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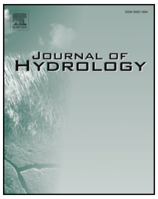

Significance of the connection between bedrock, alluvium and streams: A spatial and temporal hydrogeological and hydrogeochemical assessment from Queensland, Australia

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ABSTRACT

Catchment-scale hydrological and hydrogeological investigations commonly conclude by finding that particular stream reaches are either gaining or losing; they also often assume that the influence of bedrock aquifers on catchment water balances and water quality is insignificant. However, in many cases, such broad findings are likely to oversimplify the spatial and temporal complexity of the connections between the different hydrological system components, particularly in regions dominated by cycles of droughts and flooding. From a modelling perspective, such oversimplifications can have serious implications on the process of identifying the magnitude and direction of the exchange fluxes between the surface and groundwater systems.

In this study, we use 3D geological modelling and historic water chemistry and hydraulic records to identify the origins of groundwater at different locations in the alluvium and along the course of streams in the Lockyer Valley (Queensland, Australia), a catchment impacted by a severe drought ('Millennium Drought') from 1998 to 2009, followed by extensive flooding in 2011. We also demonstrate how discharge from the sub-alluvial regional-scale volcanic and sedimentary bedrock influences the water balance and water quality of the alluvium and streams. The investigation of aquifer geometry via development of a three-dimensional geological model combined with an assessment of hydraulic data provided important insights on groundwater flow paths and helped to identify areas where bedrock aquifers interact with shallow alluvial aquifers and streams. Multivariate statistical techniques were then applied as an additional line of evidence to groundwater and surface water hydrochemical data from large historical datasets. This confirmed that most sub-catchments within the Lockyer Valley have distinct water chemistry patterns, which result from mixing of different water sources, including discharge from the sub-alluvial bedrock. Importantly, in addition to the observed spatial variability, time-series hydrochemical groundwater and surface water data further demonstrated that the hydraulic connection between alluvial aquifers, streams and sub-alluvial bedrock aquifers is temporally dynamic with very significant changes occurring at the transition from normal to drought conditions and following flooding, affecting both catchment water quality and water balances.

1. Introduction

Hydrogeological investigations aim to address critical natural resource management issues, such as the over-exploitation or contamination of ground- and surface-water systems. Understanding connectivity between aquifers and their interactions with the surface-water system is a critical component of such investigations (e.g. Guggenmos et al., 2011; Duvert et al., 2015a,b; King et al., 2015; Barthel and Banzhaf, 2016). Alluvial aquifers are in close vicinity of the land surface and often form significant aquifers in mid reaches of worldwide rivers, where most agricultural activity occurs. They are therefore susceptible to over-exploitation, cross-aquifer mixing through interaction with underlying bedrock aquifers and anthropogenic inputs (e.g. through the application of fertilizers) (e.g. Famiglietti, 2014; Cheng et al., 2017).

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Alluvial aquifers are also more readily influenced by climatic variability, due to the greater level of dynamic interaction with surface water (Helena et al., 2000; Ahmed et al., 2004; Liu et al., 2014; Filippini et al., 2015; Izbicki et al., 2015; Meng et al., 2015; Atkins et al., 2016; King et al., 2017).

The move towards conjunctive river-aquifer management has led to the development of large-scale integrated models that simulate surface-groundwater interactions at various levels of complexity. Identifying the spatial and temporal complexity of the connections between the different system components is an essential step towards identifying the active interaction processes within a particular surface-groundwater system (Rassam, 2011; Rassam et al., 2013). However, integrated surface-subsurface hydrological models (ISSHMs) developed to simulate catchment-scale groundwater-surface water interactions usually represent catchments as simplified and relatively shallow groundwater systems that are typically not affected by the bedrock (e.g. Barthel, 2014; Paniconi and Putti, 2015; Barthel and Banzhaf, 2016; Fatichi et al., 2016; Kollet et al., 2017). Although model structural or conceptual model error is often identified as a main source of model predictions uncertainty (e.g. Marty et al., 2003; Refsgaard et al., 2006; Rojas et al., 2009; Holman et al., 2012), the uncertainties associated with oversimplifications of the connections between bedrock, alluvium and streams in catchment hydrological investigations are not typically considered. However, from a modelling perspective, over-simplification of connectivity may have serious implications on predictions, as for example in studies where the impacts of resource development (e.g. coal seam gas/coal bed methane) from sedimentary bedrock systems on alluvial aquifers, streams and groundwater-dependant ecosystems are investigated (Cui et al., 2016; Janardhanan et al., in preparation; Cui et al. (under revision)).

This study uses the Lockyer Valley in south-east Queensland, Australia, to demonstrate how the integration of multiple independent lines of geoscientific evidence including groundwater and surface water hydrochemistry and a 3D geological model can enhance the understanding of connections between connectivity between surface water, alluvial aquifers and the underlying shallow and deep bedrock. Although many local hydrogeological studies have been conducted (e.g. Dixon and Chiswell, 1992; Durick and Bleakley, 2000; Wilson, 2005; Pearce et al., 2007; Galletly, 2007; Cox et al., 2013; Wolf, 2013; Cui et al., 2018; WetlandInfo, 2018), no comprehensive integrated geological and hydrogeological conceptual model of catchment-wide recharge and connectivity mechanisms exists for the Lockyer Valley.

The Lockyer Valley is an ideal catchment to examine the significance of the connection between alluvial and sub-alluvial bedrock aquifers and with surface water, including its temporal and spatial variability. Several key points support this: a) it has a diverse geology consisting of several compositionally different aquifer types (Quaternary alluvia, Neogene volcanics and Triassic to Jurassic sedimentary bedrock aquifers); b) there is an extensive groundwater monitoring bore network with several hundred groundwater bores screened in different aquifers. Importantly, in contrast to most other catchments in south-east Queensland such as the adjacent Condamine River catchment (Fig. 1) and many catchments elsewhere in Australia, a large number of groundwater monitoring bores were installed in the sedimentary bedrock in the early 2000s as part of a national salinity monitoring programme (Pearce et al., 2007), providing invaluable baseline data to support hydrochemical and recharge assessments; c) there are important regional economic drivers for groundwater extraction for agricultural purposes in the Lockyer Valley (in 2014/15, AUS$374 million of agricultural output (Trade and Investment Queensland, 2018)) was generated in the Lockyer Valley, and d) time series data cover a drought-flood cycle that extended from 1998 to 2009 ('Millennium Drought').

This study aims to: (1) highlight the significance of the bedrock contribution on both water fluxes and quality and illustrate to what extent aquifer geometry influences connectivity between the different system components; (2) identify aquifers that discharge to streams (and areas where this discharge occurs), and conversely, areas where streams recharge underlying aquifers; (3) define mechanisms and areas of recharge for different aquifers and assess the temporal variability of these processes during droughts and following flooding.

2. Geological and hydrogeological setting

The Lockyer Valley is an approximately 2300 km^2 catchment in the north-east of the Clarence-Moreton Basin, which is infilled with a variety of sedimentary rocks of fluvial-lacustrine origin (Fig. 1). A comprehensive description of the aquifer systems of the Clarence-Moreton Basin is provided by Rassam et al. (2014) and Raiber et al. (2017b).

In recent decades, the Clarence-Moreton Basin has been extensively explored for conventional and unconventional gas, with a primary focus on Coal Seam Gas (CSG) resources in the Walloon Coal Measures (WCM). In the Lockyer Valley, the Clarence-Moreton Basin consists of four major stratigraphic units of Late Triassic to Jurassic age, namely, the Woogaroo Subgroup, the Gatton Sandstone, the Koukandowie Formation and the Walloon Coal Measures (Figs. 1 and 2). These sedimentary bedrocks are overlain by extensive extrusive volcanic rocks (Main Range Volcanics; MRV) and Quaternary alluvial aquifer systems.

The Late Triassic Woogaroo Subgroup forms an aquifer consisting mostly of conglomerate beds and thin beds of sandstone composed mainly of quartz-rich sand (O'Brien and Wells, 1994). It is overlain by the Gatton Sandstone (lower member of Marburg Subgroup), a partial aquifer which is dominated by thick-bedded, medium- to coarse-grained quartz-lithic and feldspathic sandstone (Ingram and Robinson, 1996). The Koukandowie Formation (upper unit of the Marburg Subgroup) consists of sheets of interbedded quartzose-feldspathic-lithic sandstone, siltstone, claystone and minor coal (Willis, 1994), and is considered as a partial aquifer (Raiber et al., 2017b). The WCM is composed of volcaniclastic, lithic and silty sandstone with interbedded mudstone, coal and siltstone (Wells and O'Brien, 1994); ash-fall tuff and basalts also occur in the sequence (Doig and Stanmore, 2012), as commonly observed in lithological logs. In the Lockyer Valley, the WCM is limited to the southern and south-western part of the catchment, where it outcrops or is overlain by fractured basalts of the MRV (Fig. 1). It has a thickness of typically less than 100 m in the Lockyer Valley, which makes it an unlikely target for CSG exploration in this area (Raiber et al., 2017a).

The Cenozoic MRV are widespread in the Lockyer Valley, and cover large areas in the southern and western part of the catchment where they cap the peaks of the Great Dividing Range (Fig. 1). They unconformably overlie the Gatton Sandstone, the Koukandowie Formation and the WCM with a thickness of typically less than 200 m, but can be considerably thicker close to peaks and volcanic eruptive centres. Importantly, the MRV do not consist of a single homogeneous basalt flow or correspond to a single aquifer but are composed of many overlapping volcanic flows with a maximum thickness of approximately 10 m each, which are commonly separated by lower-permeability layers including clay-rich weathering profiles developed during volcanic hiatuses. Well-developed fracture networks (secondary porosity) connect vesicular zones of different basalt flows within the MRV (Raiber et al., 2017a).

There are several major geological structures in the Lockyer Valley, namely the Gatton Arch and the Helidon Ridge (Fig. 1), as well as many local-scale fracture and fault zones.

Extensive alluvial sediment sequences have infilled the alluvial valleys of the Lockyer Creek and its tributary systems. The geometry and composition of the alluvial sediments is discussed in more detail in Section 5.1.

3. Climate, vegetation and surface water flow

South-east Queensland has a subtropical climate dominated by hot

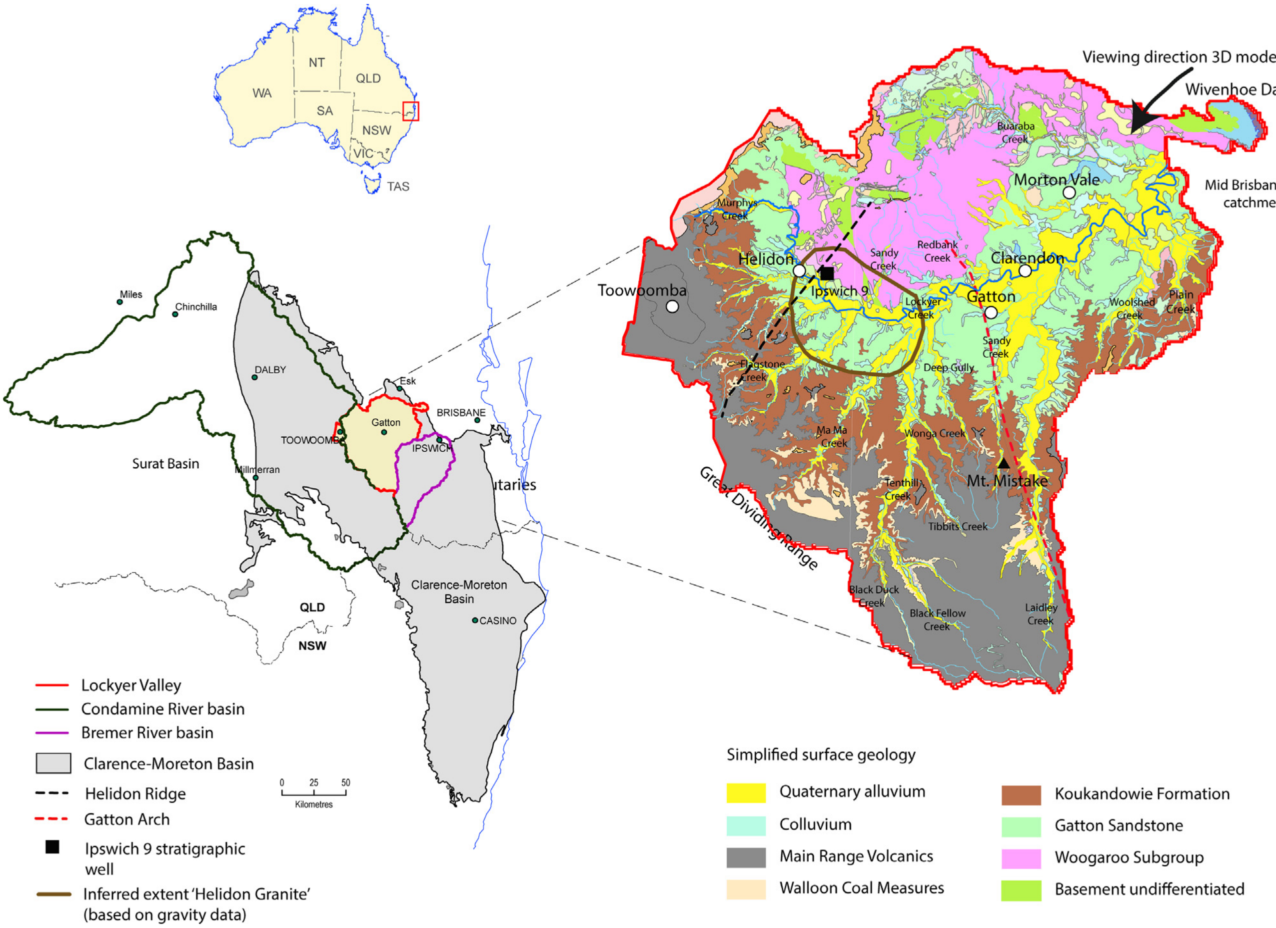


Fig. 1. Location of Lockyer Valley and adjacent catchments within the Clarence-Moreton Basin and simplified surface geology of the Lockyer Valley.

