwater availability and impact of climate change in this area with the overview of change in pumping cost. In this regard water balance of the area was determined and it was found that surface supplies are less by about 1027 mm/year. As a result, the average groundwater mining is determined as @ 0.34 to 0.6 m/year in the area.

The results of the study revealed that acute shortage of groundwater in the central and lower parts of Bari Doab and it is moving in the direction from east to west. This was due to heavy pumping rate from upper to lower part of Bari Doab as currently the farmers are compelled to install their tube wells with varying depth i.e. 46 to 79m from head to tail of Lower Bari Doab Canal. Similarly, the study results showed high tube well installation cost as well as pumping and operating cost with electricity.

It is therefore, recommended to construct artificial recharge channels in the area in order to maintain groundwater levels and to avoid enhanced pumping cost. In this regard old bed of Sukh-Beas River can be used for artificial recharge. A discharge of 156.3 m3/s (5518 cfs) can be diverted in Sukh-Beas channel.

Regulation, Policies & Management

Setting the strategic direction for the Great Artesian Basin

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Managing water in the Great Artesian Basin presents many complex environmental, social and economic challenges and opportunities for governments, water users and other stakeholders. When considering the often-conflicting values in the Basin, one plus one does not always equal two when it comes to articulating a future management approach. The draft Great Artesian Basin Strategic Management Plan 2019 has been developed to provide guidance for policy, actions and outcomes over the next 15 years.

Over the last four years Basin governments, in consultation with the Great Artesian Basin Coordinating Committee, have developed the next iteration of a management plan for the Basin. The Plan takes into account feedback from a rigorous consultation period held in the latter half of 2018. This process has not been without challenges and delays, demonstrating the complexities of developing such a Plan. The production of the Plan is significant, impacting the management of the Basin now and into the future.

The new Plan provides a principles-based approach focussing on areas of coordinated governance, judicious use, secure and managed access, Aboriginal and Torres Strait islander and community values, a healthy resource, education and information generation. This will enable benefits gained from previous activities to be maintained and support development throughout the Basin.

The principles in the new Plan emphasise the importance of scientific input to Basin management discussions and decisions. Great Artesian Basin science requires support, investment and careful consideration, in relation to balanced outcomes for all water users and economic and environmental outcomes. The Plan seeks to encourage the utilisation, sharing and development of information (scientific and otherwise) by all Basin stakeholders, including governments. Better understanding of the Basin will support policy, management, activities and usage, and enable balanced and beneficial outcomes to be achieved for the Basin and its communities.

Can we model management?

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A methodology to quantitatively evaluate the effectiveness of groundwater management plans by structuring groundwater management as a systems control problem and simulating sequential management decisions that evolve based on aquifer/management feedback was developed. The method indicated how a plan may proceed in reality under alternate timings and frequencies of management decisions in systems with differing response times. Generally, effectiveness decreased as the interval between management interventions increased and

intervals greater than annual showed minimal improvement compared to entitlement only. However, given the high degree of parameter uncertainty typical in groundwater models, a study aim was to determine how much calibration data was necessary to quantitatively evaluate management plan effectiveness. A calibration-constrained predictive uncertainty analysis investigated whether reducing parameter uncertainty decreased predictive uncertainty. A synthetic study was used to evaluate the uncertainty around predictions generated from four different groups of model realisations, created based on increasing amounts of observation data generated by a numerical groundwater model designated as reality. Four simple models of the reality system were built based on prior knowledge, and a calibrated solution to each of the three different observation datasets (three posterior distributions). Each model was used to predict the effectiveness of management decision-making on a monthly basis and both entitlement-only and unmanaged scenarios. The predictive uncertainty was quantified for prior and posterior models, through a calibration-constrained uncertainty analysis using Null-Space Monte Carlo methods. Due to model simplifications, certain parameters, assumed inappropriately high values to compensate, resulting in calibration-induced model bias that caused the models to make erroneous predictions. Even with use of current best practice uncertainty analysis methods, the effectiveness of management could not be determined due to the limitations of the numerical models utilised, which raised serious question over our current ability to model management.

Groundwater regulation-governance-management nexus: a case study from Punjab, Pakistan

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Groundwater is key for societies that depend on irrigated agriculture for their food and fibre. Humanity is using water that has been stored underground for millennia and which cannot be easily replenished. An estimate from 2010 suggests global extraction of groundwater from aquifers is 982 km^3 per year, with the agricultural sector using 70%. Pakistan is the 4th largest user of groundwater, with annual extraction of around 65 km^3. Feeding Pakistan's growing population, currently at 208 million, is moving the country's status from water-stressed to water-scarce. The aquifer underlying the Indus Basin in Pakistan, one of the largest underground water reservoirs in the world, caters for drinking, industrial, commercial water needs of Pakistan, and especially irrigated agriculture, which uses around 90% of pumped groundwater. This groundwater is estimated to contribute 40-45% of Pakistan's irrigation water requirements. As groundwater is a hidden, common pool resource, its governance has faced socio-political challenges for centuries, but the need for improving institutional frameworks is becoming urgent. This paper traces the development of institutional and regulatory frameworks in Pakistan's Punjab province, from the Canal and Drainage Act (1873) to the National Water Policy (2018) and the Punjab Water Policy (2019). It introduces findings from a current ACIAR funded project that is using case studies to explore how to improve groundwater management for enhanced farming family livelihoods. The project is

identifying opportunities using improved groundwater modelling, enhanced networking among researchers and managers and case study-based stakeholder forums. It is anticipated that with opportunities identified, and capacities built, this project may help support the development of a holistic policy framework crucial for effective groundwater governance in Punjab and across Pakistan. The project has highlighted the importance of including contributions from both community stakeholders and sound science and modelling when formulating and implementing policy.

How to make a quantum leap for the hydrogeological profession in Australia – the case for groundwater guidelines and codes of practice

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Groundwater science in Australia represents a relatively young and immature profession. Relative to other scientific and engineering disciplines, the science of hydrogeology is still rapidly evolving. Individual hydrogeologists frequently undertake field testing, data analysis and interpretation activities using their own approach or that of the organisation in which they work. This often results in highly variable quality and poorly defined products. No minimum standard, code of practice or technical guidance exists for many activities which the hydrogeological profession in Australia undertakes. Consequently, we are sometimes seen by other technical disciplines (e.g. engineering) as being unprofessional and technically weak. It is proposed that an increased focus on the development of Groundwater Guidelines and Codes of Practice will help to address this deficiency and, in time, move the whole profession to a new level of rigour. Much of what we do does not lend itself to tightly defined standards and this is not generally proposed. Rather, the almost infinite hydrogeological variability in which we work will be better served by less formal guidelines. Many such guidelines already exist at the local and state scale, but there is no National consensus on their content, with some notable exceptions, e.g. the Australian Groundwater Modelling Guidelines. Some suggested topics where new guidelines would be helpful are:

Data collection and field-testing methods:

1. Groundwater level measurement and correction methods.
2. Slug and packer test design, implementation and interpretation.
3. Surface water groundwater interaction investigations.

Analysis and planning methods:

1. Design groundwater levels for civil engineering design and construction.
2. Application of climate change science to groundwater resource management planning.
3. Minimum requirements for groundwater resource management plans.
4. Economic analysis methods for groundwater development and MAR schemes.

Organisational options to achieve this goal are presented.

Groundwater quality management and environmental regulation in Queensland

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Groundwater quality is protected in Queensland under the *Environmental Protection Act 1994*. The intent of the legislation is to maintain the groundwater quality within the range of natural quality variations established through baseline characterisation to ensure that there is no adverse effect on groundwater quality from the operation of any activity.

In Queensland, groundwater conditions are required as part of Environmental Approvals for major activities that potentially affect the groundwater environment. Triggers and limits are often imposed within these conditions to help monitor and protect the groundwater quality. However, there are a range of challenges with the derivation and application of these trigger and limits.

Frequently there is limited baseline water quality data and guidelines, or water quality objectives may not be available for the specific location. In the past, guidelines such as for aquatic ecosystems or stock watering have been generically set as limits in Environmental Approvals. However, natural groundwater quality can exceed these water quality guidelines, or conversely, the guideline values may be way above baseline levels. This can result in either false non-compliance or a significant allowance for worsening water quality and potentially environmental harm.

Up-gradient bores have also been adopted in many approvals to provide a comparison with down gradient bores. However, finding appropriate up-gradient bores is frequently not possible as groundwater flow direction is not easily identified. Other complexities include: the choice of monitoring locations; the indicators being measured and the timing and frequency of sampling.

This presentation will look at typical groundwater conditions used in Queensland and some of the potential limitations. Examples of new approaches being implemented to improve the management and protection the groundwater quality in Queensland will be discussed. This will include the use of site-specific values where no default values are available or when groundwater contains naturally occurring concentrations that exceed guideline values.

Evaluation of Community Centric Aquifer Management Strategies in coastal regions of Gujarat State, India

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The present paper explains about collaborative attempts of community, industry, Bhujal Jankars, voluntary organization and a knowledge firm on management of shallow and deep aquifer systems in coastal areas of Gujarat State of India. The project has been implemented at two types of aquifer systems sandstone as regional deep aquifer and fractured and weathered shallow basalts in Kachchh and Saurasthra coastal regions respectively. The coverage of various project activities is in around 350 rural pockets, 6 towns from both the project locations.

The key activities implemented are participatory aquifer mapping, groundwater and rainfall monitoring, data collection and dissemination, demand supply estimation based micro level water security plans, demonstrations and implementation GW recharge activities, action research for designing MAR structures, capacity building of Bhujal Jankar, formation farmer groups, aquifer based institutions, developing protocols, educating decision makers, setting up of knowledge centers managed by Bhujal Jankars and field learning laboratory for MAR.

An independent self-reliant enterprising firm of BJ's catering knowledge services to area, adaptation of various practices such as selection of water efficient crops, use of silts collected in MAR structure to improve soil fertility and moisture holding capacity, discharge measurement based groundwater usage by farmers, reorganization of local resources as primary drinking water source and investment on its maintenance by Gram panchyat and district administration are important outcomes of the projects so far.

All these outcomes have proven that knowledge support provided by centers have empowered community for proper demand and supported administrations for region specific plan and investments. Also, the process has attracted many donors to revive the GW resources as sustainable solutions. Attempts are still going on how to design an institution framework at state level and what should be the exact shape, roles, responsibilities, ownership and partnership fabrics of such knowledge centers.

Western Australia's State Groundwater Investigation Program - a holistic prioritised approach to delivering evidence-based science for groundwater management

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Western Australia more than any other state relies on groundwater for drinking water supplies, irrigated agriculture, industry, mining, economic development and liveable communities. Groundwater is also essential to the environment - maintaining iconic, natural features that West Australians love.

Since 2005, the Department of Water and Environmental Regulation (DWER) has invested over $50 million into groundwater investigations, arguably the largest, longest running, state-led program of this type in the country. In total the investigations have drilled over 60 kilometres, installed well over 500 monitoring bores, collected Airborne Electromagnetic data over an area of more than twice that of Tasmania, collected and analysed countless water samples, and completed a range of 2D geophysics surveys including seismic, magnetotellurics and electrical-resistivity. This data has been used to construct dozens of conceptual and numerical models around the state which have underpinned the balanced management of our shared groundwater resources.

To ensure the ongoing flagship State Groundwater Investigation Program (SGIP) continues to deliver benefits to Western Australia, DWER developed a systematic prioritisation process to determine the area's most in need of groundwater information. This resulted most recently in the "next generation" of SGIP projects. Our program has shifted from more traditional investigations to targeted, demand hotspots where rapid regional growth, climate change, cumulative impacts, and an increasing need to acknowledge and incorporate Aboriginal values into groundwater

management requires better groundwater information, new methods and is some cases, innovative water solutions.

The investigation program invests a portion of the budget into research and development activities, which aims to test new methodologies for data collection, interpretation, and monitoring. This includes a current groundwater telemetry trial, collection of nuclear-magnetic resonance data from bores, sampling and analysis of novel tracers, and development of new modelling workflows. The DWER actively partners with industry and academia to develop this shared science.

Case studies from the investigation program will be selected and summarised to highlight the prioritisation process, the novel methods used for data collection, and how the information will be used. Finally, a recently completed evaluation of the program by DWER will be described.

Metered groundwater extractions for stock and domestic use in the Surat Basin, Queensland

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Objectives: The Great Artesian Basin is the only reliable source of water for many graziers in remote areas of Australia and recent drought has caused considerable stress. In some areas, concerns about groundwater pressures are amplified by mining and unconventional gas operations. Although water extraction for stock and domestic use accounts for the majority of consumptive water use in the Basin, stock and domestic bores are rarely metered and current water resource planning and management relies on modelled estimates of stock and domestic water use. To support improved estimates, a program of metering was implemented in 2015 to obtain high resolution extraction data for stock and domestic bores in the Surat and Bowen basins.

Design and Methodology: The metering program involved deploying ultrasonic flow meters to 42 bores used for stock water supply. Roll out of the program posed many challenges including identifying landholders willing to participate, identifying bores in accessible locations with suitable infrastructure for metering, designing equipment to minimise animal damage and data cleansing. Since the presentation of this project at the 2017 AGC, additional data on type of beef cattle operation, stocking rates, bore purpose, bore infrastructure and other available water sources have been provided by landholders; and two more years of extraction data are available so that water use dynamics can be seen, including during the dry conditions that prevailed throughout the region in 2018.

Original data and results: The presentation will describe the project approach and how the quantitative and qualitative data have improved understanding of property-scale water demand and spatial and temporal variability of groundwater extractions for stock and domestic use in the Surat and Bowen basins.

Conclusion: The program has provided an important data set to improve methods for estimating stock and domestic water use in the Basin and to understand inter-annual and inter-property variability.

Regional Scale Studies

Hydrogeology of inland basins in NW China

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The inland basins in NW China include the Junggar Basin, the Caidam Basin, the Tarim Basin and the Hexi Corridor, covering an area of about 2.14 million km^2. Groundwater is a major water source in these regions; hence China Geological Survey has launched a series of projects to characterize hydrogeological conditions of these basins. This presentation will summarize the main findings of these studies through related reports, papers and monographs review. Annual precipitation is usually less than 100 mm in most areas except the mountainous areas. In contrast, the annual potential evapotranspiration is higher than 1500 mm over the majority of inland basins. Annual the mean annual groundwater recharge is about 49 billion m^3, mainly from river water infiltration, irrigation return flow. Groundwater is mainly used for agricultural section, accounting for over 80%, and has been overexploited in some areas, including the Hexi Corridor, the Junggar Basin and the Tarim Basin, resulting in a severe ecological impact, such as tree dieback and wetland shrink. A key character is the frequent transformation of surface water and groundwater, usually at least three times. Groundwater flows through difference systems, i.e., local or regional systems. In the future, more studies are needed, such as the impact of climate change on groundwater resources and water allocation to ecosystem recovery.

NSW Great Artesian Basin Bore Survey and pressure prediction projects

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Since the time of European settlement water pressures within large portions of the Great Artesian Basin (GAB) have been in decline due to uncontrolled artesian flows from bores drilled for stock and domestic purposes. This problem has been exacerbated by the deteriorating condition of many of the aging bores. From the 1990s the NSW Government has been supporting the replacement or capping/piping of these bores. As part of this work, the NSW Department of Industry has initiated two projects in the NSW portion of the GAB.