and humid summers and dry, mild winters (ABARES, 2016). In the headwaters of the Lockyer Valley at Mount Mistake (Fig. 1), the mean annual rainfall is 863 mm/yr, although total annual rainfall can be highly variable ranging from about 450–1500 mm/yr (Station number 040205 (BOM, 2017)). The low rainfall during the Millennium Drought resulted in very low creek flow, with flow in most creeks ceasing completely especially from mid-2006 until early 2008. This period of drought was followed by several wet years and flooding in January 2011. Flows in the Lockyer Creek (and catchments in south-east Queensland in general) are characterised by high flood variability (Croke et al., 2016). At Rifle Range Road (Fig. 1) near the outflow of the catchment, the median flow is approximately 57 L/s, whereas the peak flow recorded during flooding in January 2011 was more than 690,000 L/s (DNRM, 2017).

The dominant land-uses are pasture (47%), and woody vegetation (41%), with 11% of the area used for cropping (Apan et al., 2002). Extensive forests and woodlands cover most of the MRV and Woogaroo Subgroup outcrop areas.

Alluvial groundwater is used extensively for irrigated seasonal horticulture, with some irrigated cropping. Dryland agriculture also occurs in the areas away from the alluvium on outcrops of the Gatton Sandstone and other sedimentary bedrock hydrostratigraphic (ABARES, 2016).

4. Methods and data sources

4.1. Hydraulic and geological data and 3D geological model development

4.1.1. Groundwater bore data and potentiometric surface map development

Historical groundwater levels and bore construction details, as well as lithologic and stratigraphic data were compiled from over 5000 registered groundwater bores (including bores at the periphery of the Lockyer Valley in adjacent catchments to avoid modelling artefacts near the margins), sourced from the Queensland Department of Natural Resources and Mines (DNRM) groundwater database (DNRM, 2014, 2015). In addition, data from a smaller number of deeper stratigraphic or petroleum wells within the catchment were used, obtained from the DNRM Queensland Digital Exploration Reports (DNRM, 2014) and from Wells and O'Brien (1994).

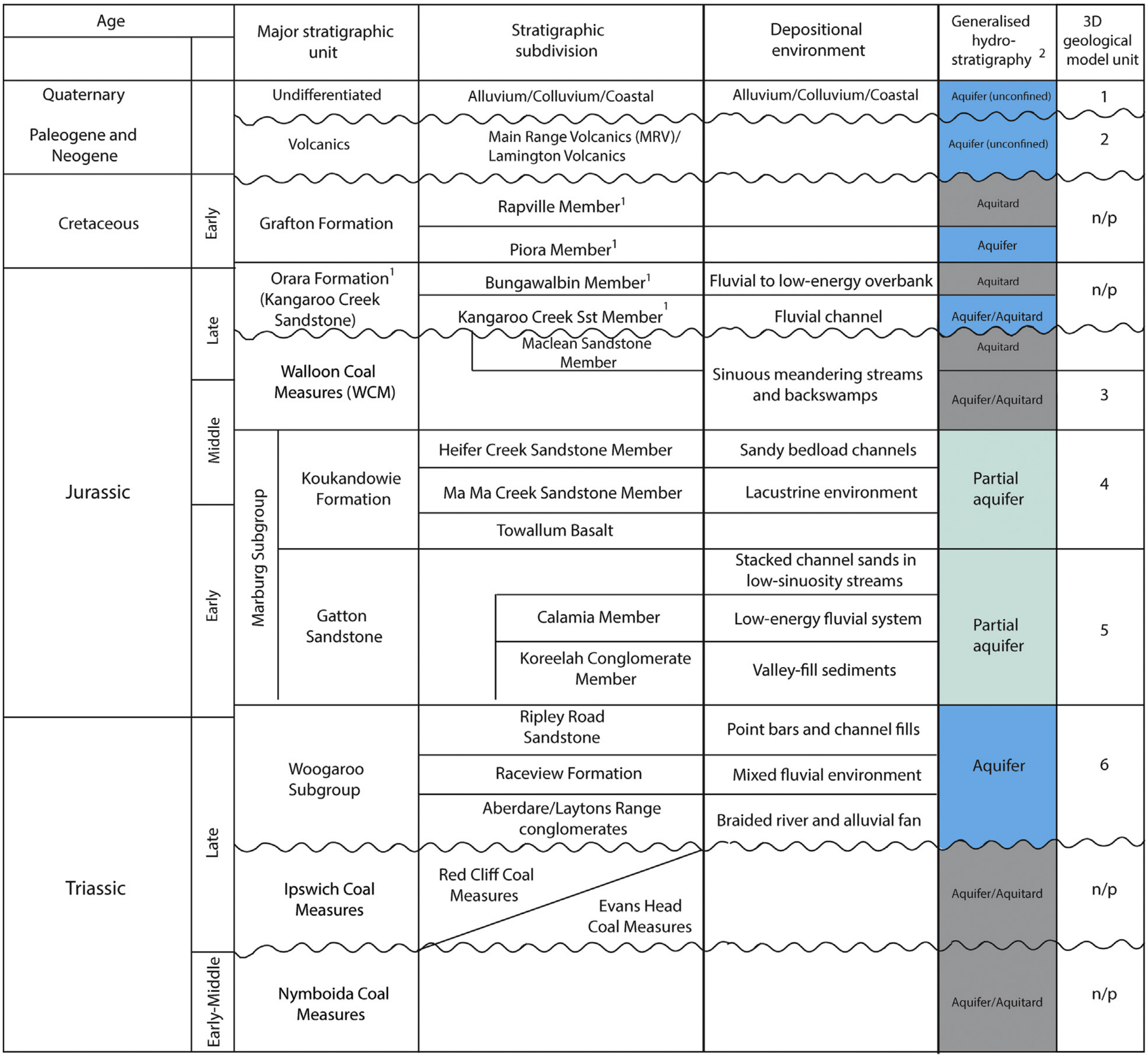
The potentiometric surface of the shallow sedimentary bedrock was created using ordinary Kriging with a fitted linear semi-variogram model in ArcGIS based on the available groundwater level data from 2000 to 2012 (DNRM, 2014).

4.1.2. Development of 3D geological model

The three-dimensional (3D) geological model of the Lockyer Valley was assembled using SKUA-GOCAD™ software (Paradigm Geophysical Pty Ltd) in combination with Mira GoCAD mining utilities. The 3D geological model of the Lockyer Valley consists of the seven major model units, as listed in the stratigraphic table (Fig. 2).

Input data included a 1 degree digital elevation model (SRTM, Geoscience Australia and CSIRO Land and Water, 2010) and a variety of geological data, such as 1:100,000 geological maps (DNRM, 2002) as well as stratigraphic and lithologic data from the Queensland DNRM groundwater database (DNRM, 2013). Stratigraphic data close to the boundaries with adjacent river catchments (i.e. Condamine Catchment, Bremer Catchment and mid-Brisbane River Basin, see Fig. 1) were also included to avoid modelling artefacts near the margins.

Lithological logs were first simplified and standardised outside the 3D geological model environment, and then imported into the 3D



Age		Major stratigraphic unit		Stratigraphic subdivision	Depositional environment	Generalised hydro-stratigraphy[2]	3D geological model unit
Quaternary		Undifferentiated		Alluvium/Colluvium/Coastal	Alluvium/Colluvium/Coastal	Aquifer (unconfined)	1
Paleogene and Neogene		Volcanics		Main Range Volcanics (MRV)/ Lamington Volcanics		Aquifer (unconfined)	2
Cretaceous	Early	Grafton Formation		Rapville Member[1]		Aquitard	n/p
				Piora Member[1]		Aquifer	
Jurassic	Late	Orara Formation[1] (Kangaroo Creek Sandstone)		Bungawalbin Member[1]	Fluvial to low-energy overbank	Aquitard	n/p
				Kangaroo Creek Sst Member[1]	Fluvial channel	Aquifer/Aquitard	
		Walloon Coal Measures (WCM)		Maclean Sandstone Member	Sinuous meandering streams and backswamps	Aquitard	
	Middle					Aquifer/Aquitard	3
		Marburg Subgroup	Koukandowie Formation	Heifer Creek Sandstone Member	Sandy bedload channels	Partial aquifer	4
				Ma Ma Creek Sandstone Member	Lacustrine environment		
				Towallum Basalt			
	Early		Gatton Sandstone		Stacked channel sands in low-sinuosity streams	Partial aquifer	5
				Calamia Member	Low-energy fluvial system		
				Koreelah Conglomerate Member	Valley-fill sediments		
Triassic	Late	Woogaroo Subgroup		Ripley Road Sandstone	Point bars and channel fills	Aquifer	6
				Raceview Formation	Mixed fluvial environment		
				Aberdare/Laytons Range conglomerates	Braided river and alluvial fan		
		Ipswich Coal Measures		Red Cliff Coal Measures Evans Head Coal Measures		Aquifer/Aquitard	n/p
	Early-Middle	Nymboida Coal Measures				Aquifer/Aquitard	n/p

[1]proposed stratigraphic revision by Doig and Stanmore (2012)

[2]generalised hydrostratigraphy is modified from Radke and O'Brien (2012)

Fig. 2. Stratigraphic table of Clarence-Moreton Basin (modified from Rassam et al., 2014) and stratigraphic tables represented in the 3D geological model (n/p indicates that these stratigraphic units are not present in the Lockyer Valley). Three-dimensional geological model unit 7 (basement undifferentiated) is not represented in the stratigraphic table. Curved lines indicate an unconformable or erosional contact between hydrostratigraphic units, whereas straight lines indicate a conformable contact.

geological model framework. Using regular sets of perpendicular cross-sections (> 100 in total), the data were manually checked and corrected where required. This included checks for geological inconsistencies and obvious terminology errors, as exemplified by the presence of the lithological log description 'basalt' in areas where basalts are absent (Raiber et al., 2017a). As part of this procedure, lithological logs were initially converted into simple stratigraphic logs that differentiate "alluvium", "Main Range Volcanics" and "sedimentary bedrock" following the iterative procedure described by Raiber et al. (2017a). These were then used to create surfaces that represents the interface between the alluvium and the underlying sedimentary or volcanic bedrock. Using the data from a smaller number of deep stratigraphic or exploration wells or deep groundwater bores with reliable stratigraphic data, the binding surfaces that separate the bedrock formations were developed.