The first project's objectives are to identify conditions of the bore head and type of water distribution system; measure head, flow, temperature and water quality; estimate water requirements; and determine the source of water for GAB springs through isotopic studies. Contractors were engaged to conduct landholder interviews

and undertake field assessments. The water samples for quality and isotopic analysis were collected, stored and transported to Australian guidelines and analysed by NATA registered laboratories. So far about 700 bores have been assessed.

For the second project, a consultant was engaged to model when and where artesian conditions will reoccur. A trend analysis of pressure data, partitioned into areas of approximately 50 km by 50 km in size, resulted in the development of area specific trends for the confined aquifers in the NSW portion of GAB. Information collected during the bore survey was used to refine the analysis. The trend analysis identified regions currently recovering and when and where artesian conditions can expect to be regained. Basin-wide potentiometric maps were prepared to identify bores 'at risk' of failure or at risk to contribute to water losses.

The data and information gained is informing the prioritisation of bore replacement and capping/piping activities, development of future infrastructure management strategies, the strategic policy in the GAB, the ongoing management of the GAB resource, and the remake of Water Sharing Plan for the NSW GAB Groundwater Sources.

Building a regional geological model for hydrogeological applications

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The Office of Groundwater Impact Assessment (OGIA) is responsible for assessing and reporting (UWIR) cumulative groundwater impacts resulting from petroleum and gas activities in the Surat Cumulative Management Area (CMA).

The Surat CMA covers an area of around 300,000 km^2 and comprises three geological basins, three main gas reservoirs and two main groundwater aquifers systems – the Great Artesian Basin and the Condamine Alluvium. A comprehensive regional 3D geological model was built by OGIA, using extensive datasets from various sectors: petroleum and gas, mining and groundwater.

The objectives of the geological model are to:

- Provide a framework for the groundwater flow model to predict impacts
- Attribute formations for over 35,000 water bores, critical for determining bore impairment, monitoring and extraction
- Support conceptualisation and hydrogeological investigations.

The methodology adopted for the generation of the 3D geological model using the Petrel E&P Software Platform is a standard approach taken in the petroleum industry. The model is primarily based on the interpretation of geophysical logs (over 7,000 wells) and stratigraphic interpretation of about 25,000 water bores. The model represents the main hydrostratigraphic units at a 250-metre lateral resolution to capture spatial variability over the whole Surat CMA. The model also acknowledges and integrates recent geological mapping, previous local and regional geological

models and interpretation of structures and horizons from seismic interpretation sourced from various industry, research and government entities.

The third generation of this model has been successfully developed and used to produce:

- Grids to develop regional-scale and sub-regional-scale numerical models
- Aquifer and aquitard mapping and detailed cross-sections for characterisation projects including spring assessment, fault studies and hydrogeological impact assessments
- Model layering to define aquifer attribution for over 35,000 water bores, including confirmation of monitoring intervals and intake zones for water use supply bores
- Communication materials for stakeholders and industry.

Recommendation for groundwater management for lower Indus basin: a case study of Sukkur barrage left bank command

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Objectives: In Pakistan, where agriculture production is of prime importance for its economic development, the increasing dependence on groundwater for irrigation and drinking purposes makes it vitally important to assess underground water balance to recommend policy measures for its sustainable management. The key objectives of this study are to enhance groundwater management and to develop sub-regional groundwater model for informed decision making.

Design and Methodology: First objective was achieved by developing a geo-database for the groundwater information available with departments. Historical data sets were digitized, and additional data sets for groundwater level and quality were acquired by installation of data loggers in newly established observation wells in the command area. With the available data, a physical process-based groundwater model was developed for achieving second objective. Calibrated model of sub-regional level was used to assess the policy scenario for sustainable water use and protection against water logging and salinization. The assessment of the scenarios was performed by aquifer stress analysis, water level threshold assessment, and water balance impact assessment.

Original data and results: Lithologically, the area consists of sands of various grades with silt and clay down to several hundred feet. Sand is predominant and is highly transmissive and constitutes the potential aquifer in the area. The groundwater flow in the region is divided into two directions, with the hydrological divide seen near the Rohri canal-constituting world largest single canal area for irrigated agriculture. There are zones of shallow to deep water tables in the area. Depth to water table increases near the river Indus and decreases near the main canals. The Indus River and the canals are the main sources of groundwater recharge in the area. The area has recently seen an increase in groundwater pumping, especially at the tail reaches of canals. Reasons for this growth include less availability of water at these tail reaches, and subsidized cost of tube well installation.

Conclusion: Tail reach of canal commands are highly dependent on groundwater, and long-term trends shows that water balance will become negative if high pumping continue in regions near the Indus River. There will be positive impact on waterlogged area with water levels going below root zones, which will ultimately bring good crop yields. Government has to cap the groundwater in regions near the river and should allow pumping of groundwater in waterlogged area where the groundwater quality is suitable for irrigation.

Monitoring groundwater extraction impacts within multi-level sandstone aquifers near World Heritage Blue Mountains National Park, west of Sydney

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For more than 20 years the NSW government has monitored groundwater conditions at keys sites across the Blue Mountains to address increased urbanisation and demands on groundwater use close to sensitive environments. The Blue Mountains sandstone aquifers located approximately 50 kilometres from the city form a plateau that rises up to over 1,000 m above the coastal plain. There are small urban areas which surrounded by National Park that occurs along a major transport route linking Sydney to western New South Wales.

There are dominant spectacular cliffs, canyons and waterfalls made up of Triassic aged Narrabeen Group and Hawkesbury Sandstone geology and geomorphology. These make up a series of multiple porous rock aquifers at different levels. The sandstones cover an area of about 3,238 km² of which 2,375 km² is National Park and are part of the broader Blue Mountains World Heritage Area. The shallow and intermediate aquifers are considered critical to spring flow and to stream baseflow in the upper plateau rivers. Groundwater has been shown to support hanging valley communities particularly in the upper Blue Mountains near Katoomba.

The NSW government manages groundwater across the state of NSW under the Water Management Act 2000 and the gazetted Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources 2011. In support of this management monitoring has been progressively established using automatic groundwater level loggers and a substantial period of record has now been obtained. Hydrogeological investigations in the past have shown that complex multi-layered sandstone aquifers occur within the Blue Mountains Sandstone and there is a high degree of connectivity with surface water systems.

Examples of long term hydrographs and geological cross sections will be presented specific to differing aquifer characteristics. This information is being used to monitor and assist in managing groundwater extraction currently and into the future.

Classification of springs derived from volcanic aquifers of the Nulla Basalt Province, north Queensland

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The Nulla Basalt Province, a 7300 km^2 lava-field province resulting from numerous effusive volcanic eruptions over the last 5 Ma, hosts groundwater supplies that support stock and domestic water use, sustain springs and wetlands, and contribute baseflow to the Burdekin River. The province comprises stacked lava flows with concentrated flow-top vesiculation. Weathering has expanded vesicular pore space, and fractures have enhanced connectivity, leading to numerous discrete permeable zones and heterogeneous hydrogeological properties. Possible increased demand for water from agricultural development would impact on water availability for natural ecosystems. Managing water resources requires an understanding of interactions between groundwater and surface water systems, to enable the protection of groundwater-dependent ecosystems and define critical components of the water balance. Characterising springs will aid this understanding.

For this project, springs have been identified, mapped, and categorised using existing spring databases together with new and existing geological, hydrogeological, hydrochemical, and geomorphic data, including recently acquired 1 m resolution LiDAR elevation data, and Landsat earth observation data from Digital Earth Australia. Springs vary from local discharge features occurring as small seeps to regionally significant discharge features exhibiting high flow rates. Different temporal dynamics and hydrochemical signatures are present, which may reflect various groundwater sources and positions in the landscape.

This work shows that contacts between lava flows; the presence and distribution of Cenozoic sediments that exist beneath, between, and above basalts; variation in the paleotopographic surface and basement geology; modern topography; and the potentiometric surface combine to determine the position of springs in the Nulla Basalt Province. Conceptual models are presented for each spring type identified. These models describe the factors that affect the location and source of each spring type. This work informs understanding of the hydrogeological system, thus improving conceptualisation of the water cycle processes in the region.

Hydrogeological characterisation of faults in the Surat Basin

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Background and Objectives: The Queensland Office of Groundwater Impact Assessment (OGIA) is responsible for assessing cumulative groundwater impacts arising from coal seam gas extraction (CSG) in the Surat cumulative management area (CMA). A key component of the assessment is the characterisation of faults. Faults have the potential to influence aquifer connectivity and are therefore key inputs to the construction of both geological and numerical models.

Significant advances were made in 2016 by OGIA to better represent regional fault systems in a groundwater-modelling framework. Since then, OGIA has focused on the characterisation of a large number of smaller faults.

As such, the main objectives of this project were to document the current understanding of faults in sedimentary basins and to assess fault-induced connectivity between CSG reservoirs and adjacent aquifers.

Methodology: OGIA's approach to conceptualising faults comprises of three steps:

1. Fault mapping and attribute determination

This involved a review and interpretation of available seismic data to identify faults of interest. Once faults were identified, attributes such as displacement, stratigraphic and lithological contact and fault permeability were estimated utilising several fault seal methods.

1. Multidisciplinary case studies

Case studies were conducted in each aquifer of interest. This was done in order to understand the likely processes occurring at each site and to validate the fault parameterisation approach. Detailed numerical modelling was also utilised to test the parameterisation approach.

1. Identification of sites with increased potential of connectivity

Following validation of the approach, the fault seal analysis is carried out at all known fault locations in the Surat basin in order to identify faults, which may increase the connectivity between formations of interest.

Results and Conclusions: Mapping and characterisation of a large number of faults in the Surat Basin have improved the conceptual understanding of groundwater flow, aquifer connectivity and analysis of monitoring trends. Overall, there are some faults that are likely to affect aquifer connectivity particularly between the Springbok Sandstone and the Walloon Coal Measures. However, the assessment so far provides no basis to expect that faulting will have implications for the propagation impacts at regional scale.

As part of this study, several key attributes have been estimated for all known faults in the Surat basin including, location, displacement and key parameters pertaining to fault permeability. These datasets can be used in future numerical modelling workflows to estimate the impacts of faults on groundwater flow.

Protection Schedule in Daihai Lake Basin

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Daihai Basin is located in Ulanchabu City, Inner Mongolia Autonomous Region, China. It is surrounded by mountains, which is a typical closed inland brackish lake. Daihai Basin is in the transition zone from temperate semi-arid zone to arid zone. In the past 30 years, the area of Daihai Lake has shrunk sharply and COD_{Mn} has remained high due to the influence of human activities and natural factors. The project collects

and collates relevant historical data and scientific research achievements of water environment, water resources, social economy and land use in Daihai Lake basin; The seasonal changes of water quality, sediment, ecology and the sources of surface runoff pollution were investigated; The population, social economy, pollution, source of load, land use status etc were investigated. The source-sink relationship of Daihai Lake, water resources balance analysis and COD_{Mn} were Analyzed. On this basis, the range of environmental quality baseline values of COD_{Mn} in Daihai Lake under non-human activities is analyzed, and the phased objectives of its protection are put forward.

Groundwater Settings & Systems

Continental scale hydrogeochemistry: Groundwater system processes and prediction of groundwater chemistry through water-rock interactions across Australia

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As the driest inhabited continent, Australia's groundwater resources are essential to sustain our communities, food production, industry and environment. Groundwater hydrogeochemistry allows us to identify the processes controlling groundwater movement and quality, however, to date no integrated national spatial analysis of water-rock interactions has been conducted. As part of the Australian Government *Exploring for the Future* Program, this study aims to integrate geological and hydrogeochemical datasets to use water-rock interactions as a tool to identify groundwater system processes and predict groundwater composition and quality across Australia.

This study uses a new spatial analysis portal of Geoscience Australia to combine new national hydrogeochemistry datasets (Ried et al., 2019, Nation et al., 2019) with updated solid geology, cover material and mineral thermodynamics datasets to identify dominant water-rock interactions spatially. Additionally, machine learning was used for predictive modelling of rock geochemistry (Wilford et al., 2018) and integrated with hydrogeochemistry data for prediction of groundwater chemistry.

The results of this study show groundwater chemistry across Australia is largely controlled by water-rock interactions with solid geology and cover materials. Groundwater chemistry that does not reflect geology indicates groundwater flow-paths and system dynamics. The consistency of the Spatial and hydrogeochemical relationships between groundwater and geology show that water-rock interactions can be used to predict groundwater chemistry. Machine learning applied to detailed environmental datasets has been upscaled to predict geochemistry at a national level. Integrating this predicted geochemistry with water-rock interactions allows a

consistent approach for interpreting groundwater processes and predicting groundwater chemistry.

This study establishes continent-wide spatial relationships between chemistry of groundwater and rocks. This demonstrates the utility of nationally consistent datasets and hydrogeochemistry to understand groundwater system processes and predict groundwater composition and quality. The applications of this work include targeting groundwater sampling of existing bores, planning of new groundwater bores and geological sampling for geochemical endmembers to benefit community water supplies, mineral exploration and environmental monitoring.

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Can we use deep formation water in basalt for CO_2 disposal?

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The permanent disposal of CO_2 in the subsurface has been considered a viable mitigation option to reduce global warming. CO_2 is injected and permanently stored through different trapping mechanism in porous rocks at depths greater than 800 meters. Continental flood basalts are considered unconventional CO_2 storage reservoirs where interbedded massive basalt zones serve as barriers for upward CO_2 migration. However, vertical joints and sub-vertical fractures in those massive basalt zones may serve as conduits for buoyancy-driven CO_2 migration and thereby pose a risk to CO_2 containment. The objective of this study is to determine whether mineral precipitation will seal joints and fractures during the vertical migration of CO_2-enriched water and thereby contribute to CO_2 containment. Interactions of CO_2-enriched water with basalt powder, wafers, and artificially fractured core samples were studied in experiments at different temperature and pressure conditions representing various depths. At pressure and temperature conditions representing a depth of ≈800m only Mg, Fe and Si were mobilized presumably due to olivine dissolution while at conditions of ≈1200 m also Ca was released presumably from pyroxene dissolution. Smectites, zeolites, Fe-oxides, and magnesium-rich carbonate were observed as secondary minerals on the basalt wafers at conditions representing a depth of 800 m, which is in agreement with calculated mineral saturation indices. Precipitation exceeded dissolution by volume leading to a net porosity reduction by 1 % in incubations over 85 days. Our result suggests these secondary minerals could be potential sealants and mitigate CO_2 leakage pathways contributing to the containment of CO_2 in these particular formations.

Conceptualisation of groundwater systems in the Peel Region (WA) using multiple lines of evidence

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Water availability is a critical factor for effective and sustainable regional development; it underpins business development options and plays an important role in the viability of capital investments; the Peel Integrated Water Initiative (PIWI) is such an example, which is part of the Transform Peel Program. Two of the main PIWI objectives include a detailed characterisation of the hydrogeological setting and a spatially explicit groundwater resource assessment for the region. Geological and hydrogeological conceptualisation of the area was first done in late 2000, based on data from more than 4244 bores (from 5m to more than 800m depth).