4.2. Hydrochemical data and multivariate statistics

4.2.1. Groundwater, surface water and rainfall chemistry data

Groundwater chemistry data from the Queensland DNRM groundwater database (DNRM, 2015) for the period January 1976 to May 2015 were included in the multivariate statistical analysis. Prior to 1976, potassium (a major ion) was typically not measured. The 3D geological model (Section 4.1.2) was used to independently verify the source aquifer for each bore by determining the hydrostratigraphic unit at the screened interval. This meant that substantially more bores with known aquifer membership were included in the hydrochemical, hydrogeological and recharge assessment. Bores where the aquifer membership was ambiguous or where the screens were unknown or extended over multiple formations were excluded from the assessment.

In addition to groundwater samples, surface water samples from the DNRM surface water database (DNRM, 2017) and from a 2012 survey of surface water quality at 28 sampling locations within 15 different creeks throughout the Lockyer Valley were also included in the assessment.

Rainfall time-series chemistry data were sourced from Crosbie et al. (2012). There are two rainfall chemistry monitoring stations near the Lockyer Valley (Toowoomba and Brisbane, Fig. 1), and major ion data from these stations were used for comparison with groundwater and surface water data.

4.2.2. Multi-variate statistical analysis

Hierarchical Cluster Analysis (HCA) is commonly adopted in groundwater hydrochemical studies. It allows detection of spatial patterns in large datasets and enhances the understanding of physical and chemical catchment processes (e.g. Stetzenbach et al., 1999; Güler et al., 2002; Menció and Mas-Pla, 2008; Daughney et al., 2012; Raiber et al., 2012). Where available, a large number of variables should be used in HCA to accurately characterise groundwater chemistry and the processes that control it; the selection of the parameters to be included requires a balance between selecting a wide range of variables but also aiming for a large number of complete cases to ensure a good spatial coverage, as HCA considers only cases where a value exists for each variable (Raiber et al., 2012). In this study, ten variables were selected (Ca, Mg, Na, K, HCO_3, Cl, F, SO_4, pH and electrical conductivity) as they were measured across most sites. An extended description of the methodology is provided in Appendix 1.

Many of these groundwater bores were only sampled once, although some bores were sampled multiple times (the largest number of time series hydrochemical records for a single groundwater bore included in the cluster analysis is 16). In contrast to other studies where the median was used as a representative of time-series data from particular groundwater bores (e.g. Guggenmos et al., 2011), all sampling records that met the data quality checks (Appendix 1) were included in this study to evaluate temporal patterns.

Surface water data were not integrated into the HCA, as there are a very large number of measurements available at some sites (up to 170 hydrochemical time-series records at a single monitoring station). Using all of these data could potentially skew the dataset, but there are different ways of dealing with such extensive time-series data. For example the median of all time-series data can be included to represent surface water monitoring datasets (Martinez et al., 2015). In this study, however, discriminant analysis (DA) was used for this purpose. This approach provides insights into the similarity between groundwaters and surface waters without skewing the groundwater chemistry dataset, and it also allows assessment of temporal variabilities within the surface water time series data. DA predicts into which of two or more a priori defined categories an observation is most likely to fall based on a set of classification functions and a certain combination of input variables (e.g. Davis, 1986; Papatheodorou et al., 2007; Daughney et al., 2010; Raiber et al., 2012). More detail on the methodology is provided in Appendix 1.

5. Results

5.1. Aquifer geometry and groundwater flow paths

Aquifer geometry and groundwater flow paths, as inferred from the 3D geological model and the potentiometric surface map were used to develop an initial hydrogeological conceptual model.

The 3D geological model of the Lockyer Valley (Fig. 3) represents the thicknesses and geometric architecture of the different aquifers. An isopach map (Fig. 4) shows the thickness and geometry of the central Lockyer Creek alluvium and its tributary systems. Two cross-sections through the 3D geological model (Fig. 5a and b) further highlight key elements of the catchment geology, including geometry, variations in thickness and areal extent between alluvial aquifers and the underlying sedimentary and volcanic bedrock.

The composition of alluvial sediments varies considerably throughout the catchment. In the headwaters of the Lockyer Creek tributary systems, the thin alluvial sequences (less than 20 m) are dominated by boulders, gravel and sand deposited by braided streams during high-energy flow events in steep v-shaped valleys. In contrast, fining upwards sequences with gravels and coarse sands at the base and clay on top dominate the alluvial sequences in mid and lower reaches of tributaries and generally throughout the central Lockyer Creek alluvium. Here, the valleys are wide and u-shaped with total alluvial thicknesses of up to 40 m. Weathering profiles of several meters separate the alluvial sediments from the underlying sedimentary bedrock, and bedrock outcrops or shallow bedrock highs occur sporadically within the extent of the alluvium, influencing the course of streams and the deposition and thicknesses of alluvial sediments.

The potentiometric surface map of the shallow bedrock in the Lockyer Valley (i.e. representing the Gatton Sandstone and the Koukandowie Formation) (Fig. 3) suggests that groundwater flows towards the northern margin of the Clarence-Moreton Basin in the Gatton Sandstone and Koukandowie Formation (there are insufficient data points to determine the flow direction in the WCM). The Gatton Sandstone, which underlies most of the alluvium throughout the lower part of the Lockyer Valley, thins towards the northern basin margin, where it on-laps the Woogaroo Subgroup and pinches out (Fig. 5a). This suggests that as the Gatton Sandstone pinches out and thins from several hundred meters to zero thickness, groundwater will be pushed upwards into the Lockyer Creek alluvium and ultimately will discharge to streams; this hypothesis will be tested independently using hydrochemistry (Section 6).

The groundwater flow direction in the Gatton Sandstone contrasts with groundwater flow in the Woogaroo Subgroup, which in some parts of the Lockyer Valley flows in the opposite direction. This mainly occurs from the elevated northern outcrop areas towards the deeper parts of the basin in the south-east.

Furthermore, the equipotential lines of the shallow sedimentary bedrock also suggest that the lower parts of the major tributaries (e.g. Laidley Creek, Sandy Creek and Tenthill Creek) (Figs. 3 and 5a and b) and much of the course of minor tributaries such as Tibbits Creek, Wonga Creek or Stockyard Creek (Fig. 5a and b) form likely discharge points from the sedimentary bedrock to the alluvial aquifers and their associated streams.

Insufficient groundwater level monitoring data exist for direct assessment of flow directions in the MRV in the headwaters of the Lockyer Valley. However, studies in other sub-catchments within the Clarence-Moreton Basin suggested that discharge from the MRV to the alluvium and streams occurs in upper reaches (e.g. Martinez et al., 2015; Duvert et al., 2016; Martinez et al., 2017), predominantly via spring discharge (Brodie and Green, 2002). This is also indicated by the geometry of the aquifers in the Lockyer Valley (Figs. 3 and 5), with the major streams and associated alluvia (e.g. Laidley Creek and Black Duck Creek) deeply incised into the MRV. Consequently, the natural flow paths within this extensive fractured rock aquifer are commonly intercepted by the surface water system and alluvium.

The interface between the MRV and the WCM, interpreted as a low permeability boundary due to the clay-rich weathering profile typical of the top of the WCM, is close to the base of the alluvium and streams in these upper reaches (Fig. 5a). This suggests that the lateral hydraulic conductivity likely exceeds the vertical conductivity, and that lateral discharge from the MRV to the alluvium and streams substantially outweighs downwards percolation from the MRV into the WCM.

Although only limited groundwater level monitoring data are available for the sedimentary bedrock in the western part of the catchment from Helidon to Toowoomba, the presence of a bedrock/basement ridge indicates the likely existence of a groundwater divide for these aquifers (Fig. 5b). This coincides with a structural feature previously termed 'Helidon Ridge' (Smerdon and Ransley, 2012), proposed as the hydrogeological boundary between the Surat and

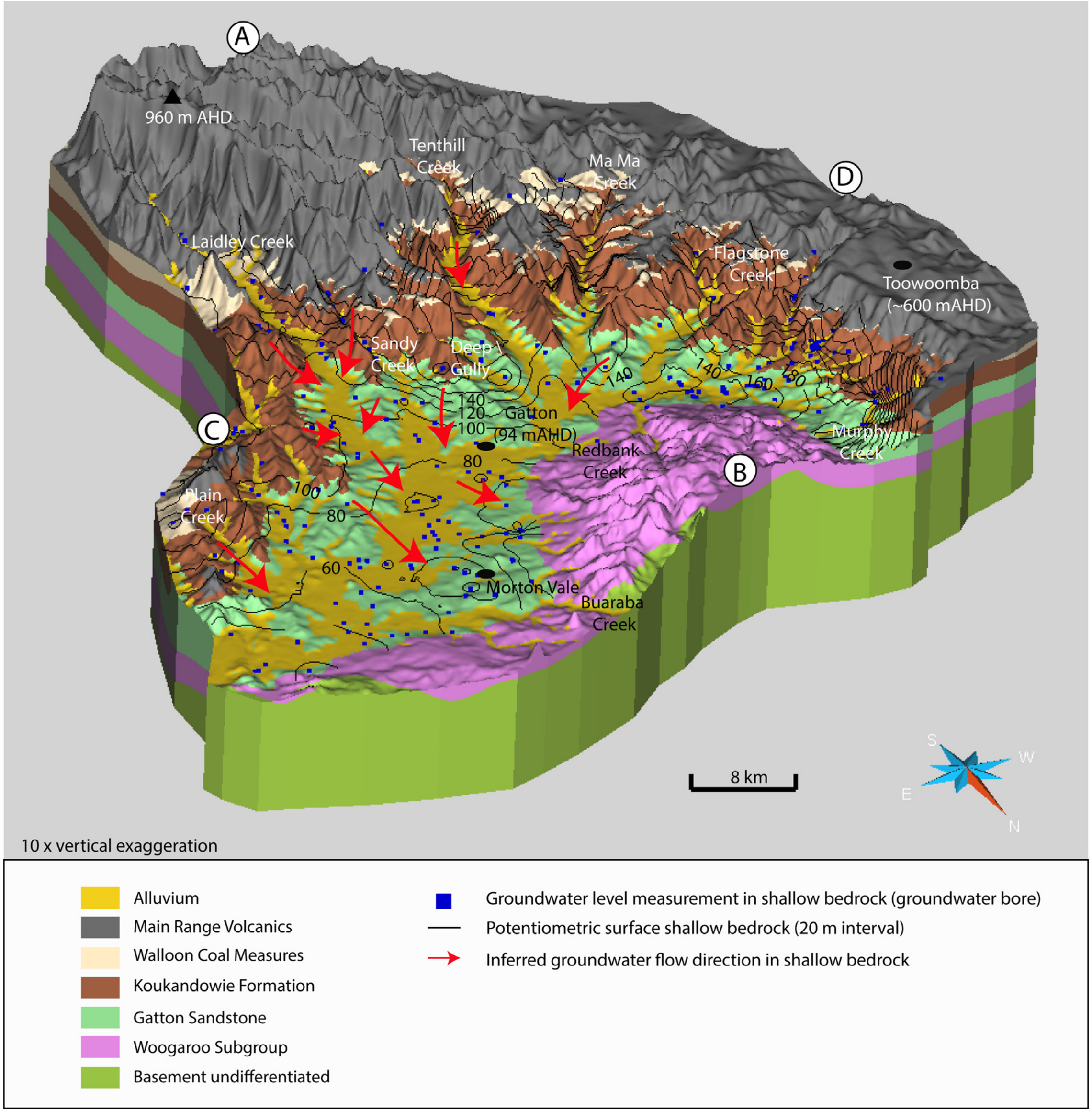


Fig. 3. 3D geological model of the Lockyer Valley and potentiometric surface of shallow sedimentary bedrock (i.e. Koukandowie Formation and Gatton Sandstone). A-B and C-D refer to the endpoints of cross-sections in Fig. 5. In the 3D geological model, the different basement units are not differentiated due to the small number of deep wells. Faulting has been previously described for this area (Dempster, 1986), but there are insufficient data (e.g. seismic data) available to determine locations and geometry of faults in the Lockyer Valley, and faults are therefore not represented in the 3D geological model.

Clarence-Moreton basins (although this boundary remains contentious) and thus part of the eastern margin of the Great Artesian Basin in this area. Furthermore, in the area near Helidon, a shallow-buried granite (herein named Helidon Granite) is intersected in stratigraphic bore GSQ Ipswich 9 at 304 m below ground surface (Wells and O'Brien, 1994; Fig. 1), with the extent of this intrusive body inferred from gravity data (DNRM, 2002) (Fig. 1).

5.2. Groundwater hydrochemistry

Groundwater salinity (represented here by the electrical conductivity (EC)) within the sedimentary and volcanic bedrock in the Lockyer Valley ranges from 100 µS/cm to 39,000 µS/cm, and from 200 µS/cm to 32,000 µS/cm for the alluvial aquifers. Following the identification and removal of outliers, seven major clusters were identified in the alluvial and bedrock units (Fig. 6a).

5.2.1. Aquifer-cluster relationship

A chi-square test was conducted to test for independence between aquifers and clusters to determine whether the cluster attribution of hydrochemical records is linked to aquifers. Since the P-value is less than 0.05, the hypothesis that the aquifer and cluster classifications are independent can be rejected at the 95.0% confidence level. This is also demonstrated by the cross-tabulation in Fig. 6a, which shows the relationships between aquifers and clusters. It demonstrates for example that Cluster 1 groundwaters originate primarily from the alluvium, Gatton Sandstone and Woogaroo Subgroup. It also shows that groundwaters assigned to Cluster 6 (groundwaters with the highest salinities) are almost exclusively sourced from the Gatton Sandstone and the alluvial aquifer. The spatial distribution of cluster assignments for bedrock and alluvial aquifers (Fig. 7) is discussed in Section 6.

5.2.2. Major characteristics of clusters

The median values for hydrochemical variables of the seven clusters are represented in a Piper plot in Fig. 6b and in Table 1, and the spatial

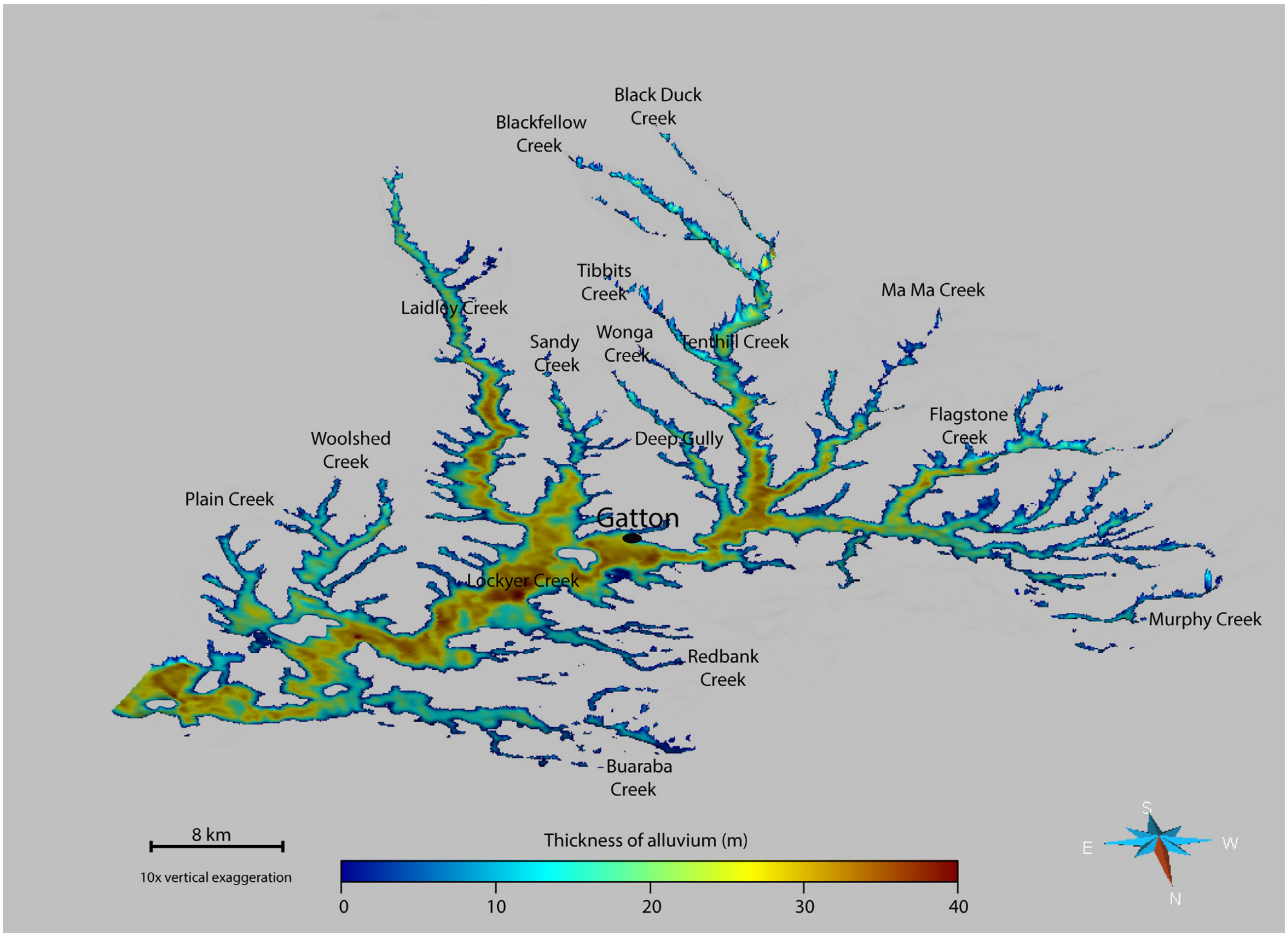


Fig. 4. Isopach map showing the thickness and geometry of the Lockyer Creek and its tributary alluvial systems.

distribution of clusters in alluvium and sub-alluvial bedrock is presented in Fig. 7. The ratios of selected ions versus Cl for all samples in the bedrock and the alluvium are shown in Figs. 8 and 9, respectively.

The major characteristics of each cluster are:

Cluster 1: This group contains brackish samples (median EC of 2600 µS/cm; Table 1), mostly from a small area near Helidon (Fig. 7a). Groundwaters in this cluster are marked by very high HCO_3/Cl ratios (Fig. 6b, Fig. 8e and 9e), and they are mostly oversaturated with regards to calcite and dolomite and very low concentrations of Ca and Mg (Fig. 8b,c and 9b, c with ratios clearly below the 1:2 M Ca/HCO_3 ratio) and low but measurable concentrations of SO_4 and high concentrations of F.

Cluster 2: this cluster contains brackish groundwaters with median EC of 2029 µS/cm and a dominance of HCO_3 over Cl (Fig. 8e, Table 1) and elevated Na and Mg versus Cl ratios relative to local rainfall (Fig. 8c).

Cluster 3: Clusters 3 contains fresh groundwater with median EC of approximately 690 µS/cm (Table 1), respectively, and a dominance of HCO_3 over Cl (Fig. 8e and 9e). Na is the dominant cation in Cluster 3 groundwaters, and for many samples, the Na/Cl ratio is above the Na/Cl ratio of local rainfall (Fig. 8a); potassium is also elevated relative to local rainfall in many samples (Fig. 8d). Most Cluster 3 groundwater samples follow a 1:2 trend for Ca/HCO_3 and Mg/HCO_3 ratios, and most are under-saturated with respect to calcite and dolomite.

Cluster 4: Cluster 4 contains fresh groundwater samples (median EC of 1039 µS/cm) with a dominance of HCO_3 over Cl (Fig. 8e) and elevated Na and Mg versus Cl ratios relative to local rainfall (Fig. 8c).

Cluster 5: Cluster 5 contains the freshest groundwaters (median EC of 370 µS/cm) in the Lockyer Valley. Similar to Cluster 3, most clusters 5 groundwater samples follow a 1:2 trend for Ca/HCO_3 and Mg/HCO_3 ratios, and most are under-saturated with respect to calcite and dolomite.

Cluster 6: Cluster 6 includes widespread groundwater samples containing saline groundwater, with a median EC of ~6800 µS/cm (Table 1) and maxima of up to 35,000 µS/cm. Na/Cl ratios of these saline groundwaters scatter around the ratios of local rainfall, and with increasing salinity, there is a progression towards the Na/Cl ratios of local average-weighted rainfall (Fig. 8a), as also observed for saline groundwaters in many other areas in Australia (e.g. Edwards and Webb, 2009; Raiber et al., 2009). In addition, this cluster is characterised by a dominance of Cl over HCO_3 and low potassium concentrations, which are strongly depleted relative to local rainfall (Fig. 8d, e and 9d,e).

Cluster 7: Groundwater samples assigned to Cluster 7 have similar characteristics as Cluster 6 groundwaters. However, they have slightly lower EC (median 4230 µS/cm), lower SO_4 and higher Ca and Mg concentrations.

5.3. Temporal variability of groundwater chemistry and water levels

The hydraulic gradients between alluvial aquifers, bedrock aquifers and streams can reverse during different climatic periods. For example, Laidley Creek in its deeply incised lower reaches changed from a disconnected creek, at the climax of the Millennium Drought in 2007, to a losing stream recharging the underlying alluvial aquifer in 2009 and into a gaining stream in 2013 (Raiber et al., 2017b; Cui et al., 2018).

Hydrochemistry can be used as a tool to determine if water level changes represent an actual aquifer recharge event resulting in a change in aquifer storage, or a pressure loading. We highlight the

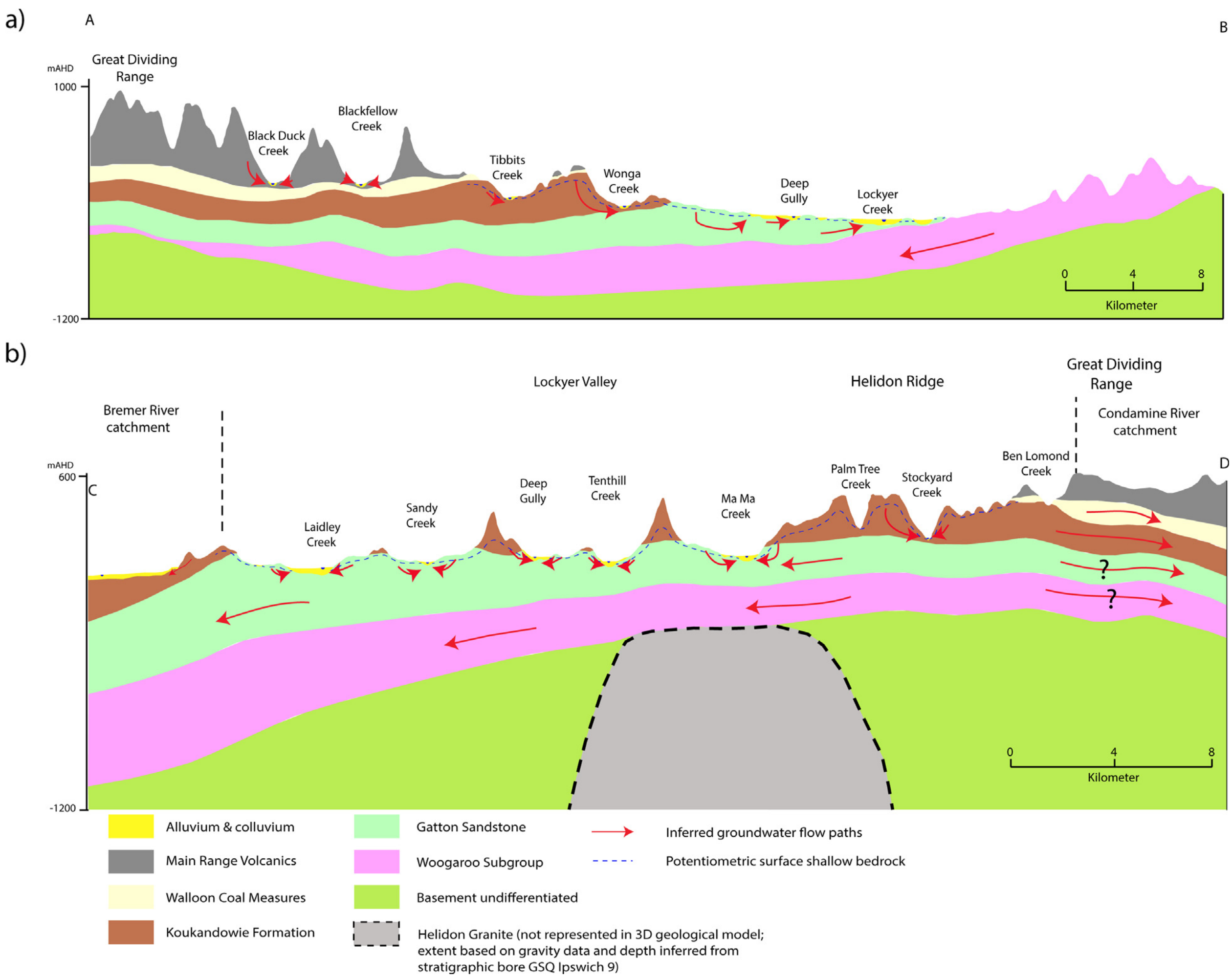


Fig. 5. Cross-sections through the 3D geological model of the Lockyer Valley and potentiometric surface of shallowest sedimentary bedrock; orientations are shown on Fig. 3.

hydrochemical changes that have occurred throughout the Lockyer Valley at four sites where long-term water level and groundwater chemistry data are available to determine if there is a change in the relative contribution from different recharge sources:

Monitoring site 14320101 (distance from creek approximately 600 m): Eleven complete groundwater chemistry records exist at this site in the alluvium of the lower Lockyer Creek (Fig. 7b). The cluster analysis showed that the variability of groundwater chemistry at this site is overall relatively small, as the cluster membership only changed once from Cluster 4 to Cluster 2 (and back to Cluster 4), even though there was a relatively large change in water level, from ~11 to ~26 m below ground surface (bgs) (Fig. 10a). This indicates that despite significant water level fluctuations, the principal recharge source or relative contributions from different sources to the alluvium is unlikely to change at this site.