However, given the abundance of data, the PIWI project illustrated how groundwater system conceptualisation can be notably altered based on repurposing available data; this was achieved by adopting new techniques to analyse existing large data sets, in addition to new data acquisition such as seismic and airborne electromagnetic (AEM) surveys, environmental tracers, and aquifer barometric efficiency. The new findings include:

- The 500 m wide Serpentine fault zone was characterised as a hydraulic boundary for the east–west groundwater flux. It separates the groundwater system into two markedly different sub-regions, with unique hydrogeochemical signatures, levels of confinement, and groundwater flux directions.
- A complex architecture of the groundwater system was identified in the eastern sub-region where spatially constrained sandy formations were mapped below 100m depth, which may form an aquifer.
- The three-dimensional lithological model developed within the project allowed a 3D representation of the aquifer's hydraulic properties (i.e. a 3D data cube).
- The conceptualisation of regional groundwater flow was re-evaluated due to discover of a saline wedge under the river channel, which forms one of the project area boundaries.

The results allowed to close previously identified knowledge gaps (fault existence) and unearthed previously unknown features (e.g. hydrogeological architecture of the eastern sub-region). The updated conceptual model reduces uncertainties in a decision-making process.

Hydrogeology of the Elang Copper Deposit, Sumbawa Island, Indonesia

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Studies have been undertaken to characterise site hydrogeological conditions in the context of the proposed development of a new mining project in a high rainfall environment.

The site is a copper-gold porphyry deposit that occurs within a north-east to north-north-east trending corridor of epithermal intrusives. The surrounding host rocks are of volcanic origin which have a massive, rather than bedded, structure. Both the intrusives and host rocks are of a fine-grained nature.

Core logging and packer testing has been undertaken in boreholes to evaluate hydrogeological conditions and estimate permeabilities at the site. The results of this testing indicate hydraulic conductivities across the various geological domains and at depths of more than 40-50 m were relatively consistent and generally low, ranging from 8 x 10^{-10} to 5 x 10^{-8} m/s. Airlift testing from open boreholes and wells indicate much higher (orders-of-magnitude higher) hydraulic conductivities in the shallower (less than 40-50 m depth) hydrogeological units. These units and local faults will provide the key preferential pathways for groundwater flows, as hydraulic gradients change during mine dewatering.

The local conceptual hydrogeological model comprises a shallow "active" groundwater system of weathered / altered rocks (Unit 1) that experiences high rates of rainfall recharge and is directly connected, and feeds, local river systems. Unit 1 is underlain by a deeper, less permeable and less active groundwater system (Unit 2). Both Units 1 and 2 comprise the same intrusive and volcanic host rock lithologies but are differentiated by the degree of alteration and fracturing, which are significantly higher in Unit 1. The results of hydrogeological borehole investigations, and observations of flowing (artesian) boreholes, suggest that deep, highly permeable faults are present and will likely provide key pathways for groundwater inflows to the pit once open pit mining progresses.

The results of baseflow analyses of local river flows and groundwater (numerical) model development and model calibrations indicate that groundwater recharge rates are high, and that the local groundwater system is highly connected to local rivers. Long term constant rate tests result in wells undertaken near pit boundaries and adjacent to rivers also reach the same conclusion, i.e. that the groundwater system and local rivers have high connectivity and will influence rates of pit inflow.

The study concludes that hydrogeological conditions at the proposed copper mine will be controlled by alteration and faulting, with connectivity to local rivers significantly influencing mine inflows.

Investigating the source waters of the Doongmabulla Spring Complex

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The Doongmabulla Springs Complex (DSC) is a collection of permanent freshwater springs that provide water to approximately 160 wetlands, which are ecologically significant and provide niche habitat for several threatened species (Fensham et al. 2016). Currently, the source of water to the DSC is uncertain, and with proposed developments within the vicinity of the springs, it is essential that the source waters of the DSC are properly examined. Alternative conceptual models have been presented for the source of the springs, and there is conjecture as to the contributions from the Triassic Clematis Formation and deeper Permian sediments; these being separated by the Triassic Rewan Formation, a regional aquitard that represents the base of the Great Artesian Basin (Habermehl and Lau 1997; CSIRO and Geoscience Australia 2019). This presentation describes efforts to collate available hydrochemical data and supplement this with additional measurements from a field sampling campaign to address knowledge gaps in the existing hydrochemistry dataset for the DSC and nearby sedimentary units. Statistical analyses, including Principal Components Analysis (PCA) and K-Nearest Neighbours Clustering (KNN), were applied to hydrochemical data for the DSC and the aquifers of the region. PCA suggested an overlap between the hydrochemical signatures of the water types of the region's aquifers and the DSC. Hydrochemical overlap can be indicative of inter-aquifer mixing, which may suggest connectivity between the Triassic and Permian aquifers. KNN, a supervised classification technique, provided an insight into the most likely source aquifer of individual springs of the DSC. These preliminary results shine new light on the statistical association between individual DSC springs and groundwater in Triassic and Permian aquifers. These findings highlight the importance of continued investigation of alternative conceptual models for the source of discharge to the DSC.

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Conjoint use of hydraulic head and groundwater age data to detect hydrogeologic barriers

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Hydraulic head and groundwater age data are effective in building groundwater system understanding. Yet their role in detecting and characterising near-vertical low-permeability geological structures—hydrogeologic barriers, such as faults and dykes—has not been widely studied. Here, numerical flow and transport models, using MODFLOW-NWT and MT3D-USGS, were developed with different hydrogeologic barrier configurations. Computed hydraulic head and groundwater age distributions were compared to those without a barrier. The joint use of these datasets helps in detecting vertically oriented hydrogeologic barriers for a range of hydrogeologic conditions. Two forms of recharge were compared: (1) applied across the whole aquifer (uniform); or (2) applied only to its upstream part (upgradient).

The hydraulic head distribution is significantly impacted by a barrier (with gaps) that penetrates the aquifer's full vertical thickness. This barrier type also perturbs the groundwater age distribution when upgradient recharge prevails. However, with uniform recharge, groundwater age is not successful in indicating the barrier's presence. When a barrier is buried, such as by younger sediment, hydraulic head data does not clearly identify the presence of a barrier. Groundwater age data could, on the other hand, prove to be useful if sampled at depth-specific intervals. These results are significant for the detection and characterisation of hydrogeologic barriers where they may play a significant role in the compartmentalisation of groundwater flow, spring dynamics, and drawdown and recovery associated with groundwater extraction.

Using appropriate methods to understand groundwater recharge: a case study in semi-arid areas

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Choosing appropriate recharge methods is important for understanding how groundwater recharge is impacted by successive land-use changes in semi-arid areas. This study examines two contrasting catchments in western Victoria, Australia, that were cleared following European settlement ~180 years ago, one of which was subsequently replanted with plantation eucalypt forest (~15 years ago). Both catchments comprise deeply weathered Devonian ignimbrite overlain by ferruginous duricrust and laterite regolith. Major ion geochemistry suggests that evapotranspiration is the dominant process controlling groundwater geochemistry. The 3H activities range from <0.02 to 4.10 TU and are generally lower than those of present-day rainfall (~2.8 TU) in this region. The 14C activities of dissolved inorganic carbon range from 70.7 to 103.6 (pMC) in the pasture and 29.5 to 100.8 (pMC) in

the forest. The spatial variation of 3H and 14C activities imply that groundwater flow is heterogeneous, present-day recharge occurs across both catchments and that mixing between younger and older groundwater has happened locally. The residence times of groundwater calculated using a variety of lumped parameter models and the 14C activities are up to 24,700 years. The typical recharge rates estimated from chloride mass balance are 0.2 to 8.8 mm/year, and 3H renewal rates are 0.01 to 8.0 mm/year; these are generally lower than those estimated from water table fluctuation (15 to 500 mm/year). However, the pre-land clearing recharge rates from chloride mass balance with longer residence times are typically consistent with short-lived 3H activities and annual 3H renewal rates, suggesting that water table fluctuation overestimates the annual to decadal groundwater recharge and most likely an inappropriate method to document groundwater recharge in semi-arid areas, where the recharge rates are generally low due to present-day distribution of rainfall over higher evapotranspiration that has been successively affected by land-use changes.

Understanding groundwater processes in New Zealand aquifers

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We use environmental isotope and chemical tracer tools to understand complex groundwater flow and evolution processes including nitrate contamination. Examples where these environmental tracers, in addition to conventional hydrologic investigations, have significantly improved the understanding of groundwater processes include:

- Nitrate contamination of groundwater and subsequent discharge into streams in the Horizons region
- Source and lag time of legacy nutrient loads and future loads in the lakes Rotorua and Taupo catchments
- Connection and disconnection of rivers and aquifers, groundwater recharge source, flow rates, and young water fractions with potential to carry live pathogens in the Heretaunga Plains aquifer
- Dynamics of the water movement through the entire catchment of the Wairau River, Marlborough, from rain, through the river catchment, and connection to Holocene and Pleistocene gravel aquifers

This summary aims to show where the combination of the age tracers, water and nitrate stable isotopes, gas tracers, nutrients and major ions enabled us to understand recharge source and rate, interaction between surface and groundwater, lag times, discharge pathways, and denitrification processes, in order to enable better management of groundwater problems and resources.

Groundwater Studies to Solve Geotechnical Issues

Groundwater studies to solve geotechnical problems

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Groundwater has the potential to result in significant geotechnical issues for development of infrastructure projects such as:

- Tailings dam embankments.
- Waste dump emplacements.
- Open cut and underground mining.
- Excavations/basements.
- Tunnelling.

The presence of water within a rock, engineered or residual soil excavation batter can have a detrimental effect on the stability of that structure. This is principally due to the action that increased or elevated pore water pressure can have on the strength of the rock or soil. Groundwater occurs within pores spaces, fractures, bedding plains and other discontinuities within the rock or soil where these features are below the saturated groundwater surface or water table.

The implications of increased pore water pressures in a batter slope can result in slope failure. In an open cut or underground mine operation, excavation, tailings dam embankment or waste dump, this can impact on geotechnical performance, having a financial impact on the project and more importantly create a safety threat for mine workers and the general public.

Hydrogeological studies are therefore intrinsic for addressing geotechnical issues relating to slope stability. A hydrogeological assessment must define the existing groundwater conditions, describe how groundwater can be managed to enable design to minimise slope stability issues, and provide a safe working environment.

Recognising the significance of groundwater in slope stability, investigative techniques applied to an open cut mining situation can include, but are not limited to;

- Investigation, measurement and monitoring of pore water pressures through monitoring bores or vibrating wire piezometers.
- Determining permeability of rock, structural features (faults, joints, or partings), and soil strata.
- Slope depressurisation options.
- Borehole drilling to identify depth, type of aquifer, and groundwater yields for dewatering options (pumping tests).
- Groundwater seepage/inflows to open pits.

How the results from these investigation methods allow for design of appropriate management systems are presented, showing how dewatering for slope depressurisation options can achieve acceptable outcomes for protecting the asset as well as the environment, and particularly human safety.

Aquifer drawdown and tunnel blast zone permeability changes in a basalt aquifer

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The Pacific Highway Upgrade between Tintenbar to Ewingsdale near Byron Bay, NSW includes a tunnel beneath St Helena Hill. The permanent tunnel lining was required to be impermeable to prevent dewatering of the surrounding groundwater system, which is located within a series of Neogene basalt lava flows. The tunnel extends through two primary geological units including weathered low to medium strength basalt and high to very high strength jointed basalt, with the latter being the most prevalent geology. Hydraulic testing of this geology indicated that the average percentile permeability approximated 4.3E-2 m/day for the medium strength rock and 1.0E^{-1} m/day for the high to very high strength rock.

Initial hydrogeological modelling was undertaken to assess the potential effect of changes in rock mass permeability due to blasting damage (i.e. within the "Excavation Disturbance Zone or EDZ"), the risk of exceedance of the specified groundwater drawdown criteria and whether post-excavation grouting would then be required.

Numerical simulations of blasting induced vibrations were used to estimate that the area inside the 750 mm/s peak particle velocity contour (extending approximately 0.7m beyond the tunnel excavation), would represent the zone where significant permeability changes could occur. A range of permeability changes were assessed in the modelling, which indicated that groundwater elevation changes were indeed sensitive to changes in the permeability of the EDZ.

To clarify the requirements for any remedial grouting, 21 shallow packer tests were completed behind the temporary shotcrete lining of the tunnel during construction.Â The post-excavation packer testing was compared with 93 pre-construction packer tests and a single "constant discharge" pumping test. Statistical analyses of these data indicated that the increase in permeability of the EDZ was less than 10 times pre-excavation permeability of the basalt rock mass. Revised hydrogeological modelling based on these measured permeability changes in the EDZ indicated that the risk of significant dewatering of the aquifer system was low and that remedial grouting would not be required.

This paper provides quantitative data on the impact of drill and blast excavation on the permeability of the EDZ; data on the link between blast velocities and permeability changes; and, demonstrates that shallow packer testing coupled with hydrogeological modelling can be used as a rational basis to decide whether remedial post-excavation grouting is required to meet tight groundwater drawdown criteria.

Predicting tunnel inflows - statistical models for Packer Test Information

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Inflows into deep rock tunnels are controlled by the highly variable nature of the fractures. The tunnel may be dry in most places, damp in others and subject to significant inflows at localized positions. It is likely that the highest inflow encountered along the tunnel comes from a fracture that was not encountered in the borehole investigation. Infrastructure projects in urban areas include water treatment and pumping facilities, which need to be designed and sized, despite the technical difficulties of predicting the total inflow.

The most common type of information that is provided to designers are the results of water pressure tests carried out between packers over various intervals in the boreholes, called "packer" or "Lugeon" tests. The packer test results are also dependent on the variable nature of the fractures and vary widely. There are some important pre-conditions for fitting packer test data to a distribution and these are described in the paper. Raymer (2001 and 2003) describes the analysis of packer test data, based on the assumption that the data is log-normally distributed and provides a methodology for predicting tunnel inflows.

It should be expected that a data set of 3m long packers should be able to be merged into a data set of 6m long packers without a change in the mean value. However, the log-normal distribution is not mathematically set up for such a transformation. Other authors have considered alternative distributions, and the paper reviews these alternatives.

This paper describes the possible choices of distributions for packer test data and using a large database of real packer test data, attempts to fit the variously proposed distributions. The paper reviews the results and discusses the possibilities - is there evidence that a different distribution is suitable or do the difficulties with the log-normal distribution result from an inherent issue within the problem. The paper provides conclusions and suggestions for further research.

Hydrogeological lessons learnt from major tunnelling projects in hard rock in Australia

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1. Jacobs, Melbourne, VIC, Australia

Groundwater processes are recognised as critical to design and construction of major tunnels. These issues have achieved prominence in many tunnelling projects due to mistakes in the past. The full range of groundwater investigation and analysis tools are now required to define impacts and to ensure safe and acceptable tunnelling projects. This talk will focus on groundwater fundamentals in tunnel investigations, analysis and modelling tools, design approaches and acceptable groundwater impacts, and control and mitigation strategies.

Determining the effective hydraulic conductivity along the tunnel continues to be a challenge as investigation methods (principally slug tests and packer tests) produce

widely varying results. Interpretation approaches of these test results (including from pumping tests) often produce very different answers. A suggested analysis approach is proposed. The determination of design groundwater levels requires the evaluation of extreme and long-term hydrogeological processes. These levels drive the design in many cases and even relatively small changes in levels have significant financial implications.

Analytical and numerical analysis methods are often hampered by a lack of data for the development of a good conceptual hydrogeological model. Nonetheless these methods are very useful for weighing up various options. The currency of numerical models during construction is often poor and regular updates of models are needed, although rarely undertaken. Calibration of numerical models against pumping tests continues to be a necessary evil, as frequently there are no alternatives to undertake a transient calibration. Grouting is both a fundamental design tool and a remedial measure. Grouting behaviour can also provide a fundamental investigation tool and predictor of groundwater impacts.

These approaches all lead to hydrogeological judgements which are based on science but heavily influenced by construction practices and operational functionality and the perception of what is an acceptable impact. A case study of Melbourne's City Link will illustrate the often-difficult decisions to be faced in the art of hydrogeology as applied to tunnelling.

Case study of groundwater inflow control into a basement excavation in a Fractured Rock Aquifer in Parramatta, NSW

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Groundwater flow through rocks is mainly governed by the fracture permeability, which is related to the nature, intensity and interconnectivity of the rock fractures. Excavations and underground openings in rock are frequently affected by the groundwater inflows that incurs heavy maintenance costs, delays in construction, threats to the natural groundwater resources and groundwater drawdown related risks.

A proposed multi-storey mixed use commercial and residential building at Parramatta NSW encountered significant groundwater inflow (approximately 12 L/s) during the excavation of the 24 m deep basement. The large inflow was due to sheared and crushed zones which is associated with faults and folds. Treatment and disposal of the encountered groundwater was not economically feasible. To address this issue, a grouting programme was employed to seal the rock fractures below the excavated depth. The grouting programme aimed to create a "grout curtain" to permanently reduce groundwater inflow into the basement excavation. The initial grouting stage targeted known sheared/crushed zones based on the assessment of available site investigations and mapping of the exposed rock faces in the excavation. This was followed by review of grouting records to identify deeper rock fractures and to inform the subsequent target grouting to help achieve an adequate grout curtain. This paper also discusses how the development of a new graphical tool help in identifying areas offering high potential for reduction in inflow. The method successfully achieved reduction of groundwater inflow by 85%. Post-construction back analysis of the grouting records also provided useful insight into the hydraulic properties of the fractured rock aquifer in Parramatta.

Horizontal drain design for slope drainage

Ross J. Best [1]

1. Geotechnics, Coffey Services Australia Pty Ltd, Sydney, NSW, Australia

Horizontal drains are widely used for control of pore pressure in slopes and retaining structures. Control of groundwater levels is a critical requirement for economic design

The design of these drains is typically guided by experience and observed performance. Design charts are available covering a range of conditions presented in the form of improvement in factor of safety for slopes. The paper presents relationships for design of drain spacing and length to achieve target pore pressures with a slope or behind a retaining structure. Analytical methods were used to develop the design relationships presented and comparison with published results are presented.

The need for monitoring to check performance is discussed.

Influence of groundwater on embankments, a mechanism for change and TSF management

Gideon G. Steyl [1]

1. ATC Williams, Brisbane, QLD, Australia

Tailings dam embankment stability has re-emerged as a critical issue in the operation and management of tailings storage facilities (TSF). In particular, Samarco (Morgenstern et al., 2016), Mount Polley (Morgenstern et al., 2015) and Cadia Valley (Jefferies et al., 2019). Due to increased production rates and cost efficiency drives, TSF numbers have followed suit. As a consequence, incidence rates and fatalities increased, but normalised rates of failure per ton tailings are steady (Penman and Williamson, 2001; WMTF, 2019). Placement and operation of TSF remain a key concern as it is expected that global demand for resource production will only increase.

The mechanism of failure is complex, but a critical component is related to pore water in the embankments and footprint, causing foundation failure. Mobilisation of the foundation, shearing and lateral displacement, results in loss of containment. Groundwater, permeability, and composition of the substrate are important factors that influence short and long-term performance of a TSF.

In this paper, the influence of groundwater on the residual strength of the material properties is presented. It will include the assessment of the substrate, TSF footprint, geology, design criteria, and final landform. An important factor that is commonly overlooked by TSF design efforts is the impact of chemical and physical properties of seepage, rainfall, and groundwater on TSF containment structures. Long-term stability, closure, and liability are highly dependent on these factors. Under operational conditions, groundwater and seepage pathways can influence stability criteria which are connected to the rate of rise, loading of the footprint, consolidation and pore pressure dissipation.

Research outcomes include impacts of groundwater and seepage on footprint placement, design criteria, management and embankment stability in the operational and long-term setting.

Use of geophysical techniques to investigate seepage around tailings dam embankments

Chris F. Taylor [1]

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Seepage contributed by groundwater can pose a major threat to the safe operation of tailings dams, with the potential to compromise stability of containment embankments if left undetected and unmanaged. Visual inspection and intrusive geotechnical investigation are commonly used to characterise such problems, however, often prove unreliable in identifying the source and extent of seepage flow paths, and any interaction with groundwater. Early identification is therefore critical to assessing the integrity of dam structures, with the use of geophysical surveys proving effective in achieving this outcome.

Geophysical techniques were utilised at two mine sites in Queensland to investigate areas of known seepage expression at tailings dam embankments. The purpose of the work was to compliment desk study analysis to gain an understanding of the seepage mechanism, which would in turn inform design of suitable groundwater management systems. Electrical resistivity (ER) and time domain electromagnetic (TDEM) methods were selected due to ease of use and rapid turnaround time for results. Both techniques produce a depth electrical profile of the conductivity of soil/rock for geotechnical interpretation and contrasting groundwater conductivity to signify preferred seepage pathways.

At the case study sites, the key objective was to assess the likely pathways of seepage, either through the embankment or via more permeable zones located within underlying aquifers. These works demonstrated the benefit of using geophysical methods to target known seepage issues and assisted in the siting and design of effective groundwater management systems for maintaining embankment integrity. It is concluded that for assessment of the post-construction performance of tailings dams, regular geophysical surveys could act as an early warning of any developing groundwater issues.

Hydrogeological assessments to support the design and groundwater impact assessments for drained motorway tunnels beneath Sydney, NSW Australia

Graham Hawkes [1]

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Increased traffic delays during peak commuter periods, combined with forecast population growth has resulted in the NSW Government upgrading Sydney's road network. Motorway tunnels are currently being constructed beneath the city to link major arterial roads to create an orbital road system and ease traffic congestion. Although the tunnels are to be constructed predominately as drained or un-tanked tunnels, grouting will be undertaken during construction to reduce groundwater inflows to maintain the operational inflows below the design criteria of 1L/sec/km. Ongoing passive groundwater inflow to the tunnels during the construction and operations phases will cause impacts to the local hydrogeological regime, including groundwater losses, groundwater drawdown, impacts to groundwater users and groundwater dependent ecosystems and potentially saltwater intrusion. The

palaeochannel aquifer, underlying some of the modern creeks are composed of unconsolidated sediments are hydraulically linked to the tunnels, and are also likely to be impacted.

Proposed tunnelling depths for the WestConnex projects including the M4 -East, New M5 and M4-M5 Link extend up to 80 metres below ground surface. To support the groundwater impact assessments geotechnical and hydrogeological field investigations included extensive drilling programs along the alignment, packer testing, construction of monitoring wells, groundwater level and quality monitoring and laboratory testing of core to measure permeability and porosity. Fully cored boreholes extend up to 100 metres depth. Baseline data was used to characterize groundwater and develop a hydrogeological conceptual model. This conceptual model formed the platform for a numerical groundwater model that simulated the hydrogeological conditions along the alignment and was used to predict potential groundwater impacts. At St Peters Interchange a cut-off wall was designed to reduce leachate generation by restricting groundwater inflow from the Botany Sands aquifer to the former Alexandria Landfill. The outcomes of the hydrogeological investigations were used to minimize groundwater impacts and develop mitigation measures.

Groundwater impacts assessment and minimisation for rail trenches in a sensitive location

Tony Cauchi [1]

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The objective of this project was to obtain environmental approvals to remove two level crossings via 'rail under road' (rail trench) construction methods. The Edithvale and Bonbeach project area is sensitive owing to a nearby Ramsar listed wetland, numerous beneficial uses of groundwater and its complex urban coastal setting.

In order to meet project timelines, a staged approach to groundwater impact assessment was required to identify and address the requirements of relevant state and commonwealth environmental approvals and relevant stakeholders. This involved:

- Preliminary conceptual and numerical modelling – which informed an Environmental Effects Statement (EES) *and EPBC Act (Environment Protection and Biodiversity Conservation Act 1999*) referral to the Victorian and Commonwealth Governments respectively.
- Site investigations – which informed the development of a regional numerical groundwater model, as well as risk and impacts assessment
- Modelling the water environment – which focussed on the numerical groundwater model, and included a saltwater intrusion model, wetland water balance model and analytical modelling
- Impacts assessment – which used the model predictions as a basis for assessing the relevant risks.

Data from the predictive modelling was used to assess potential impacts of the identified risks. Preliminary modelling indicated the potential for the projects to impact Edithvale Wetlands (Ramsar site), and an EES referral was developed in response to these predictions.

Site investigations progressed in advance of the EES referral outcome, in recognition of project timeframes. Detailed modelling indicated that based on the initial

assessment, groundwater level changes (either groundwater mounding or groundwater drawdown) could occur as a result of the tanked pile walls. Groundwater levels were predicted to increase on the up gradient (inland) side of the pile wall and decrease on the down gradient (coastal) side of the pile wall, as groundwater throughflow is impeded by the pile walls.

Because of the potential impacts identified in the initial assessment for Edithvale, modifications to the construction design were considered to minimise the impacts. Additional modelling was undertaken to assess the effectiveness of the design changes.

The assessment provided a detailed understanding of the project's potential hydrogeological impacts. The staged and collaborative approach adopted by the project team informed and involved relevant stakeholders and peer reviewers at each stage of the assessment. This achieved the benefit of harnessing the collective knowledge of experienced (technical and non-technical) project members, maximising multidisciplinary collaboration and achieving an outcome that informed the development of management measures within a robust Environmental Management

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Novel Investigation Techniques

Tidal subsurface analysis using Earth and atmospheric tides: a step forward in the characterisation of the subsurface

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The analysis of the groundwater response to naturally ubiquitous Earth and atmospheric tides (EAT) holds the potential to revolutionize groundwater characterisation. Management of this environment is often hampered by sparse hydrogeological data both temporally and spatially to enable reliable groundwater modelling. The sparsity or lack of measured key hydrogeological variables such as permeability or specific storage is often the result of cost, staff and time limitations associated with current investigative techniques (e.g. long-term aquifer tests). Traditional hydrogeological investigations assume that the matrix of an aquifer is rigid. However, in order to understand EAT influences on groundwater systems, a theory allowing the elastic deformation of both rocks and water must be invoked. Tidal subsurface analysis (TSA) methods are passive techniques which use standard piezometers and pressure transducers to capture the groundwater response to the naturally occurring astronomical and atmospheric forcing (produced by EAT's) to characterize the subsurface under the premise of *Poroelastic Theory*. They neither require active hydraulic testing nor bores designed for large groundwater pumps. As such TSA methods can use data from normal monitoring bores which will expand the number of field-determined hydrogeological variables in the subsurface by orders of magnitude. The method also has potential to be applied to long-term groundwater level timeseries so that the variability of hydrogeological parameters can be assessed against long-term groundwater trends (e.g. declining groundwater levels and subsidence). Finally, TSA is far less expensive and resource-intensive than hydraulic aquifer testing. TSA can be used to either complement or, with further development, replace current techniques altogether. With further development and industry adoption TSA methods could become a routine approach that can add enormous value to existing monitoring programs and represent a potential for a paradigm shift

in how we investigate and manage groundwater and subsurface resources globally, significantly exceeding our current capabilities.

Influence of automation methodology and fitting with error corrections in HydroRate

Gideon G. Steyl [1] , Matthew M. Nimmo [2]

1. ATC Williams, Brisbane, QLD, Australia
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The development of pump test methods is well documented, have extensive limitation and rely on a limited number of aquifer stress periods to evaluate the yield and stability of an aquifer. In some instances, major planning and implementation decisions are made on a handful of aquifer tests. The limitation of this approach is the intermingling of historical data with recent aquifer test data. The latter assumption is that the aquifer system is static in performance behaviour over an extended timeframe or that recent results are indicative of future performance.

Experience indicates that the stability of bore fields is not stationary. Bulk aquifer parameters can be influenced by several factors, which include the development of bore fields, mineralisation potential, saline intrusion, geological stability, and aquifer type.

In potable water supply for a regional council, the evolution of the water yield from abstraction points is a critical factor. The ability to track performance over time and react in a pro-active manner is of vital importance to maintaining regional development. In order to support the council, we applied HydroRate software, which automates the fitting and evaluation of multiple pump test results. It can implement a number of models in its assessment methodology, producing statistically relevant data for pump and recovery phases. The resultant data yields a higher confidence interval in the input parameters for planning and decision support systems.

The second feature of HydroRate is automated fitting of slug test data, although of lesser concern in large scale planning it can supply valuable information for contaminated land sites. It can evaluate over- and underdamped data with the evaluation of multiple permeability factors.

The paper will present data and analysis from two cases studies, which includes performance criteria and application results.

A revised packer test method for determining hydraulic conductivity

Stephen Parsons [1] , Jack Raymer

1. Jacobs Group (Australia), Melbourne, VIC, Australia

Hydrogeological investigations for tunnels and large excavations routinely use packer tests to estimate the large-scale hydraulic conductivity of the rock mass. The standard five-step method of testing is quite time consuming, which leads investigators to test selectively in order to complete the work within time and budget. In our experience, this is the wrong approach; we see much greater value in testing all the rock drilled, with only one step per test. We are proposing a change in how geotechnical investigations are conducted for rock-tunnel projects in order to provide results with more scientific and engineering value for less time and money.

These proposed changes are based on several thousand packer tests from over a dozen, hard-rock tunnel projects, both in Australia and in the United States. Many of these tests were run with five pressure steps, as described in Houlsby (1976) and many were run with only one step as advocated in this paper. The results are compared statistically, and no significant difference was found in how the large-scale hydraulic conductivity was interpreted; the main difference was that the five-step method required about four times the time and money as the one-step method.

In the proposed method, the entire relevant portion of each borehole is divided into stages of equal length (3 or 6 m are typical). No stages are skipped, no matter how solid the rock might appear. Each stage is tested using a single pressure step lasting about 10 minutes. Then the packers are moved to the next stage. The procedure and equipment are kept simple because, in over 90 percent of the tests, sophisticated methods and equipment are not needed. If an excessively high-taking stage is encountered, then there may be value in coming back to that stage later and using more sophisticated methods and equipment.