Monitoring site 14320277 (distance from creek approximately 200 m): The groundwater level at this site in the lower Laidley Creek sub-catchment has fluctuated considerably during the last 40 years (varying from about 2.5 to 20.5 m bgs) (Fig. 10b). During this period there were also considerable changes in groundwater chemistry. When the groundwater table was relatively shallow (< 5–10 m bgs), groundwater was generally assigned to clusters 2 or 4, either fresh or slightly brackish (the freshest groundwater at this site had EC of 1100 µS/cm). After significant declines in groundwater levels in the mid to late 1990's, groundwater salinity increased (~9000 µS/cm) with a change to Cluster 7. In contrast, the reverse occurred under wetter conditions.

Monitoring site 14320313 (distance from creek approximately 1000 m): Groundwater at this site in the Sandy Creek sub-catchment (Fig. 7b) is brackish or saline (clusters 6 or 7). However, the overall range of EC is relatively small (~5500 to 7600 µS/cm), suggesting that there is no major variation in the recharge source.

Monitoring site 14320823 (distance from creek approximately 150 m): In the lower Flagstone Creek sub-catchment (Fig. 7b) groundwater chemistry changed from 1998 to 2015. Most groundwater chemistry records were assigned to Cluster 6 (median of 6870 µS/cm) during the period of drought. A considerable freshening is marked by a change of cluster membership from Cluster 6 to Cluster 2 with a change in EC from ~8000 µS/cm to approximately 1400 µS/cm) (Fig. 10d). Even though the groundwater level remained relatively shallow, data from 2013 confirm an increase in salinity accompanied by a reversal to Cluster 6.

5.4. Surface water chemistry

Surface water salinity in the Lockyer Valley measured at low-flow conditions during a synoptic sampling survey in 2011/2012 (all samples collected at flowing reaches rather than pools), and sourced from the DNRM water monitoring portal (DNRM, 2017), is spatially highly variable and ranges from approximately 200 µS/cm to more than 16,000 µS/cm (Figs. 11 and 12). The freshest surface waters occur in Buaraba Creek which drains the Woogaroo Subgroup. Fresh surface

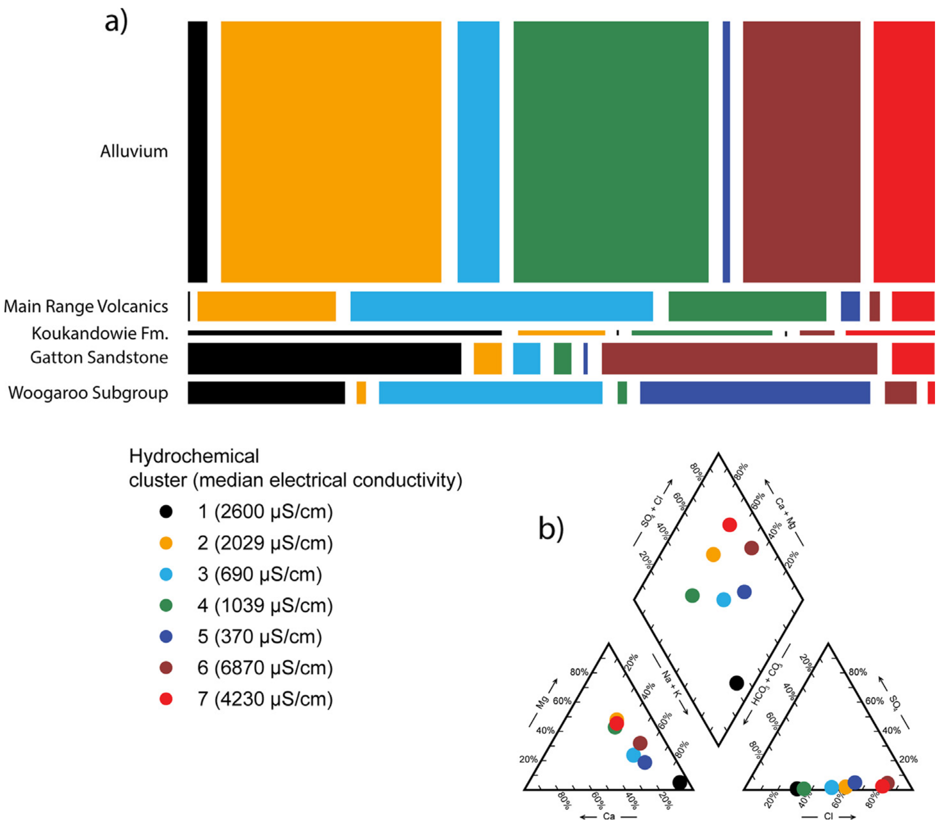


Fig. 6. a) Aquifer cluster membership of all major aquifers in the Lockyer Valley. The width of the bars represents the relative percentage of groundwater records assigned to each cluster. The thickness of the boxes is proportional to the number of existing hydrochemical records for each formation (e.g. a large number exists for the alluvium, whereas only a small number of records are available for the Koukandowie Formation); b) piper plot showing the median major ion concentrations of the seven groundwater chemistry clusters.

waters also occur in the headwaters of Laidley Creek, Tenthill Creek and Black Duck Creek (approximately 300 µS/cm) within or near the footprint of the MRV. The water in Lockyer Creek is relatively fresh throughout, although salinity does increase notably where smaller tributaries such as Plain Creek enter the main creek-line (Fig. 11). The flow in Lockyer Creek is dominated by input from the larger tributaries (Laidley Creek, Tenthill Creek and Murphy Creek) that all originate near the peaks of the Great Dividing Range and source a considerable portion of discharge in their headwaters from the MRV.

The hydrochemical similarity between groundwaters and surface waters was assessed using discriminant analysis, which was conducted to determine into which groundwater chemistry clusters each surface water hydrochemical record would likely be assigned.

Ion ratios of surface waters in the Lockyer Valley cover a similar range as those of the alluvial (Fig. 9) and bedrock aquifers (Fig. 8). Similar to groundwaters, the freshest surface waters are characterised by elevated major ion/Cl ratios. As stream salinity increases, the ion/Cl ratios decline and evolve towards ratios similar to or below the ratios of local rainfall. The discriminant analysis also suggests that the surface water hydrochemical records are most similar to groundwater chemistry clusters 2 (15% of all surface water samples are assigned to this cluster), 3 (~50%), 4 (15%) and 5 (14%), whereas only relatively few samples are assigned to clusters 1, 6 and 7.

Surface water chemistry time-series data at three stream gauging station locations reveal considerable variability over time, highlighting the complexity of the interactions spatially and temporally. At Laidley Creek in Mulgowie (Figs. 11 and 12), located close to the upper part of the catchment and the outcropping MRV, the relatively fresh Cluster 4 dominates. At Tenthill Creek (at Tenthill, Fig. 12), which is more representative of the mid-catchment, there is a more pronounced change of surface water chemistry when compared to upstream, with the lower flows having slightly higher salinity (Cluster 2), with fresher surface waters (Cluster 4) observed around many of the high-flow hydrograph peaks. Lockyer Creek in the lower section (at Rifles Range Rd, Figs. 11 and 12) also shows variation in chemistry, with many relatively fresh (Cluster 3) measurements, as well as a few occasions where the stream salinity increases as low-flow periods extend, with some cluster 2, 4 and 6 hydrochemical records.

The available surface water chemistry data highlight the variability in stream chemistry between the different tributaries. In trying to use this information to better understand the relationship between streams and underlying aquifers, it is important to note that the current DNRM surface water gauging sites primarily monitor flows and surface water quality of Lockyer Creek and its largest and highest yielding tributaries (e.g. Laidley Creek, Tenthill Creek and Ma Ma Creek). In contrast, relatively few historic surface water chemistry records are available for smaller tributaries such as Plain Creek, where the one-off surface water quality survey for this study indicated highly saline surface water similar in composition to groundwaters of clusters 6 and 7.

6. Discussion

6.1. Hydrogeological conceptual model of groundwater recharge and aquifer and surface water groundwater interactions

6.1.1. Interactions between bedrock aquifers

In order to use hydrochemistry to identify areas where bedrock aquifers interact with alluvial aquifers and streams, it is important to understand the spatial variability of hydrochemistry and its controls within the bedrock.

Hydrothermal groundwaters have been described near Helidon and interpreted as originating from the Great Artesian Basin (Dempster, 1986), and as a possible discharge area for the Precipice Sandstone (equivalent of the Woogaroo Subgroup) from the linked Surat Basin (Fig. 1). Previous analyses of groundwater also revealed the presence of very high ^{222}Rn, radium and lithium concentrations in the groundwaters at springs near Helidon (Dempster, 1986), characteristics commonly associated with groundwaters that have interacted with granites.

There are several notable geological and hydrogeological features in this area that may influence this distinctive water chemistry. Firstly, as