Tracking footprint of evapotranspiration in stream flow hydrographs

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1. School of Engineering, University of Waikato, Hamilton, New Zealand

Actual Evapotranspiration (AET) is at the core of the hydrological cycle. Developing accurate estimations of AET is therefore foundational to hydrological studies and the understanding and management of the hydrological cycle. Despite the importance of AET and accurate estimation, obtaining reliable values for AET remains a significant challenge for hydrological engineers. Theoretical methods often used to estimate AET, such as potential evapotranspiration (PET), have a wide range of uncertainties. Lysimeter remains the most accurate and direct AET measurement. However, it requires significant labour work and funding to establish and maintain; in addition, lysimeters only measure AET at the location of the lysimeter, and therefore the data requires modification to represent AET for the entire catchment area.

Our finding research at a small stream in Toenepi, New Zealand has demonstrated a clear difference in flow rates between day and night hours. Assuming an unchanging groundwater discharge for a daily period, the daily flow fluctuation measured should represent a difference in AET rate between day and night. While several studies have investigated diurnal-fluctuation of the water table (1–16) and soil moisture (17–20), streamflow daily-fluctuation has not received enough attention so far. To address these issues, we offer a new way to estimate a catchment average for AET that uses signal processing on the daily fluctuation of streamflow hydrograph during recession curves.

Depth-resolved groundwater chemistry by longitudinal sampling of ambient and pumped flows within long-screened and open borehole wells

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Groundwater chemistry samples are essential to many investigations. If a well intersects intervals with different concentrations, the pumped sample is a composite of the inflows, which mix in the well. Excessive mixing diminishes the value of samples and potentially gives misleading information. However, dedicated sampling installations at discrete depths (e.g. nested piezometers) are expensive so there is an incentive to make the most of existing infrastructure (e.g. supply wells) where possible. Despite potential complications, long screened or open borehole wells can provide valuable data and insight with a little extra work and appropriate methods. In particular, the resolution of groundwater chemistry derived from such wells can be improved by measuring and sampling the in-well vertical flow regimes in ambient (un-pumped) or/and pumped conditions. The head-driven ambient flow regime is shown to be particularly useful to sample groundwater native to defined inflow zones within the screen (head in the zone > head in the well), and avoid zones impacted by the invasion of intraborehole flow (head in the zone < head in the well). Longitudinal samples from specific depths in the well are interpreted as either native groundwater from a defined source, subject only to analytical error, or a mixture from multiple sources that can be deconvolved, incorporating error in both flow and concentration measurement. Depth-resolved age tracers (CFCs, Carbon-14 and He) in groundwater from three supply wells are verified with samples from a multi-depth nest of piezometers. Results show old groundwater at all depths and the simultaneous occurrence of young water at shallower depths, particularly near a watercourse, in undisturbed dual-porosity fractured aquifers in the Pilbara region of Western Australia. Although this approach does not completely replace the need for piezometers, it does provide valuable data and helps to minimise the expense and impact of additional drilling.

Infiltration characterisation of non-newtonian fluids through cold porous media for investigating remediation of adsorbed contaminants

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Non-Newtonian fluids such as biopolymers (e.g., Polyacrylamide solution) have been used for soil and groundwater remediation and fracking for enhanced oil recovery. While laboratory and field scale studies including modeling of non-Newtonian fluid flow in porous media as a remediation agent has been studied, but those have been limited to temperatures at or above 30°C. Little is known about the flow characteristics of biopolymer solutions through a porous medium, especially at the range of low temperatures that are experienced in cold regions. Hence, it is critical to understand the impact of temperature on the flow or rheology of non-Newtonian fluids in soils, because the adsorption kinetic of each contaminant is different. Once

the flow characteristic is understood, the effectiveness of non-Newtonian fluids in remediation of adsorbed contaminants can be assessed. Our hypothesis is that the difference in rheological characteristics between Newtonian and non-Newtonian fluids make the latter a better candidate for remediation of adsorbed contaminants from soils at different thermal regimes. We have investigated the rheological characteristics of non-Newtonian fluids in comparison to Newtonian fluids at 0.6°C, 5°C, 15°C, 19°C and 30.6°C to understand their strain, contact angle and viscosity changes at different stress and concentration levels. We used both Guar gum and Xanthan gum solutions as non-Newtonian fluids. OFITE model 900 viscometer and Tantec contact angle meter were used to record the changes in viscosity and contact angle for concentrations of 0.5g/l, 1g/l, 3g/l, 6g/l and 7g/l of the polymer solution. The range of shear rate applied varied from 17.02 s^{-1} to 1021.38 s^{-1}. Effect of salt on rheological characteristics were studied by separately adding NaCl (10g/l) and KCl (10g/l) to each polymer solution. It was observed that the sample solutions with high concentrations (3g/l, 6g/l, and 7g/l) behaved as non-Newtonian shear-thinning fluids. Shear thinning behaviour decreased with decrease in concentration. Currently, flow characteristic of Newtonian fluid and non-Newtonian fluids in a synthetic (glass-tube-bundle setup) porous media is being studied at temperatures of 5°C and 19°C. Through these experiments, the mobility and behaviour of non-Newtonian fluids under various thermal regimes will be characterized and its effectiveness in removing contaminants from porous media will be understood. Results of laboratory studies of rheological and flow characteristics of non-Newtonian fluids in synthetic porous media will be presented. The outcome of this research is expected to help design remediation of adsorbed contaminants in cold soils.

Integrating web and mobile applications for improved groundwater management in a developing world context

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Background: Groundwater managers, farmers and researchers face challenges regarding paucity of information, especially in a developing country context like Pakistan. Groundwater problems are characteristically complex and computational analyses can assist managers and farmers improve their understanding. Multiple activities such as groundwater modelling, economic modelling and spatial analyses are required to address problems faced by water resource managers, but most of the time such activities do not directly address immediate decision-making needs. For these needs to be effectively addressed, an easy-to-use platform is required capable of integrating science-based groundwater information with other socio-economic and physical data and processes.

Design and Methodology: A Decision Support System (DSS) is presented based on integrated assessment of hydrological modelling with socio-economic drivers for optimal decision making. The users of this 4-tier web and mobile based DSS can estimate crop water requirements, surface water deficiencies, groundwater status and profitability by comparing available cropping options. The DSS comprises client application, web server and graphical user interface, a modelling server which uses

built-in databases and models to generate location specific outputs such as crop water needs, shortfalls in surface water supply to be filled by groundwater, and alternate cropping options. Crop water needs are estimated by calculating actual evapotranspiration using weather data, and crop area. The economic suitability of different crops is assessed by calculating net return using crop yield statistics, market prices and production costs.

Original Data and Results: The web-based crop water requirement estimation tool and mobile application have been prepared and launched. Updated results from its use will be presented.

Conclusion: With ready access to updated information, water resource users and managers can make optimal decisions on using groundwater for agriculture. Since this DSS is constructed and applied using integration as a guiding principle, a more integrated approach to groundwater management can be pursued.

Note: This abstract is part of a series of presentations related to ACIAR LWR-036 project. Authors acknowledge the financial support of Australian Centre for International Agricultural Research (ACIAR).

SAR imagery applications to groundwater science in Australia

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Space borne radar imagery can be used for numerous applications in groundwater science: delimit sedimentary units and fault systems, map land cover and spatial patterns of aquifer recharge, or to monitor ground level and its relation to aquifer hydraulic pressure, compressibility, and thickness. Until recently, these techniques based on radar imagery were challenging to apply in Australia due to either the lack of radar imagery archives or to the difficulties in obtaining the archives when available. Since 2015, Sentinel-1 satellites are automatically acquiring images over Earth's landmass and (with constant acquisition geometry) at a 12 days frequency, unleashing an important potential of applications for Australia. In 2019, few years after the start of Sentinel-1 missions, large temporal stacks of archive radar imagery are available throughout Australia. In this presentation, I explain the principles of acquisition and processing of radar imagery and provide an overview of applications in Australia using recent Sentinel-1 data. I also illustrate the challenges that hydrogeologists might face while integrating this data into their work.

Radar Interferometry (InSAR) allows to derive ground level changes from radar image time-series. Over Perth basin and Murrumbidgee regions, trends in ground level changes (subsidence or uplift) are obtained from InSAR and show that significant groundwater storage changes have occurred during 2016-2019. In other areas, the interpretation of InSAR results is challenged by the important clay content of the surficial layers of soils, which induces large seasonal changes in ground level not attributable to groundwater storage. Using other information derived from the same radar imagery datasets, it is also possible to map and monitor Groundwater-Dependant Ecosystems (GDEs). In fact, the structural stability of vegetation (and resilience during droughts) can be inferred from radar imagery and used as a proxy for GDEs.

A novel PIV image processing method for the measurement of preferential flow velocity through rough-walled fractures

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Single phase flow in fractured rock is of great importance in different branches of porous media such as oil recovery and water resources management. Velocity field among the apertures is required for modelling and estimation of flow rates within the fracture area. Particle Image Velocimetry (PIV) technique is an efficient tool for analysing the velocity field and its distribution stemmed from the high velocity gradient caused by aperture variations. In this study, the fracture surfaces were generated using a 3D printing technology and moulded using the transparent epoxy resin to trace the preferential flow path and quantify the velocity field using a PIV camera. An experimental apparatus was designed by attaching a small constant head along flow path and then, the PIV-view software was used to measure the velocity vectors in the transient flow condition. To investigate the effect of fracture geometry on velocity distribution, several synthetic fracture surfaces based on different fractal dimensions and mismatch wavelengths were designed and placed with different inclination angles in the experimental set up. The average velocity of preferential flow path for different fractures were compared using an image processing technique indicating that the horizontal velocity increased near the small aperture whereas, the maximum value of the vertical velocity was observed near the large aperture. Moreover, the influence of fracture inclination angle on horizontal velocity field and number of thin preferential channels were significant.

Monitor more groundwater bore levels with cheaper sensors and cheaper Micro Satellite Telemetry and 10-year battery packs

Matt Saunders [1]

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Technology developments are allowing a much cheaper approach to monitoring the water levels in bore holes. These advancements mean that many more bore holes can be monitored, and more data can be collected and a better model of the groundwater in a region can be achieved.

In the past, the cost to monitor hundreds of bore holes in a region was prohibitive, and only a small number could be monitored, and the monitoring was usually based on installing data loggers in the field and leaving them to collect data and then visiting site to collect the data. These processes are time consuming and expensive and wide area bore hole level and conductivity monitoring was not attempted.

Today, there are good quality lower cost pressure and conductivity sensors available and when these sensors are used with ultra-low power data loggers and very low cost micro satellite telemetry and Lithium battery packs, a self-contained Bore hole monitoring system which measures levels every 8 hours and transmits that date once per day can operate on a lithium battery pack for more than 10 years.

Such an equipment configuration is a breakthrough for groundwater monitoring because monitoring on a wide scale can be set up and monitored from a web browser in an office, and not visited on a routine basis for 10 years, which is more than the effective life of most equipment.

This presentation details the components of such systems, their accuracy and their reliability and especially their cost point and the trade-offs to operate on a lithium battery pack for more than 10 years.

Emerging Challenges in Mining & Groundwater

Geotechnical impacts on connective fracturing heights above a coal longwall

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The importance of strata strength and defect density in estimating the height of the zone of reduced pore pressures associated with connected fractures above longwall panels has been identified by numerous researchers. In this paper we compile conceptual, empirical, physical and numerical data from Australia, America, England and China. Observations from this data on geological impacts on the zone of reduced pore pressures are compared. Based on a series of numerical models that simulate the physical experiments of Whittaker, we identify the height of bridging in the over burden and the height of connected fracturing. The observations and conclusions from this data review emphasise the importance of simulating site-specific strata when considering coal mining water impacts.

Securing a mine water supply in a challenging environment- Gippsland Basin, Victoria

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1. EMM Consulting, Adelaide, SA, Australia

EMM Consulting Pty Ltd (EMM) was engaged by Kalbar Resources Ltd (Kalbar) to undertake a groundwater impact assessment of the proposed Fingerboards Mineral Sands Project, located in the Gippsland Basin, Victoria. To support the assessment, a regional numerical groundwater model, supported by drilling and pumping test programs, was developed and used to predict impacts on the groundwater system during operation of the proposed mine, including water supply aspects.

Approximately 3 GL of water will be required on an annual basis for processing, dust suppression and rehabilitation. Water for the project will be sourced primarily from surface water (i.e. winter-fill license from the Mitchell River) and supplemented via groundwater sourced from the deep Latrobe Group Aquifer (from a bore field south of the project area).

The study has identified that groundwater drawdown impacts as a result of abstraction for water supply are likely to be low, as impacts are largely constrained

to the deep aquifer with only minor drawdown predicted within the overlying aquitard. Based on the impact assessment framework, predicted drawdown and mounding have insignificant impact on groundwater dependent ecosystems (GDEs), thus environmental risks associated with the proposed mine development are considered low.

For surface water supply, the Mitchell River winter-fill allocations may be utilised between 1 July and 31 October when river flows measured at the nearby Glenaladale gauge are greater than 1400 ML/day. River flows during the winter-fill period are below 1400 ML/day 20% of the time on average through the gauged flow record. While Kalbar intends to obtain a 3 GL/year winter-fill license, stream flow analysis shows that in four years since 1938, droughts would have reduced off-take availability to less than 1.5 GL/year. Relying on winter-fill alone would result in an unacceptably high probability that the mine would experience a process water shortfall of greater than 6 months duration at least once during the mine life, likely requiring mine idling.

Interannual storage of water to buffer dry spells may be needed, with managed aquifer recharge (MAR) potentially providing a mechanism for safely storing large volumes, replenishing an aquifer that has been heavily utilised by historical coal, oil and gas industries, with the potential to assist the surrounding irrigation and horticulture community during drought and low flow periods.

Overcoming groundwater scarcity to meet mine water supply requirements in Central NSW

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The proposed McPhillamys Gold Mine (the project) is located within the eastern Lachlan Fold Belt of Central New South Wales. The local geology is predominantly fractured rock with limited potential for groundwater development due primarily to low hydraulic conductivity and porosity. Although the low productivity of the groundwater sources limits potential impacts on groundwater receptors, this also adds additional pressure on securing a suitable water supply to meet mining and ore processing requirements.

The project water demand is expected to range from 13-16 ML/day for around a decade. Securing a reliable water supply is therefore a critical aspect of the project. Water captured on site (mine water inflows, rainfall and runoff in disturbed areas) will be the priority source of the project water requirements, including reuse of that water wherever possible.

EMM Consulting Pty Ltd (EMM) is assisting Regis Resources Ltd (Regis) with approvals for the project. To support the project, an options assessment was conducted to identify potential water supply sources which included diversion of wastewater from a wastewater treatment plant, diversion of surplus water from collieries within 100 km of the proposed mine, surface water extraction (unregulated rivers and regulated rivers) and the development of a groundwater bore field within an adjacent higher productivity aquifer. The assessment suggested the most favourable option is the diversion of surplus water from a colliery operation, where there are currently water quality and stream disposal constraints. In comparison to the other options assessed, this scenario has environmental benefits as it limits additional groundwater abstraction and surface water take within the region.

The collieries near Lithgow are currently discharging excess mine dewatering volumes to watercourses within the Sydney Basin. In addition, there are flooded workings at collieries currently under care and maintenance. Diverting this brackish water will enable reuse of surplus water that would otherwise require treatment before being discharged to the environment.

Aquifer recharge in a mining operations water management strategy

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Introduction: Mandalay Resources owns and operates the Costerfield antimony and gold underground mine in central Victoria. Mine dewatering is an essential part of safe underground mining practice, and all groundwater pumped from the mine must be managed on site. Expansion of the underground workings has resulted in an increase in dewatering rates and has led to investigation of alternative groundwater management options.

Extracted mine groundwater is currently used in mine operations and excess is managed through an evaporation facility and a reverse osmosis (RO) plant. The community was consulted to gauge support of the water management options available.

Discussion: Construction and operation of additional evaporation and storage facilities are expensive and long-term projects that may create negative impacts to the environment. The community determined this option to be the least preferred.

The RO plant is a high-cost and energy intensive process producing permeate and a brine by-product. The permeate is used onsite for dust suppression and excess may be discharged into a local waterway under EPA licence conditions or provided to local community for agricultural use. The community is supportive of the process but permeate production is limited by brine storage capability, which must be stored on surface, in lined dams.

Alternative water management options were investigated to supplement current methods to meet the expected increase in dewatering from mine expansion.

Aquifer recharge (AR) was investigated to return groundwater from mine dewatering back to its original source in the regional basement aquifer (RBA). The high salinity of the RBA limits the potential for current and future beneficial uses. Due to lack of porosity within the fractured rock, large geologic fault structures were targeted to increase permeability. The confined nature of the aquifer prevents contamination of any shallow alluvial aquifer (SAA).

A 90-day AR trial was completed, discharging a total of 76ML at a rate of 7-20 L/s over two injection bores. No seepage to surface was observed and surface water quality was not impacted. The trial confirmed the movement of recharge water towards the aquifer depression created by mine dewatering. Transport modelling indicates that feed water quality would be contained within a localised area surrounding each injection well.

Conclusion: The community are supportive of the AR scheme to return groundwater back to the aquifer previously depleted by mine dewatering activity and that any risk to the beneficial uses would be actively managed by the mine.

Quantifying surface water losses from mining-subsided catchments

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How do you quantify and predict surface water losses from catchments subsided by underground mining? This is a key question for Sydney drinking water supplies, managed by WaterNSW, and many other catchments around the world. The emerging answers are complex and multi-disciplinary.

Current practice in NSW is to predict surface water impacts using groundwater models, but these are limited to estimates of changes in baseflow to, or changes in leakage from, streams and storages. Recently, the Independent Expert Panel on Mining in the Catchment (IEPMC) used a new method analogous to baseflow separation analysis to estimate the volumes of mine inflows which can be correlated to more rapid travel of surface water to the mine void. This method is robust but doesn't account for the total surface water diversions.

Two alternative methods are currently being evaluated by WaterNSW. The "volume conservation" method combines volumes of mine voids, strata subsidence and volumes of groundwater pumped during mine operation to deduce the total volume of water that will ultimately be diverted from the surface. Estimating the distribution and rate of diversion can only be inferred indirectly however, e.g. from streamflow response.

The other alternative method recently investigated by the authors is to analyse the changes in pre- and post-mining measured streamflow's and to develop a relationship between these losses to the area of catchments undermined. This relationship can then be used to estimate the total diversion as a function of time. The two methods are complementary but independent, and the consistency found between results suggests the methods are useful for estimating the total diversion as a function of time. A preliminary study (Tammetta, 2018) presents an overview of the reliability and potential limitations of these methods for several mined catchments in NSW and suggests how future work might continue to refine and improve water loss estimates.

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Groundwater modelling around underground coal mines

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We showcase the tools and techniques used by CSIRO's Coal Mining Research Program to numerically model groundwater flows around underground coal mines. Results quantifying the height of connective fracturing and its upscaling into a mining-induced permeability enhancement are presented. These results depend on overburden lithology and stratigraphy as well as mining parameters such as cutting height. The permeability enhancements have a great impact on water inflows to the mine operations. In contrast to many other groundwater settings, unsaturated flow

is important around underground mines, and our open-source software package can simulate this efficiently. We present an example of a regional-scale groundwater model involving many mines that predicts impacts for centuries into the future.

Returning surplus water to ground for future beneficial use – an approach to leading practice mine water management in the Pilbara, Western Australia

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BHP has committed to a long-term goal of becoming a global leader in water stewardship. Western Australia Iron Ore (WAIO) has five mining operations in the Pilbara region of Western Australia. The volume of below water table ore mined by WAIO has increased and will continue to do so over the next 5 years. The volume of water required to dewater the below water table pits exceeds the local mine site demands for water, producing a surplus. The water is a precious resource and BHP's WAIO operations have a goal to "preserve surplus water for beneficial use, to the extent practicable". These 'beneficial uses" may include preserving social and cultural values, retaining environmental function, or future use of the water resource by BHP or other parties. BHP's primary way of achieving this goal is through Managed Aquifer Recharge (MAR) of surplus water.

WAIO has a number of MAR schemes at various stages of development. Juna Downs MAR scheme is a 20 ML/d system with injection into a shallow karstic dolomite aquifer up gradient from the Coondwanna Flats region (an area of ecological and cultural significance). Ninga MAR scheme is a 8 ML/d reinjection system with water directed into a fractured rock aquifer consisting of mineralised Marra Mamba Iron Formation and karstic Dolomite of the Paraburdoo Member of the Wittenoom Formation. The Ninga MAR scheme provides a storage of surplus water for future beneficial use. The Ophthalmia Dam MAR scheme is the first MAR scheme built in the Pilbara, and one of the earliest major MAR systems in Australia. It consists of a detention basin (the Dam) and recharge basins constructed in the shallow calcrete of the Fortescue River. The operation of the recharge basins returns water to the sensitive Ethel Gorge area, mitigating impact from dewatering from neighbouring operations and accelerating groundwater recovery in adjacent backfilled mine voids.

Regional application of hydrogeochemistry in northern Australia for new insights into mineral prospectivity

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The Northern Australia Hydrogeochemical Survey (NAHS), part of the *Exploring for the Future* Programme, has been investigating geochemical pathfinders for mapping components of mineral and energy systems within northern Australia.

A groundwater sampling program has been conducted thus far across the Lake Woods (35 locations), Tennant Creek (46 locations) and McArthur River (60 locations) regions. Analysis for a comprehensive suite of major and trace elements, stable isotopes and dissolved gases and organic species has been undertaken. The sampling sites were selected to ensure a regional coverage, utilising existing

domestic and pastoral pump infrastructure; where applicable, higher priority was given to bores proximal to basement geology. Results presented here reflect initial findings from the survey. Interpretation is focused on understanding water-rock interaction along the groundwater flow-paths to evaluate the presence or absence of critical mineral system components. In particular, indicators are sought identify enriched or depleted source rocks for metals, evidence for significant vertical fluid pathways providing a transport mechanism for metals; and the presence of evaporites, brines or dolomitic shales that act as traps for migrating fluids.

The major element chemistry across these surveys largely matches spatial trends in existing Northern Territory (NT) hydrochemistry datasets, and broadly reflects changes in solid geology and regolith across the NT [1]. Clear divisions can be seen in the water chemistry, such as sulfur and metal and REE concentrations, for instance between younger Georgina Basin sediments overlying Paleoproterozoic basement in Tennant Creek and the Meso- to Paleo-Proterozoic McArthur Group in McArthur River. We will expand on our understanding of key regional and local scale water-rock interactions in two ways: by understanding the mineral saturation indices and how these vary spatially; and by exploring the Pb-isotope signatures in relation to $^{87}Sr/^{86}Sr$ and $\delta^{34}S$ isotope systems and the trace element chemistry.

This regional approach of utilising hydrogeochemistry as a tool for understanding mineral system components will be further expanded as later NAHS groundwater surveys are incorporated. The NAHS is ongoing with additional sampling and analysis in the southwest McArthur Basin and South Nicholson Basin; to be released in 2020.

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Integrating surplus and potable water management in the Pilbara

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Although water has always been a huge part of BHP's governance, risk and operational practices, increasing pressures on water resources such as population, climate change, and how different areas of water management integrated within the business, was not clearly defined.

The long-term directional plan for future ore bodies to be mined within BHP Western Australian Iron Ore (WAIO) has indicated that there will be an increase in mine dewatering flows associated with a growing percentage of deposits situated below the water table. In Western Australia, the Department of Water and Environmental Regulation (DWER) has established a "hierarchy of controls" for Surplus Water Management within the mining Industry.

1. Mitigate - Impacts
2. Use Onsite – Processing, dust suppression
3. Transfer – To a 3rd party – beneficial use
4. Reinject – or infiltrate back into aquifer
5. Discharge

In line with this, and BHP's Water Stewardship Statement, WAIO has determined that infiltration, and Managed Aquifer Recharge Bores (MAR) are the preferred method of discharge of excess water at our operations, to minimise environmental impacts.

At WAIO we are required to manage operational water issues, such as dewatering/discharge and process water supply, as well as provide safe and clean drinking water to our mines, towns and mining residential camps that support these operations. As mining operations expand and potential excess water discharge locations expand, there's the potential for surplus discharge schemes to interact with drinking water supply bore fields. A Surplus Water Operationalisation program was undertaken to help address this issue.

The Surplus Water Operationalisation program was developed to ensure that as assets are being planned and developed, accountabilities, operational controls within a detailed management system, to ensure an operational model with appropriate controls are implemented to manage environment, regulatory, operational, and maintenance risks, and interconnectivity with potable water sources.

An approach to development of monitoring triggers at mine sites

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Development of appropriate site-specific triggers form part of proactive site management and provides a means of reviewing and assessing monitoring data to manage the impact of site activities that may impact on groundwater quality and levels. The proposed approach highlights essential steps employed to assess groundwater quality and to define groundwater triggers. Effective assessment of the impact on groundwater quality allows future management decision and development of mitigation measures.

It is important to have a good understanding of the conceptual hydrogeological site model. Potential sources associated with the site activities should be identified for both inactive and operating facilities. Potential pathways from the various sources should be identified with consideration of local hydrogeological conditions. Potential receptors typically include third-party bores and surface water features. The source(s), pathway(s) and receptors should be qualitatively and quantitatively characterised.

The next step in trigger development is to statistically evaluate the monitoring data. This step interrogates the data and identifies outliers or trends that can be removed from the data set. A number of site-specific conditions should be considered, for example, the location of the monitoring bores, geographic position in terms of the potential sources on site, potential groundwater migration and location of the potential impact to the receiving environment.

Compliance bores are intended to be monitored and assessed against site-specific trigger values, while diagnostic bores are used to collect information to inform the mine about the trigger limits of different facilities on site. Groundwater trigger limits are frequently used to inform the groundwater management plan and assesses the groundwater quality and groundwater levels at an operation for both compliance and diagnostic purposes. Trigger values should be fit for the purpose but also conservative enough that they provide an early warning of emerging potential impact

on the quality of groundwater. If triggers and limits are set too low, natural variability can be mistaken for site impact on groundwater.

Regional Scale Studies

Nested groundwater flow simulated through a fully coupled modelling approach

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The water table is often found to be a subdued form of topography. This undulating water table can result in nested (local, intermediate and regional) groundwater flow systems (Tóth, 1963). The existence of this nested groundwater flow phenomenon was largely derived from analytical and numerical solutions in which the undulating water table was treated as a fixed upper hydraulic head boundary condition. Although this phenomenon has been widely accepted, the appropriateness of using a spatially varying hydraulic head as the top boundary condition in previous studies has not been assessed. In this study, we use the physically based, spatially distributed hydrological simulator HydroGeoSphere to investigate this issue. HydroGeoSphere allows us to relax boundary conditions and to simulate coupled surface water and groundwater flow. Two classic regional flow models introduced by Tóth (1963) were adapted to perform numerical simulations. Two different hydrologic regimes representing semi-arid and humid regions were employed as contrasting settings. We first ran the two models by using the hydraulic head from Tóth (1963) as the boundary condition (i.e., a pure groundwater process). The results show that extremely large, physically implausible, spatially varying groundwater recharge fluxes are required in high-elevation areas for consistency with the hydraulic head boundary applied in the original Tóth (1963) models. These recharge fluxes exceed reasonable precipitation rates. In the second set of models, we let flow systems generate themselves naturally. We did this by simulating surface flow and groundwater flow in a fully coupled hydrological process. The top boundary was driven by reasonable and physically based precipitation and potential evapotranspiration. The results show an undulating water table and that nested groundwater flow develops in low-elevation areas but that a relatively flat-water table and exclusively regional flow occurs at high-elevation areas. Overall, this study demonstrates the critical role boundary conditions play in the development of nested flow systems.

Underground technologies pre-feasibility study: sand dam and sub-surface dam potential in Queensland

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The Queensland Bulk Water Opportunities Statement provided a framework for sustainable, regional economic development through better use of existing water infrastructure and appropriate investment in new infrastructure. An initiative from the statement was the need to consider alternative technologies and approaches to traditional bulk water supply infrastructure. Alternative technologies include several underground technologies, more commonly referred to as Managed Aquifer Recharge. The Underground Technologies project focused on mapping the prefeasibility potential of alluvial areas in Queensland for creating augmented groundwater storages using sand dams and sub-surface dams.

Previous sand dam and sub-surface dam site assessments involve multi-stage, multi-component analysis utilising Geographical Information Systems that are variants of Preference Ranking Organization Method for Enrichment Evaluations methods and follow a Multi-Criteria Decision-Making process. These methodologies are customised for drainage sub-catchment scale assessments and are reliant on detailed mapping and high-resolution data. Previous methodologies are not suited to multi-drainage catchment scale investigations due a lack of detailed mapping data, differences in data resolution and incomplete spatial data coverage.

A modified methodology was developed to address limitations associated with the multi-drainage catchment scale investigation. Publically available datasets were assessed for suitability. Attribute data in each dataset was characterised, classified and ranked. These datasets were then ordered, overlaid and processed in ArcGIS to integrate and classify attribute combinations to indicate prefeasibility potential.

The sand dam and sub-surface dam prefeasibility mapping products including GIS datasets, are the key outputs from the Underground Technologies Prefeasibility Study. The mapping products are designed to display the relative state-wide potential for developing sand dams or sub-surface dams to augment groundwater supplies in alluvial sediment areas. Based on the assessment criteria, target areas are ranked to display their potential to host sites for sand dam or sub-surface dam development. The mapping products are designed to provide a guide for prioritising more detailed feasibility studies.

Chasing helium: Mantle-to-Surface connections to water quality and Geomicrobiology

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Objectives: The discovery of oceanic black (and white) smokers revolutionized our understanding of mid-ocean ridges and led to the recognition of new organisms and ecosystems resulting from mixing of fluids. Continental smokers, defined here to include a broad range of carbonic springs, hot springs, and fumaroles that vent

mantle-derived fluids in continental settings, exhibit many of the same processes of heat and mass transfer and ecosystem niche differentiation.