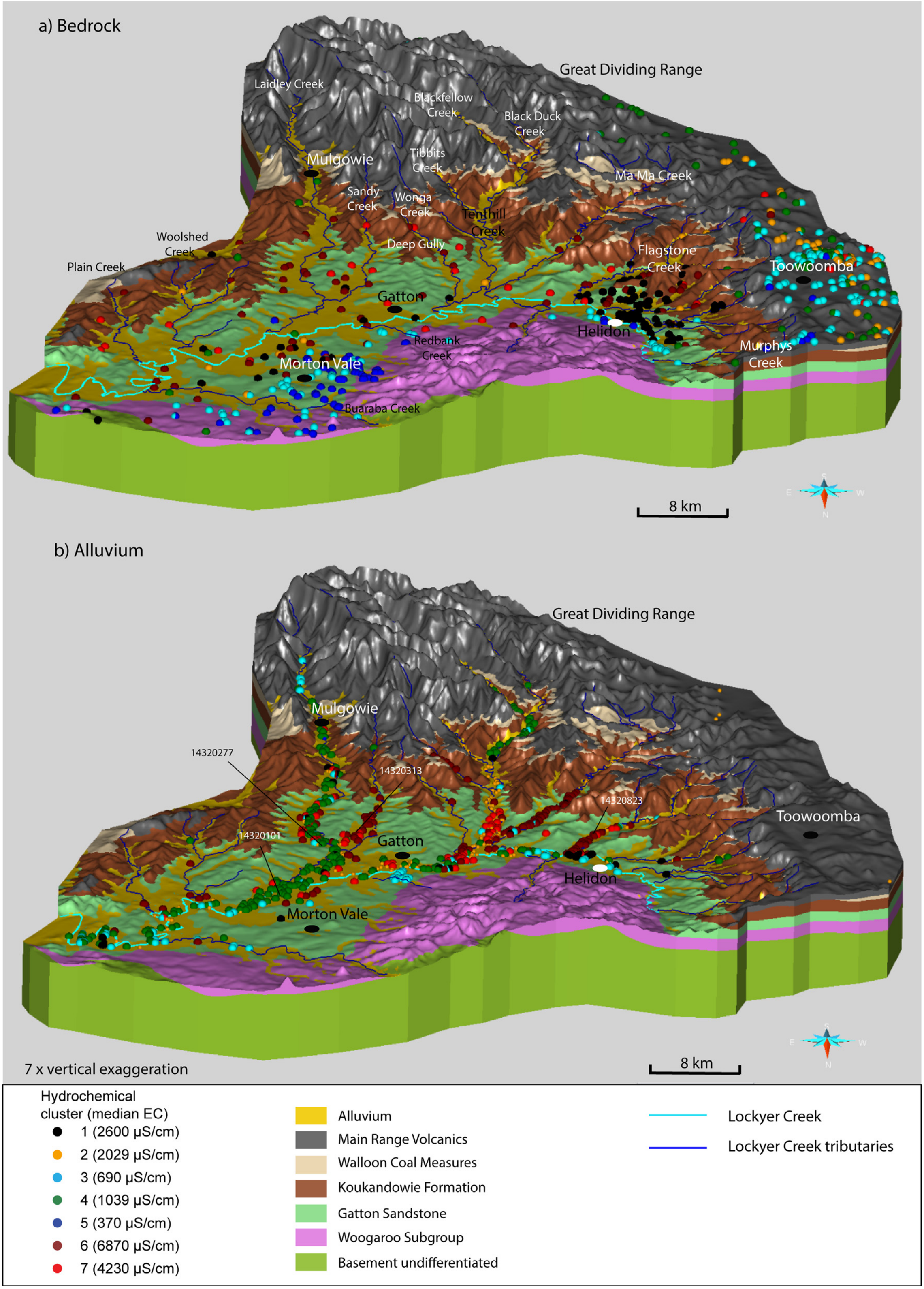


Fig. 7. Hydrochemical clusters in a) bedrock and b) alluvial aquifers in the Lockyer Valley projected on the 3D geological model. The locations of selected bores with hydrochemical time series (Fig. 10) are also shown.

previously mentioned, a subsurface granite is present in this area (Wells and O'Brien, 1994; DNRM, 2002). Furthermore, as suggested by Smerdon and Ransley (2012) and confirmed by the 3D geological model in the present study, a major structural feature, the Helidon Ridge, traverses this area. Local faults and fractures in this area possibly associated with this ridge were also described and proposed as an influence on the spatial extent of the spa waters by Dempster (1986).

The similar water chemistry in the Gatton Sandstone and the Woogaroo Subgroup (groundwaters from both aquifers in this area are assigned primarily to Cluster 1; Fig. 7a) here indicates that these two

Table 1
Median concentrations of hydrochemical parameters for the seven groundwater chemistry clusters of data in the Lockyer Valley.

Cluster	Number	EC (μS/cm)	pH	all parameters in mg/L									HCO_3/Cl	SO_4/Cl	Na/Cl	Ca/Na	Mg/Na	K/NA
				Na	K	Ca	Mg	HCO_3	Cl	NO_3	SO_4	F						
1	259	2600	8.0	544.0	16.0	27.6	18.5	1200.0	315.0	1.5	14.0	0.6	3.81	0.04	1.73	0.05	0.03	0.029
2	845	2029	7.9	140.0	2.0	93.0	111.0	474.0	420.0	6.0	30.0	0.2	1.13	0.07	0.33	0.66	0.79	0.014
3	369	690	7.7	81.8	3.0	31.0	20.0	180.0	110.0	0.8	7.0	0.1	1.64	0.06	0.74	0.38	0.24	0.037
4	773	1039	8.1	73.0	1.4	52.0	52.0	402.0	125.2	1.9	9.0	0.1	3.21	0.07	0.58	0.71	0.71	0.019
5	110	370	6.7	42.0	5.8	12.0	7.2	70.5	56.0	0.5	5.5	0.1	1.26	0.10	0.75	0.29	0.17	0.138
6	538	6870	7.6	794.5	5.4	203.5	270.0	591.5	2100.4	11.1	149.1	0.2	0.28	0.07	0.38	0.26	0.34	0.007
7	261	4230	7.7	284.0	3.0	195.0	225.0	463.0	1200.0	4.4	40.0	0.1	0.39	0.03	0.24	0.69	0.79	0.011

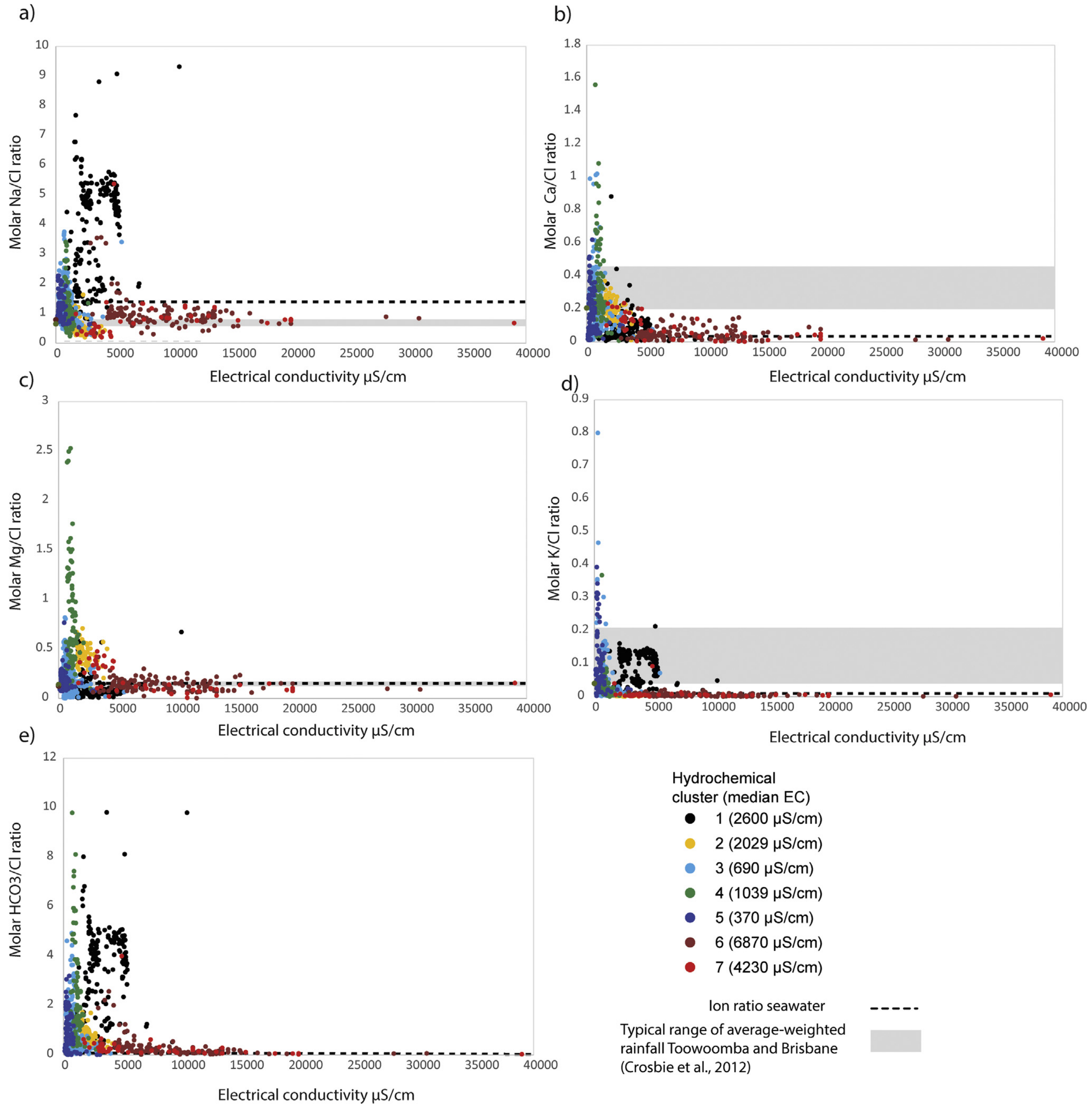


Fig. 8. Ion/Cl versus electrical conductivity plots for groundwater in volcanic and sedimentary bedrock aquifers in the Lockyer Valley. Average-weighted rainfall ion ratios are based on Crosbie et al. (2012).

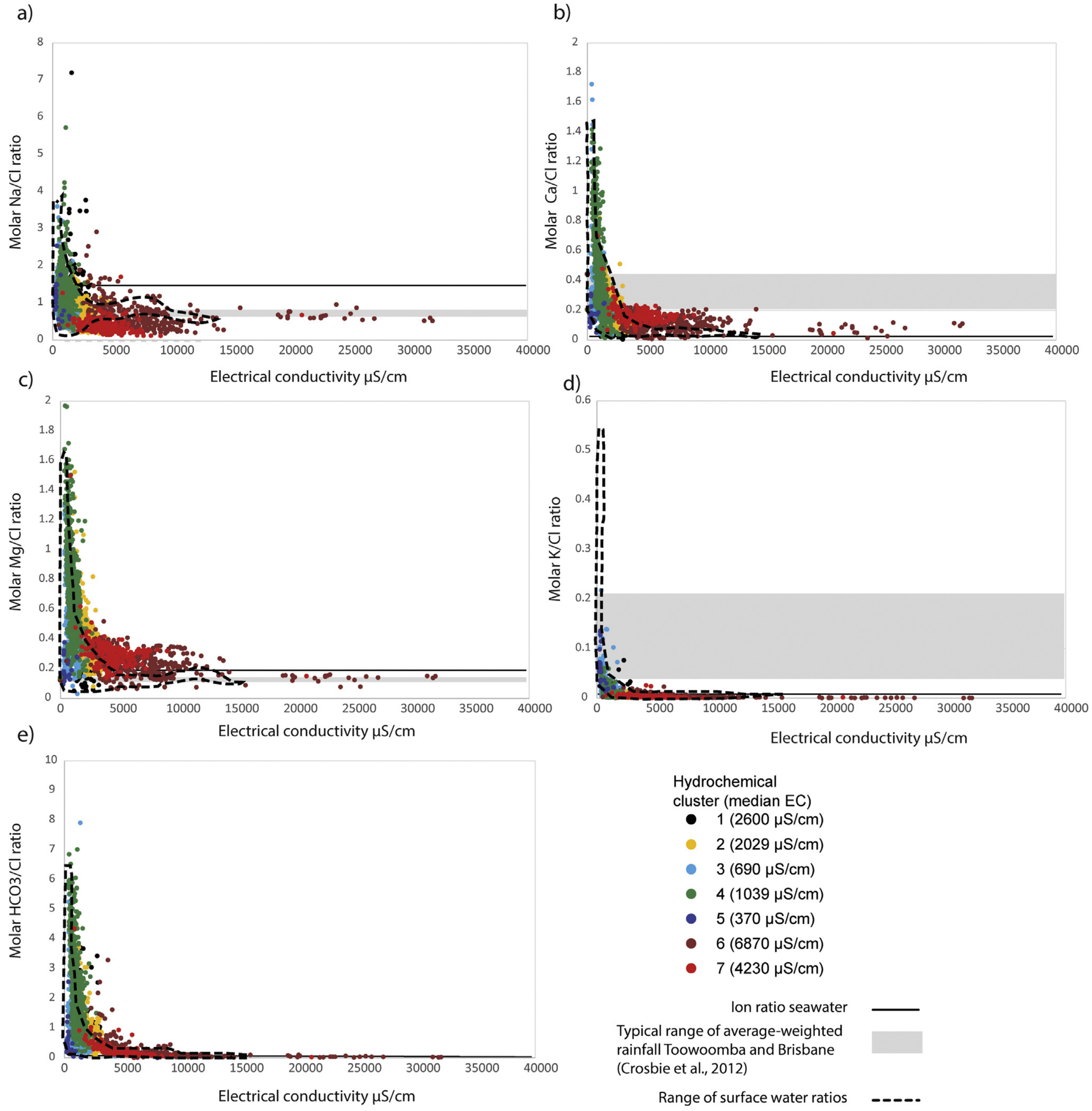


Fig. 9. Ion/Cl versus electrical conductivity plots for groundwater in alluvial aquifers and surface water in the Lockyer Valley. Average-weighted rainfall ion ratios are based on Crosbie et al. (2012).

aquifers are likely connected locally. This distinct water chemistry composition occurring in both the Gatton Sandstone and Woogaroo Subgroup here may be influenced by the geological structures in this area or by interaction with the subsurface granite. Although the mechanism of this proposed connection is not clear, it appears that faults and fractures may form gas and water migration pathways possibly linking the subsurface granite, the Gatton Sandstone, the Woogaroo Subgroup and springs observed in this area. Whether there is a possible hydraulic connection to the Surat Basin remains an open research question.