Design and Methodology: The application of noble gas geochemistry (specifically helium isotope ($^3He/^4He$) analyses) indicates widespread mantle degassing in perhaps unexpected tectonic locales: including the western U.S.A., Great Artesian basin of Australia, Western Desert of Egypt, and the Tibetan Plateau (Crossey et al., 2013 and 2016; Karlstrom et al., 2013).

Original data and results: Our work shows that variations in the mantle helium component measured in groundwaters correlate best with low seismic-velocity domains in the upper mantle and with abrupt lateral contrasts in mantle velocity rather than crustal parameters such as strain rate, proximity to volcanoes, crustal velocity, or composition. Microbial community analyses applied to several of these areas indicate that these springs can host novel microorganisms. Our work yielded the first published occurrence of chemolithoautotrophic Zetaproteobacteria in a continental setting (Crossey et al., 2016; Love et al., 2017).

Conclusion: These observations lead to two linked hypotheses. 1) that mantle-derived volatiles transit through conduits in extending continental lithosphere preferentially above and at the edges of mantle low velocity domains. 2) Elevated concentrations of CO_2 and other constituents ultimately derived from mantle volatiles drive water–rock interactions and heterogeneous fluid mixing that help structure diverse and distinctive microbial communities. This recognition of the small volume but chemically potent "lower world" contributions to groundwater systems has implications for topics as diverse as tectonics, fluid conduits, water quality, and microbial ecosystems.

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Integrated modelling using MIKE SHE for water resources assessment in the Northwest Region of Bangladesh

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In Bangladesh, about 95% of the total irrigation demand is fulfilled by small-scale irrigation. The availability of surface water resource is decreasing day by day during the dry season but the demand for irrigation is increasing and pressure is growing towards the groundwater resources in recent years. Groundwater resource is declining due to increase use of tube wells for irrigation, rapid urbanization and industrialization. Groundwater recharge that occurs during monsoon rainfall and flooding has been reduced drastically mainly because of climate change impact and unplanned paving. On the other hand, demand is increasing day by day. In this situation, appropriate and organized approach should be maintained for assessment and utilization of this limited groundwater resource to ensure environmental sustainability with fulfilling people's demand. This study attempts to investigate flow dynamics and assess the groundwater resource in the northwest region of Bangladesh. We developed MIKE SHE groundwater models for the region that were calibrated and validated with the observed groundwater level data. The model also incorporated simulation of the unsaturated zone and river flow processes using associate MIKE suite of software. In this way, emphasis was given to encapsulate the SW and GW flow dynamics in the river basin. Two scenarios were considered 1) to assess the base conditions of current water balance and existing trends of fluctuation throughout the year and 2) long-term effects of probable future abstraction and climate change impact. A comprehensive water balance analysis has also been undertaken to assess local scale groundwater recharge dynamics and interactions between surface water and groundwater.

Paired use of low-fidelity surrogate models with integrated water resources system simulators for predictive analysis of water balance and climate impacts

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Coupled surface water - groundwater interaction models are ideally the best choice of models to simulate complex hydrological processes in regional river basins. Such fully integrated models are less tenable with comprehensive parameter sensitivity and non-linear prediction uncertainty analysis workflows that require numerous runs of the simulation model. This limits the application of these models in practical decision-making contexts where reliability of the predictions is important. We proposed to overcome this limitation by the paired use of an approximate and fast-running surrogate model constrained by the quantitative and qualitative knowledge

of process details from the complex model. While the complex model focuses on process dynamics as much possible as underpinned by available data, the surrogate model is purpose-built for the predictions of interest with approximation of the system dynamics and scale supported by parameterisation schemes that are suitable for predictions of interest. We used a low-fidelity MODFLOW model together with a complex MIKE SHE model built for the North West Bangladesh region to assess district scale water balance and climate change impacts on future water balance. The MIKE SHE model is underpinned by detailed conceptualization of the alluvial aquifer and channel bathymetry, simulation of the catchment processes and flow routing by the MIKE 11 routine and calibrated to observed water levels and flow data. Each model run takes several hours to complete one simulation. The MODFLOW model approximates the process details with appropriate upscaling of parameters and was subjected to calibration and uncertainty using the PEST suite to simultaneously improve the match to observed water levels and to maintain district-scale water balance comparable with the complex model. The fast running (less than 2 minutes) surrogate MODFLOW model was then used in the scenario analysis for climate change impacts. The results indicated that the surrogate MODFLOW model simulation is able to achieve matches to the observed water levels that are comparable to the complex model simulation in majority of the locations across the region. The simplified and up scaled parameterization scheme of the MODFLOW model enabled computationally efficient uncertainty analysis of climate change impacts on district scale water balance. The study indicated that low-fidelity surrogate models developed for specific objectives can be useful when used in conjunction with complex models that can simulate complex SW - GW interaction processes. This study was undertaken as part of an Australian Government initiative to increase water and food security in Asia.

Assessing the groundwater quality of the coastal aquifers of a vulnerable delta: A case study of the Sundarban Biosphere Reserve, India

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Introduction: The Sundarban Biosphere Reserve (SBR) of India lies in the southwestern part of the Ganges delta. The SBR, suffers from the scarcity of fresh water as the rivers in SBR are saline and shallow groundwater is brackish in nature. Fresh ground water is only available from the deep confined aquifers and not easily accessible.

Objective: The 4.43 million strong population in the SBR depend fully on deep groundwater to meet their drinking water demand. It is, therefore, necessary to assess the quality of this groundwater to fulfil the sustainable development goal.

Methodology: The water quality index (WQI) has been estimated for shallow and deep aquifers based on water quality parameters like pH, TDS, EC, Cl, SO4, HCO3, TH, Ca, Mg and Na. Hydrological facies of the shallow and deep water samples have been identified using the Piper trilinear diagram. The Cl/HCO3 ratio has been calculated to study saline water intrusion in the coastal aquifer of the SBR.

Result: The groundwater in the SBR region belongs to NaHCO3, MgHCO3, NaCl and mixed type hydro-geochemical facies. The dominant cations are found in the order Na>Mg>Ca, and dominant anions in the order HCO3>Cl>SO4. The Cl/HCO3 ratio indicates that the shallow aquifers in the SBR are affected by the saline water

intrusion. Following the limit set by the Bureau of Indian Standards, the shallow groundwater in the SBR is found to be unsuitable for drinking. Although the deep groundwater is within the permissible limit of safe drinking water, its quality is poor.

Conclusion: To meet the goal of sustainable development and safe drinking water for all in future, extensive rainwater harvesting and supply of treated surface water through pipeline and desalination of subsurface brackish water are some of the feasible options in the region.

Characterisation of a Regional Aquifer System using 3D modelling: new insights to the geology and hydrogeology of the Great Barrier Reef Catchment, Australia

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Characterization of regional aquifer systems has historically been a challenge because of the heterogeneous nature of geology, high costs of gathering high spatial resolution subsurface geological data and large computational processing demands. However, the growing datasets of subsurface properties together with the development of numerical models to further constrain subsurface geology and aquifer characteristics has enabled increasingly accurate representations. In this study, we constructed 3D geological models of six regions of the Great Barrier Reef (GBR) catchment system to identify the type and number of aquifers, evaluate the geometries of the aquifer systems, and to conceptualize groundwater flow directions within the catchment. To do this, we combine surface geology, geological contacts and faults, digital elevation model and drill log data from >49,000 wells. 3D geological models integrated with potentiometric surface maps and faults data revealed that the Wet Tropics, Mackay and Burdekin regions have fractured and porous unconfined aquifer systems, while the Cape York, Fitzroy and Burnett regions have both fractured, porous unconfined and confined aquifers. The size and volume of the aquifers differed due to the differences in geologic histories and ongoing processes. The thickest upper aquifer was identified in the Fitzroy region (average 250 m) followed by Burnett (166 m), while the shallowest upper aquifers exist in the highly deformed regions of the Burdekin (average 67 m) and Mackay (60 m). The orientations of the faults trend in the NW-SE direction and could form conduits for south-easterly groundwater flow as opposed to the predominate easterly flow in the porous unconfined and confined aquifers. The 3D models, aquifer connectivities and geometries can be used as inputs for any local and regional groundwater flow simulations and accurate characterizations of non-point pollution sources in the area. The models also provide crucial information to determine sustainable yields, development potentials, and to evaluate sensitive groundwater areas.

The Far North Prescribed Wells Area groundwater model

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Groundwater in the Far North of South Australia is important for the success of the mining, petroleum, pastoral and tourism industries, and the provision of community water supplies. The continued success and expansion of these industries is dependent on balancing the needs of existing users and the environment. Of particular importance are the spring wetland communities in the discharge areas of the Great Artesian Basin (GAB).

Recent investigations focused on the western margin of the GAB indicate long-term (natural) pressure declines and may be in permanent transience. Additionally, ongoing research and data collation has improved our understanding of the complex hydrostratigraphy and hydrodynamics of the region. This improved characterisation of the groundwater system provides a basis for the ongoing management of extraction to ensure aquifer pressure reductions are within acceptable limits at defined management boundaries.

With demand expected to grow, particularly in the mining and petroleum industries, the development of a new numerical groundwater model is required to test current knowledge and determine key knowledge gaps. This model is also required as a tool to inform ongoing management of groundwater resources within the main GAB aquifer and for future assessment of resource allocations for major developments.

This presentation provides a brief overview of work currently being undertaken by the Government of South Australia and partners developing a conceptual groundwater model for the Far North of South Australia prior to the construction of a numerical groundwater model. The resultant numerical groundwater model will be primarily designed to assess changes in aquifer pressures due to: (i) extraction by existing users at full allocation according to regulatory guidelines, and (ii) an increase of co-produced water extraction. Changes in aquifer pressure may impact spring wetland communities (where dependent or partly dependent on groundwater), existing users and management boundaries.

Australian continental hydrogeochemistry: providing baselines for lithology mapping, health, agriculture and opening new areas for mineral exploration

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With high signal-to-noise, groundwater chemistry is a useful medium for geological sensing and mineral exploration in specific environments. Additionally, they are sensitive to faults and other geological structures. Hydrogeochemistry may also add

value to mineral exploration where prospective rocks are covered within basin margins.

Uptake of this technology is being encouraged through the development of a robust and cost-effective methodology with field guides, notebooks, and field apps. Site studies have tested hydrogeochemical responses to mineralisation, and sensitivity and normalisation of sampling methods.

CSIRO has obtained publicly available groundwater databases and processed them using robust QA/QC measures to develop 'seamless' data across Australia. Datasets include anything from single salinity measurements up to 60+ elements per sample. This data has now been combined with datasets from Geoscience Australia and launched on the Bureau of Meteorology Explorer portal.

At the Terrane scale, specific indices can delineate large scale lithologies and major mineral camps. Other large systems, such as IOCG's or Cu Porphyries may also be observable. At the Prospect scale, indicator elements (e.g., Au, Ni, Cu, Zn, W, As) are commonly valuable, with commodity indices developed for smaller targets such as Ni or VHMS.

In many areas across inland Australia, groundwater is commonly used by humans and livestock for consumption. Mapping of health sensitive solutes such as nitrate can inform water usage and treatment requirements.

Thus, hydrogeochemistry can positively assist exploration at varying scales, and now it has been combined and is publicly available, provide baseline chemical data for human and agricultural health.

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Groundwater in the Resources Sector / Alluvial Systems & Vadose Zone Hydrogeology

Instrumented column testing and numerical modelling of evaporation induced salt accumulation and precipitation from underlying bauxite residue to soil cover under natural weather conditions

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The best cover design for mine rehabilitation is to effectively minimise the salt uptake from mine tailings from uplifting by evaporation, so that the cover can provide healthy accommodation for vegetation. An instrumented column was constructed to test the evaporation-driven uptake of salts from compacted red mud into an overlying cover material. The PVC column is 1.2 m in length, with a 200 mm internal diameter. The top 0.6 m was filled by compacted bauxite residue with a salinity of 35 part per thousand (PPT) and the top 0.6m was covered by sandy loam material. The column was instrumented with 10 of each of moisture, suction, salinity and temperature sensors, designed and manufactured in-house at The University of Queensland (UQ). The instrumented and filled column was installed on a building roof at UQ, alongside weather stations, and was subjected to the prevailing weather conditions for two years. Numerical modelling was carried out to simulate the evapo-concentration and precipitation, and associated transport of liquid water, water vapour, salt and heat. Both the modelling and column testing results indicate when water table could be maintained in the cover material, the water table acts as a barrier layer to prevent salt uptake during evaporation. However, if water table fell in to the bauxite result, the salt in the tailings would eventually transport to the cover and deteriorate the pore water quality in the cover material. This testing and modelling results provide key physical insight on salt dynamics in the unsaturated zone and cover design criteria.

From fact to legend to fact – alluvial sedimentation in Magela Creek, Northern Territory

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The Ranger Uranium Mine lies within Kakadu National Park in the Northern Territory, Australia. Mining commenced in 1980 and the mine area is must be rehabilitated by 2026, with the hope that it can eventually be incorporated back into Kakadu National Park.

Flowing along the north-eastern side of the mine is Magela Creek whose headwaters are in the Arnhem Land escarpment and flow through Mudginberri Billabong and Magela floodplain to discharge into the East Alligator River.

Currently the alluvial thickness in Magela Creek is generally thought to be 10-12 metres. However, investigation drilling and geophysical surveys from the early 1980's indicated that the bedrock in Magela Creek is some 60 metres below the

surface. Since the early 1980s there have been many papers and reports written that provide a confusing picture for these sediment elements of Magela Creek. Much of this confusion is around the relative thickness and distribution of the Holocene and Pleistocene sediments, their lack of discrimination, the different foci of the various studies and the methodologies used.

Associated with this change in interpretation of alluvial thickness, work done in the early 1990s indicated that the current day creeks flowing into Magela Creek were originally several metres above Magela Creek i.e. were waterfalls. Investigation of the logs from nearly 200 boreholes associated with Magela Creek show a number of areas where depth to bedrock is significantly greater than surrounding areas supporting such a concept. If correct, the interpretation of a Magela Scarp (or Magela Fault), often discussed in the late 1970s and early 1980s work but since discounted may in fact also be correct.

This paper, using Magela Creek as an example, explores how historical data, knowledge and information can be misplaced and lost and misinterpretation of more recent information can become accepted as fact.

The application of horizontal dewatering in the Pilbara – The Solomon Trial

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1. Fortescue Metals Group, East Perth, WA, Australia

Fortescue Metals Group (FMG)'s Solomon Hub has a large Channel Iron Deposit (CID) that makes up most of the resource of the mine. This CID is in hydrogeological terms a palaeochannel and the ore body is the primary aquifer, hosted within low permeability bedrock. The dewatering approach using standard industry practice is to install multiple vertical production bores in the centre of the channel. This approach results in a large amount of in-pit infrastructure, which results in added complexity in the mine design with the need to allow for infrastructure corridors. The traditional approach also means that there are significant people movements in the mining area and the in-pit infrastructure is susceptible to damage by mining activities, such as blasting. Horizontal directional dewatering (HDD) is a valuable tool that borrows on technology developed in the oil and gas industry to enable dewatering infrastructure to be removed from the active pit area.