In contrast to the proposed hydraulic connection between the Gatton Sandstone and the Woogaroo Subgroup in the Helidon area, they appear to be largely separated in other parts of the Lockyer Valley. In the eastern part of the Lockyer Valley near Morton Vale (Figs. 1 and 3), for instance, opposing groundwater flow directions of the Gatton Sandstone (flow towards the north; Fig. 3) and Woogaroo Subgroup (flow towards the south-east) (Fig. 5a) as well as hydrochemical differences suggest a limited connection between these formations (Fig. 7a). Here, groundwater in the Woogaroo Subgroup is very fresh with many samples assigned to clusters 3 and 5 (median electrical conductivity of 690 and 370 µS/cm, respectively), whereas many Gatton Sandstone groundwater samples are assigned to clusters 6 or 7. Limited water-rock interaction with the dominant coarse-grained quartz-rich sandstone and conglomerates explain low salinity values in the Woogaroo Subgroup. These prevalent rock types favour rapid groundwater recharge with limited evapotranspiration. The Gatton Sandstone is also dominated by sandstones, but with higher clay and cement contents than the clean quartzose sandstones of the Woogaroo

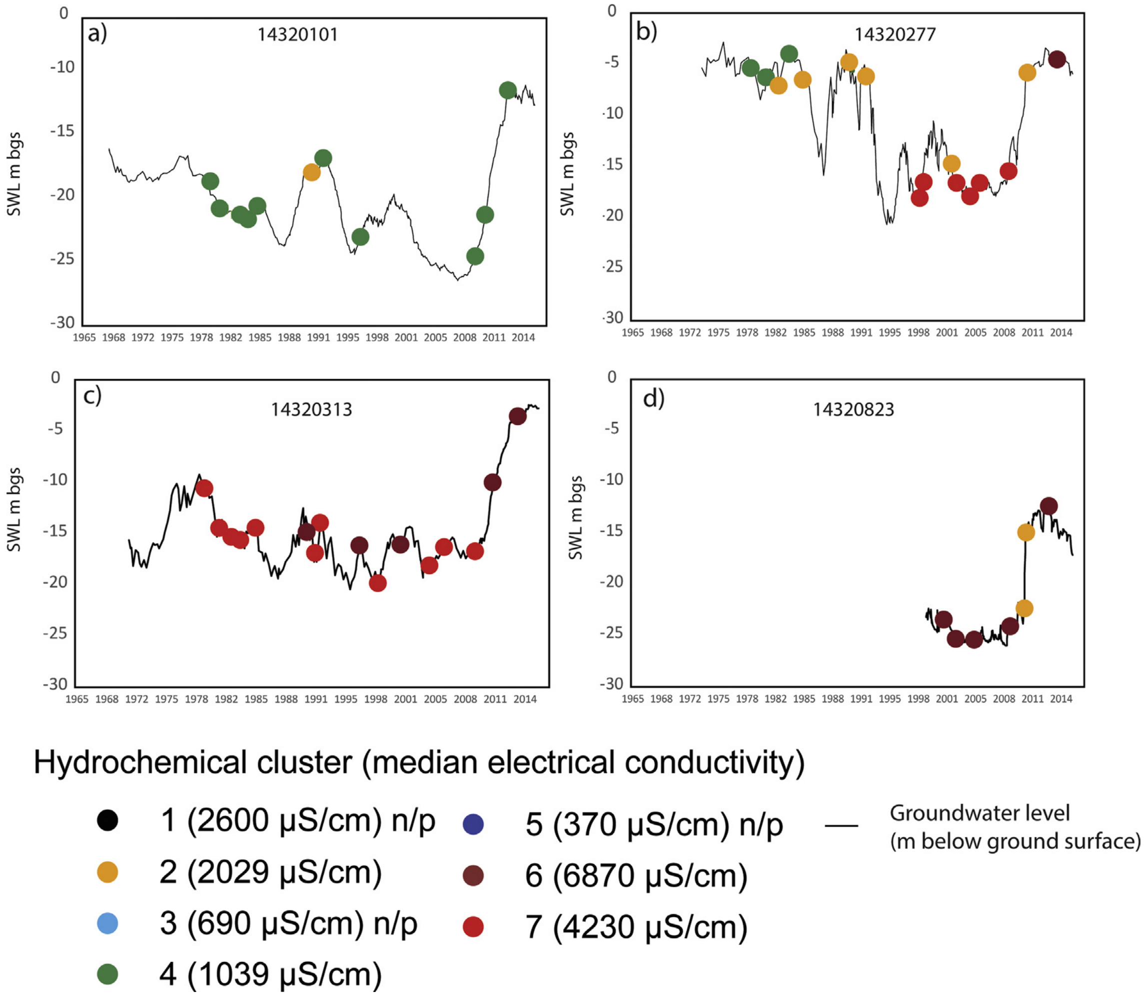


Fig. 10. Groundwater chemistry and groundwater level time series at selected alluvial groundwater monitoring sites (locations are shown on Fig. 7a). N/p indicates that no groundwater chemistry samples were assigned to these clusters at these four sampling locations.

Subgroup (Rassam et al., 2014). As a result of its more clay-rich composition and commonly thick weathering profiles, groundwater recharge to the Gatton Sandstone is likely to be slow, favouring evapotranspiration during long retention times in the unsaturated zone.

In the southern part of the Lockyer Valley near the Great Dividing Range, the lack of nested groundwater monitoring sites in the MRV and the WCM, as well as sparse hydrochemical data for the WCM, prevent an assessment of the degree of connection between these two units. However, if there is a hydraulic connection between the MRV, the WCM and underlying sedimentary bedrock units in this area, then this is unlikely to result in any significant downwards percolation into the units underlying the WCM. This is due to the strong contrast in hydrochemistry between the MRV and the Koukandowie Formation and the Gatton Sandstone, which suggests that these units do not receive substantial recharge through the overlying volcanics. Instead, these sedimentary bedrock units are recharged primarily through diffuse rainfall recharge in their outcrop areas, where thick clay-rich weathering profiles allow only slow recharge and facilitate high evapotranspiration and interaction with clays during or prior to recharge, as observed in studies elsewhere (e.g. Bennetts et al., 2006; Edwards and Webb, 2009; Raiber et al., 2015). An exception to this exists at the Great Dividing Range near Toowoomba in the western part of the Lockyer Valley, where there are greater similarities between groundwater chemical compositions of the different aquifers.

6.1.2. Interactions between Main Range Volcanics, alluvial aquifers and surface waters

The outcrops of the MRV in the Lockyer Valley are characterised by steep terrains with thin soil profiles and areally extensive outcrops of fresh and unweathered basalt (Section 2), particularly near the peaks in the southern part of the catchment. The high degree of fracturing of the basalts results in high recharge rates and low salinity groundwater in the MRV (clusters 3, 4 and 5, Fig. 6). There is a predominance of coarse-grained components within the alluvial aquifers of the upper catchment, allowing for groundwater to be stored and transmitted rapidly. The unconfined nature of alluvial aquifers in the upper catchment of tributary systems such as Laidley Creek or Tenthill Creek is comparable to that of fractured basalt aquifer systems elsewhere in the Clarence-Moreton Basin (e.g. Duvert et al., 2015b; Martinez et al., 2015, 2017), as well as other basaltic aquifers in Australia (e.g. Bennetts et al., 2006; Raiber et al., 2015) and overseas (e.g. Kebede et al., 2005; Demlie et al., 2007). The fresh groundwaters (typically less than 1000 µS/cm) in the alluvial and volcanic aquifers in the upper catchment are dominated by Na–HCO_3 (Figs. 6, 8 and 9) and high major ion/Cl ratios (e.g. Mg and Ca) (Figs. 8 and 9), with excess ions relative to average-weighted local precipitation in Toowoomba supplied by the dissolution of primary silicate minerals (e.g. plagioclase) within the basalts or alluvial sediments composed of basaltic components.

The 3D geological model showed that Laidley Creek and Tenthill Creek (including its tributary Black Duck Creek) are deeply incised into the MRV (Fig. 5a) and intercept the natural groundwater pathways of

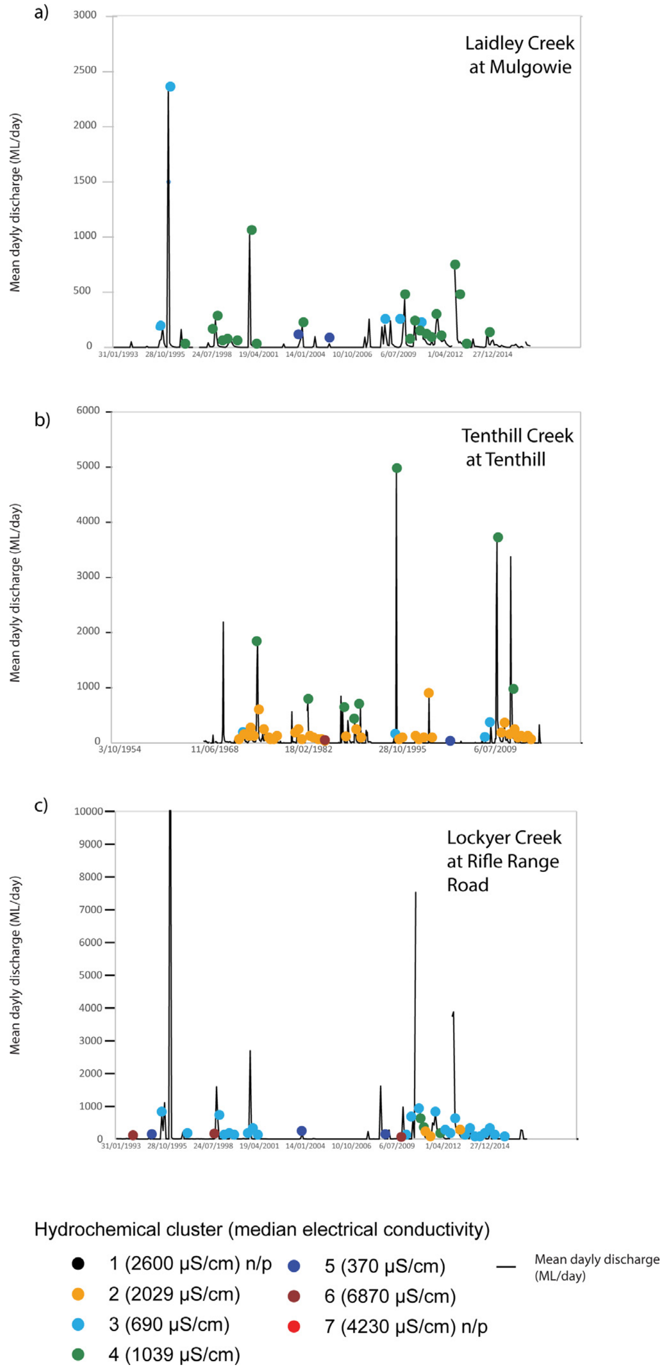


Fig. 11. Surface water chemistry and stream hydrograph time series at selected surface gauging stations (locations are shown on Fig. 12). N/p indicates that no groundwater chemistry samples were assigned to these clusters at these locations.

the volcanic aquifers, thus forming groundwater discharge points (Section 4.1). Surface waters here are very fresh (Figs. 11 and 12), dominated by HCO_3, with high Ca and Mg concentrations (Fig. 9) and with an overall composition similar to the composition of groundwater in clusters 3, 4 and 5 (Fig. 9). This suggests that a large proportion of the initial recharge to the basalts discharges into the alluvium or directly to surface water or springs where no alluvium is developed, following short flow paths and with short lag times. Only a small proportion of this recharge percolates to deeper aquifers, as highlighted by the absence of fresh groundwaters in sedimentary bedrock aquifers underneath the MRV in most areas (Section 5.1).

However, even after extended periods of no rainfall (and thus, no recharge), groundwater continues to drain from the basalts providing continuous baseflow and sustaining streams.