FMG has successfully constructed and developed a 1 km horizontal dewatering bore at the Solomon deposit. This success is the result of several years of evaluation work involving conceptualisation, modelling and mine planning. Critical elements of the work have included quantifying vertical permeability, assessing potential head losses due to turbulent flow, constructing a bore with suitable materials and sufficient open area and ultimately establishing the standoff distance to minimise disturbance. The resulting production bore is the first know application of HDD technology in Australian mining and should ultimately form an integral component of the mine dewatering scheme.

Gaining the approval by senior management within FMG to undertake the trial completion of an HDD dewatering bore highlights the potential significance and application of the technology. Whilst every potential application will ultimately need to assess the specific hydrogeological setting and constraints, the inclusion of Horizontal dewatering represents another valuable option in open pit mine water management.

Subsurface pressure waves: A kinematic explanation to rapid vadose-zone water movement to alluvial systems

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Rapid responses in wells and streams following rainfall is often attributed to macropore or bypass flow through the unsaturated zone. Yet, paradoxically, these waters are often "old" in the sense that their subsurface residence time (or age) is on the order of months or years. An alternative explanation for this so-called "Old-water, New-water Paradox" is that pressure waves propagate rapidly through unsaturated media. Laboratory and field experiments are presented to illustrate this mechanism. We then show that observed responses are not appropriate for estimating flux and fluid travel times.

WOMBAT (Water Optimisation Modelling Business Analysis Tool)

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3. Hydrogeology and Modelling, Rio Tinto, Perth, WA, Australia

The Water Optimisation Modelling Business Analysis Tool (WOMBAT) is an online software platform that integrates information and workflows relating to the management of mine water across Rio Tinto's mine sites. WOMBAT came about due to the requirement of the Water Resource - Orebody Knowledge & Planning (WRES-OKP) of Rio Tinto Iron Ore for a strategic methodology to effectively inform Rio Tinto's stakeholders of the dewatering requirements for the below water table (BWT) resources. WOMBAT addresses efficient integration, assessment and analysis of dewatering planning and operations by bringing mine planning information, numerical models and workflows into a single digital platform focused on improving operational planning and reconciliation.

WOMBAT was implemented in a series of phases which involved capturing Rio Tinto's workflows linked to various stakeholders including Mine Planners, Hydrogeologists, Groundwater modellers and Hydrogeology & data superintendents and principles. WOMBAT supports high level water strategy monitoring and planning by providing centralised volume data for tonnage and dewatering across all mine sites, deposits and dewatering models and is used for preliminary dewatering volume forecasting based on wet tonnage and ore body type.

WOMBAT enables the implementation of robust and timely PDAC (plan-do-check-adjust) management approach with the aim of reducing operating cost, optimizing capital deployment strategies, mitigating mining risks and providing a single point of truth for decision making. Planning is improved by integrating mine plans with groundwater models for short to medium term forecasting. It also provides facilitates the centralised management and archiving of mathematical groundwater models as well as of mine plans and mine schedules.

Predicting baseflow provenance: the use of tritium to quantify groundwater discharge to streams

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The short half-life of tritium (12.7 years) means the signal due to production from nuclear bomb testing in the 1950s and 1960s has essentially been lost from the atmosphere but can still be seen in young (<60 year) groundwater and provides a tracer of groundwater contribution to stream baseflow in shallow, active systems. Back calculating the mean age of baseflow in stream samples, combined with knowledge of aquifer hydraulic parameters provides a means of assessing the relative contribution of different source areas and the likely distance of provenance. This can aid in the conceptualization of groundwater-surface water systems and provides constraints on relative contributions of groundwater sources to surface water systems.

We have used tritium measurements in surface and groundwater samples across the Upper Waikato region of New Zealand to assess relative contributions of shallow and deep groundwater sources and the potential zones of contribution and to test conceptualisations of nutrient pathways and attenuation. Mean groundwater ages were calculated using known tritium decay curves for New Zealand and the USGS software package TracerLPM, comparing piston flow models with exponential mixing models to assess the most likely age distribution. This was carried out for both groundwater and surface water (baseflow) samples. A range in flow distances were then calculated to provide indicative travel paths and for comparison of data from bores on expected flow transects.

The results provided additional evidence that the surface waters are supplied predominantly by shallow, relatively fast-moving groundwater in this area and deeper groundwater is unlikely to provide a significant contribution to baseflow in this part of the catchment. This analysis lends support to nitrate attenuation estimations that suggests nitrate transport to streams is dominated by shallow flow-paths and significant denitrification prior to discharge to local waterways.

Surveillance of borehole operations using distributed temperature sensing

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Distributed temperature fibre optic sensing (DTS) is now commonly used as part of the groundwater characterization toolkit. In this paper we present examples from two recent field site operations where DTS provided invaluable information about well operations. In a CO_2 controlled release experiment in Western Australia, we discuss the surveillance of work-over operations using distributed temperature sensing in both the monitoring and injection wells. A wide range of well operations were performed in these two wells including completion installation and cementing. DTS was the sole tool used to monitor the drilling of an unexpected cement infill inside the monitoring well. In a different project in Victoria, where two deviated water wells were drilled through a fault zone, permanently installed fibre optics cable were used to inform the grouting process and the fault location. In both these case studies, DTS proved to be a valuable and reliable tool throughout the entire lifecycle of the well operations.

Estimations of dissolved methane concentrations from groundwater samples: an experimental and analytical assessment

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3. School of Chemical Engineering, University of Queensland, Brisbane, QLD, Australia

Dissolved methane samples from groundwater are prone to error due to degassing during sampling. The context of this potential error is important when using gas concentration data in scientific assessments, e.g. when assessing gas sources and migrations associated with unconventional gas resources. This research aimed to better understand the potential for methane gas loss during sampling. We collected novel experimental data from laboratory experiments to observe the behaviour of methane exsolution due to pressure changes. Analytical and numerical simulations were also used to assess gas loss due to atmospheric exposure and the effect of desorption on total free gas capture during well purging, respectively. The effect of buoyancy on gas migration in an aquifer, well and pump tube was also considered. Our experimental data show that there is an initial loss of dissolved methane due to absolute pressure changes, but the magnitude and rate of this degassing depends on the rate of depressurisation. Previously, the rate of degassing due to changes in depressurisation has not been measured and the seminal data presented here should inform further research. Analytical models show that atmospheric exposure is not a major source of error as significant gas loss via this process is unlikely in the timeframe required to take a dissolved methane sample. Numerical modelling highlighted a number of potential errors associated with closed-system sampling methods that have been largely overlooked to date, including error due to gas desorption. We propose that direct-fill methods be used as the minimum standard for dissolved methane data collection as this method produces consistent error and can be safely and repeatedly used at any well type. A standard plot for presenting dissolved methane data collected via direct-fill methods is proposed. This approach

provides a means of directly comparing dissolved methane data sets.

Under reaming of deep injection bores to improve performance

Lauren Helm [1] , Ryan Morris [2] , Rachelle Willis [1]

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2. RDM Hydro, Brisbane, QLD, Australia

The production of coal seam gas (CSG) commonly requires the extraction of groundwater from the target coals. The regulatory framework in Queensland encourages the highest value beneficial reuse of this water. Origin Energy, on behalf of Australia Pacific LNG, operates the Reedy Creek, Combabula and Ramyard gas fields in the Surat Basin, a sub-basin of the Great Artesian Basin. The gas fields currently comprise 800 CSG wells, extracting a combined volume of 14 megalitres of water per day. A bore field consisting of 11 bores was commissioned in early 2015 to inject treated CSG water into the Precipice Sandstone aquifer, at a depth of approximately 1,400 meters below ground level. To date over 21 gigalitres of treated CSG water has been injected, supporting 460+ terajoule per day of gas production.

Observed performance loss in some injection bores, and ongoing expansion of the fields, necessitated an increase in injection capacity. Under reaming of existing injectors, using an expandable drill bit, was identified as a potentially cost-effective means of increasing capacity. A trial of under reaming was undertaken on two injection bores, with the premise that reducing well losses by (i) increasing the diameter at the sandface and (ii) removal of clogging products in the near wellbore aquifer, would increase bore performance.

The trial was undertaken as follows:

1. Establishment of pre-trial bore performance through multi-rate testing (routinely undertaken)
2. Calliper logging to establish open hole diameter
3. Under reaming to an intermediate diameter
4. Injectivity test using the rig pumps
5. Calliper logging to establish under reamed diameter
6. Under reaming to a final diameter
7. Injectivity test using the rig pumps
8. Calliper logging to establish under reamed diameter
9. Post-trial bore performance testing

Bore capacities increased by more than 100% from the pre-trial to post-trial performance. A simple analytical model was built and parameterised using trial data that allowed prediction of injection performance improvements at different under reamed diameters. The model was incorporated into a water management options assessment.

Based on the performance-enhancement and cost-effectiveness of the trial, under reaming of injection bores has been identified as a successful means of increasing capacity, ensuring the injection scheme continues to return all of the treated CSG water from the Reedy Creek, Combabula and Ramyard gas fields to the GAB. Furthermore, allowing for multiple workovers and recoveries on each injector will increase the longevity of the existing injection bores and increase capacity each time under reaming is undertaken.

Predicting aquifer volume and groundwater quality in the Myalup region using AEM

Aaron Davis [1] , Richard George [2] , Nicholas Wright [2]

1. CSIRO, Kensington, WA, Australia
2. DPIRD, Perth, WA, Australia

Following on previous efforts by the Western Australia (WA) Department of Water and Environmental Regulation (DWER) in the Myalup region just south of Perth, an airborne electromagnetic (AEM) survey is available as part of the Water for Food initiative. The WA Department of Primary Industries and Regional Development (DPIRD) engaged CSIRO to provide an updated map of the electrical conductivity of the saturated zone of the Superficial Aquifer and to provide potential exploration drilling targets for groundwater resources in the Leederville Formation. In addition to these objectives, we provide an updated surface of the base of the Leederville Formation based on reinterpretation of the AEM inversions and available borehole information.

Comparison of groundwater salinity (measured from available monitoring and production bores) to inverted AEM conductivity provides the basis of a 3D atlas of Leederville Formation groundwater conductivity for the survey region. DPIRD has produced a web-based groundwater quality map for agricultural and groundwater development. The interactive map allows a user to query the survey region for specific ranges of groundwater quality. A pop-up display then informs the user on the depth and thickness of the aquifer that satisfies the search criterion. This tool will allow agriculturalists and other users to specifically target areas for groundwater extraction and provides a spatial information system for future development and maintenance of the groundwater resources in the region.

Plenary Presentations

Groundwater for a water secure world - leaving no one behind

Shahbaz Khan [1]

1. UNESCO Regional Science Bureau for Asia and the Pacific, Jakarta, Indonesia

The 2030 Agenda and Sustainable Development Goals (SDGs) have put very high emphasis on water security for all, leaving no one behind. A key target for achieving SDG 6 on water security is 6.5, which aims to implement integrated water resources management at all levels by 2030, including through transboundary cooperation as appropriate. In order to achieve water security SDG 6 and related targets, groundwater has to play an important role as it is the primary source of drinking water worldwide with over one third of world population depending entirely on groundwater as well as it is crucial for food security as 43% of the total water used for irrigation comes from groundwater. Before the 2030 Agenda, the United Nations General Assembly through resolution A/C.6/68/L.25,2013 commended to the attention of Governments the draft articles on the law of transboundary aquifers for bilateral or regional agreements and arrangements for the proper management of transboundary aquifers. UNESCO's International Hydrological Program has been actively following UNGA resolution as well as contributing to SDG Target 6.5.2 with

UNECE on mapping and management of transboundary groundwater aquifers by formalising operational arrangements. The operational arrangements consist of treaty, convention, agreement or other formal arrangement as well as joint bodies for transboundary water cooperation promoting annual exchange of data and information, which can lead to adoption of coordinated water management plans or joint objectives. This presentation will highlight the challenges and opportunities for transboundary groundwater cooperation globally and in Asia and the Pacific region through existing and new mechanisms.

Make hydrogeology great again

Anthony Lane [1]

1. SLR Consulting, Melbourne, ACT, Australia

Hydrogeology is "great" – it is a key technical discipline needed in our societies to achieve sustainable development, environmental restoration and climate change adaptation. However, we face a critical challenge in passing on the knowledge and skills needed today as well as providing the next generation of hydrogeologists.

Hydrogeology is a curiously multifaceted discipline, ranging from pure science of geochemistry through hydrology and hydraulics to the nuts and bolts of water supply engineering, including at village level. The importance of hydrogeology is evident in preventing unsustainable development including urban development, mining areas and water resources development; characterising and remediating environmental contamination and rehabilitation of mining areas; climate change adaption including managed recharge schemes to water table control planning in coastal zones impacted by rising sea level. The "four-dimensional viewpoint" of hydrogeologists provides an endlessly fascinating scientific and technological contribution to problem solving. Therefore, we need to recognise and promote the importance of hydrogeology and protect the continuity of teaching and learning as well as on-going research in hydrogeology.

Today it seems that a majority of groundwater professionals in Australia and most industrialised countries are engaged, not in water resources or groundwater control, but in the assessment and remediation of environmental contamination. Such contamination encompasses not only former industrial sites but large areas of government land a well as widespread ambient contamination by manmade chemicals. Not only does this make hydrogeology the pivotal discipline for this important sector but it fundamentally changes the demands for education and training. This also potentially drains resources from fundamental education and research in groundwater hydrology and water resources.

A recent informal survey of the Australian universities and industry training by the author highlights the nature of the challenge face universities, teaching and training institutions as well as industry groups, companies and government. The dimensions of this challenge can be seen in the shrinking pool of funding for such programs in universities; competition between universities and between research and teaching; the attitudes of students to higher education and the diverse and immediacy of demands by industry. This indicates a critical need for a review of the funding and delivery models and channels for hydrogeological education and training in Australia. What is the real demand for what skills and knowledge and how could we better fulfil these needs? We need some answers and communicate to stakeholders that hydrogeology needs to remain "great" for the benefit of future generations!

Groundwater forever – water for life

Jane Coram [1]

1. CSIRO, Canberra, ACT, Australia

In this keynote presentation, Jane Coram will synthesise the insights about the challenges and changes to groundwater management presented throughout the conference and discuss how CSIRO is encouraging deeper collaboration in this complex space to improve groundwater management outcomes. Over the last 12 months, CSIRO's Land and Water Business Unit, through its Water program and as part of CSIRO's On Prime national innovation program, undertook a comprehensive customer discovery process with nearly 100 key stakeholders across seven market sectors, nationally and internationally. Ms Coram will share how CSIRO:

- defined the sectors' most pressing groundwater issues
- identified the major knowledge gaps
- evaluated the benefits to government and industry of the ever-increasing amount of data potentially relevant to groundwater management
- identified the need for and is encouraging deeper collaboration across government agencies, academia and industries in the field of data integration and data driven scientific discovery.

Finally, Ms Coram will explore how these insights can be used in scientific projects to collectively ensure the sustainability of water for life now and into the future amidst profound and complex challenges and changes to our environment, society and economy.

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