Notably, the influence of the basalts on the hydrochemistry of the alluvial aquifers and surface waters extends beyond its footprint in the Laidley Creek sub-catchment, as also described in the neighbouring Condamine River catchment by Martinez et al. (2017). Fresh groundwaters with a similar hydrochemical composition as surface waters and basalt groundwaters occur along the entire course of Laidley Creek to its confluence with Lockyer Creek (Fig. 7b and 11). These similar compositions highlight the significance of surface water recharge and the influence of the MRV in this catchment.

6.1.3. Interactions between sedimentary bedrock, alluvial aquifers and surface water

Most of the smaller tributaries are generally not incised into the MRV (e.g. Plain Creek, Woolshed Creek, Sandy Creek, Soda Spring Creek, Monkey Water Holes Creek and Deep Gully; Fig. 12). As a result, unlike for the headwaters of larger tributaries such as Laidley Creek or Tenthill Creek, there is little or no influence of the basalts on recharge and the hydrochemical evolution of groundwater and surface water in these smaller tributary systems. Instead, the Gatton Sandstone and Koukandowie Formation commonly form the sub-alluvial bedrock aquifers in these smaller tributary systems within the Lockyer Valley.

Smaller tributaries form natural discharge areas for the Gatton Sandstone and Koukandowie Formation, as indicated by the 3D geological model and potentiometric surface map (Figs. 3 and 5). Both Gatton Sandstone and Koukandowie Formation contain brackish to saline groundwater assigned to clusters 6 and 7 in these areas, and groundwaters within alluvial aquifers of the lower parts of tributary sub-catchments or smaller tributaries such as Plain Creek, Sandy Creek and Ma Ma Creek are also dominated by groundwaters assigned to clusters 6 and 7 (Fig. 7b). This hydrochemical similarity with the water chemistry of the alluvial aquifer systems confirms the significance of upwards leakage from the sub-alluvial sedimentary bedrock. Both Cluster 6 and Cluster 7 have elevated Na-Cl ratios, and major ion/Cl ratios rapidly decrease to values close to or below those in local rainfall (Fig. 9). This suggests that the weathering-derived ions observed in groundwaters of other hydrochemical clusters are removed from solution by adsorption on clay mineral surfaces. Furthermore, many of these groundwaters have saturation indices exceeding the threshold where calcite precipitation typically occurs ($SI > 0.5$). This suggests that calcite or dolomite precipitation has removed some Ca, Mg and HCO_3 from the groundwater. Although only represented by relatively few samples from the synoptic surface water quality survey (Fig. 11) and from the DNRM surface water monitoring (DNRM, 2017), the salinity and hydrochemistry of surface waters here are similar to those of groundwaters, confirming the close hydraulic connection between sedimentary bedrock, alluvial systems and surface water in these small tributary systems.

The initial conceptual model based on aquifer geometry and the potentiometric surface of the shallow sedimentary bedrock suggested that flow paths within the sedimentary bedrock are intersected by the alluvial systems near the edge of the alluvial aquifers in the mid- to lower reaches of major tributaries. This is confirmed by the presence of brackish to saline alluvial groundwater samples of clusters 6 and 7 at the margins of the alluvium throughout different parts of the catchment, including within the Lockyer Creek alluvium and its major tributary systems (e.g. Laidley Creek) (Fig. 7b). These patterns are likely to vary spatially, and as demonstrated by the example of groundwater monitoring bore 14320277 located in the lower Laidley Creek sub-catchment (Fig. 7b and 10d), the relative significance of this discharge component from the underlying sedimentary bedrock at the edge of the alluvium varies over time. During prolonged drought periods, the relative water level difference (head gradient) between the alluvial and sedimentary bedrock aquifers can be reversed due to more rapid and

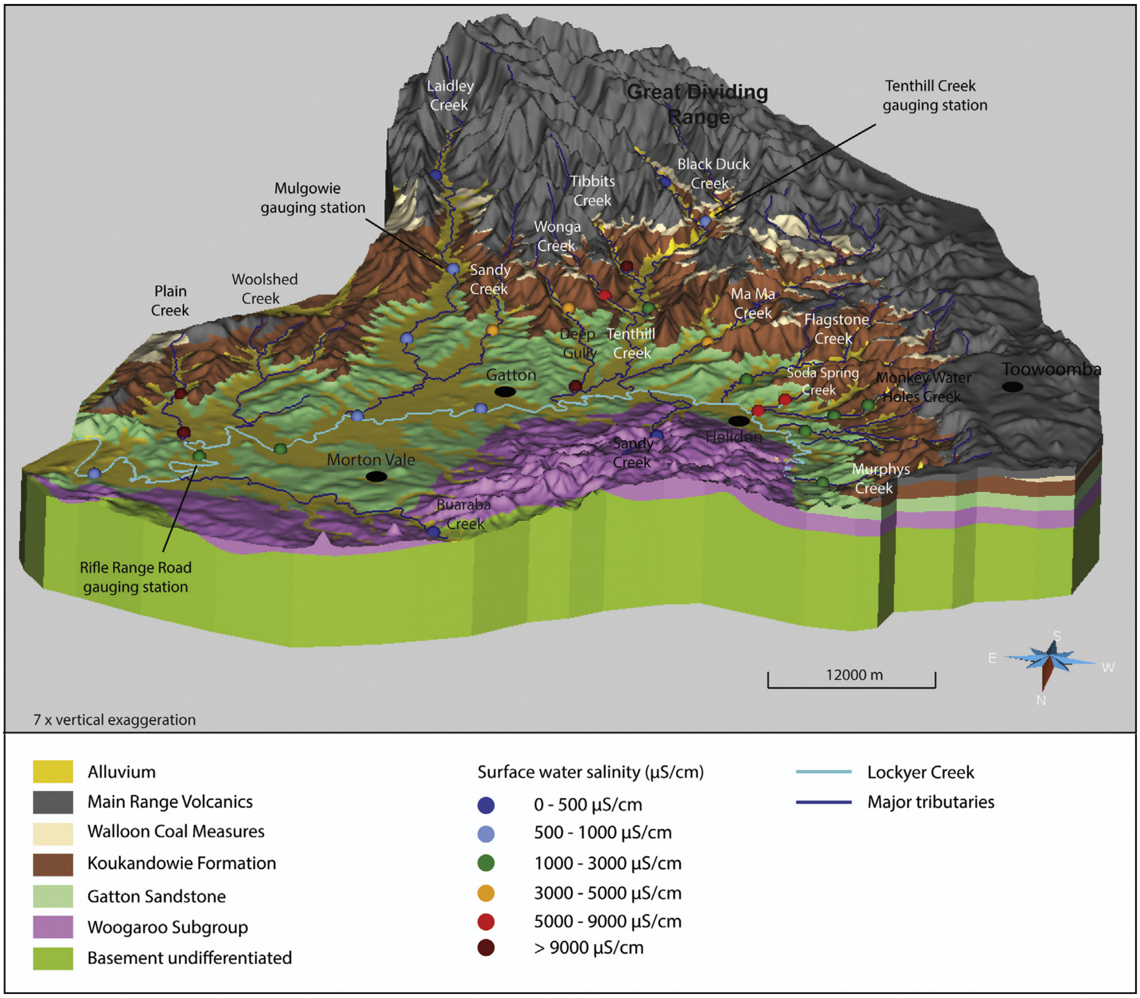


Fig. 12. Stream salinities (represented by the electrical conductivity) in the Lockyer Valley measured during low periods of low flows (synoptic survey during baseflow conditions in 2012). Three gauging stations (Fig. 11) are also shown.

pronounced declines in alluvial water levels resulting from a lack of recharge and continuous pumping compared to those of the sedimentary bedrock aquifers (Raiber et al., 2017b; Cui et al., 2018). As a result of the increasing head gradient, there is a higher potential for discharge from the sub-alluvial bedrock to the alluvium during droughts, and a considerable proportion of the alluvial groundwater in these zones may be sourced from the underlying bedrock during drought conditions. In many studies, it is assumed that there is no or insignificant connection between sedimentary bedrock and alluvial aquifers due to weathering profiles developed on the sedimentary bedrock. However, the contact between alluvium and sub-alluvial bedrock is erosional, and the weathering profiles are usually thin or absent near the edge of the alluvium. It is therefore likely that the weathering profiles that may have originally developed on the sedimentary bedrock are likely to be compromised or absent in some areas, allowing connection between the different aquifers.

In contrast to the influence of sedimentary bedrock discharge on water quality and balance of the alluvium during dry periods, during ‘normal’ (non-drought) times, the sedimentary bedrock discharge component is overwhelmed by other recharge sources (e.g. surface water recharge, diffuse rainfall recharge, flood recharge or irrigation returns) in Lockyer Creek and its larger tributary systems.

In the lower part of the Plain Creek and Woolshed sub-catchments in the eastern part of the Lockyer Valley (Fig. 7), groundwater levels within the alluvial aquifer are typically relatively shallow. Some of the most saline alluvial groundwaters (Fig. 7b) and surface waters (Fig. 11) assigned to clusters 6 and 7 occur in these areas. This suggests that in addition to discharge from the sub-alluvial sedimentary bedrock, which here contains saline groundwater, there is also likely to be some influence of dryland salinity (i.e. evaporation from shallow water tables) in these areas.

7. Conclusions

In most studies where integrated catchment-scale hydrological models are developed, catchments are commonly represented as simplified and relatively shallow groundwater systems. In these models, the influence of sub-alluvial bedrock on water balance and water quality of alluvial aquifers and streams is often neglected.

In this study, we use the multi-aquifer system (volcanic, sedimentary bedrock and alluvial aquifers) of the Lockyer Valley, an important agricultural catchment in the Clarence-Moreton Basin in south-eastern Queensland (Australia), as an example to highlight the variable spatial and temporal significance of discharge from regional-scale bedrock aquifers to alluvial aquifers and streams during cycles of drought and flooding. For this purpose, we have applied multivariate statistical techniques to groundwater and surface water data, combined with development of a 3D geological model that represents the geometry of all major volcanic, sedimentary bedrock and alluvial aquifer systems in the Lockyer Valley.

The study confirmed that the alluvial aquifers are recharged from multiple sources, and that the relative contribution from different sources varies spatially. The 3D geological model combined with hydraulic data was instrumental in identifying broad areas where alluvial aquifers and streams intercept the natural groundwater pathways of the volcanic and sedimentary bedrock aquifers, thus forming groundwater discharge points. The hydrochemical assessment confirmed that there is a high degree of variability associated with the geological complexity, as most sub-catchments within the Lockyer Valley are characterised by very distinct alluvial groundwater chemistry patterns resulting from mixing of different recharge sources and interactions with sub-alluvial bedrock. In the headwaters of the Lockyer Creek and its tributaries, for instance, the hydrochemistry indicated that there is a very strong influence of the Main Range Volcanics (an extensive fractured rock volcanic aquifer system) on recharge of the alluvial aquifer and stream flow. These systems have fresh alluvial groundwaters and fresh surface water with electrical conductivities typically less than 1000 µS/cm and a hydrochemical composition similar to the basalt groundwater. Further down-gradient, there is an increasing influence of discharge from sub-alluvial sedimentary bedrock aquifers of the Clarence-Moreton Basin on alluvial groundwater composition and surface water. This influence is particularly evident in smaller tributary systems and at the edge of the alluvial aquifers in larger tributaries, where alluvial groundwaters are brackish to saline and compositionally similar to groundwaters in the sub-alluvial sedimentary bedrock. Importantly, in addition to the distinct spatial patterns of hydrochemistry, there is a strong temporal variability in recharge sources and connectivity, as demonstrated at multiple sites where long-term groundwater and surface water time series hydrochemical records exist. In the larger tributary systems, discharge from the sedimentary bedrock to the alluvium or streams is likely to be relatively insignificant during ‘normal’ climatic periods or following flooding. However, the influence of discharge from bedrock on quantity and quality of water in shallow alluvial aquifers and streams can become significantly more important during extended dry periods and droughts. This influence can have both positive and negative effects. For example, continuous discharge from the sub-alluvial bedrock to streams observed in some areas contributes baseflow which helps to sustain flows and sustain groundwater dependant ecosystems during prolonged dry periods or droughts. On the other hand, where the water quality of the sedimentary bedrock is very poor (e.g. due to high salinities observed in some of the sedimentary bedrock aquifers within the Lockyer Valley), the relatively higher significance of sedimentary bedrock discharge to the alluvium during droughts can result in a significant deterioration of water quality in the alluvial aquifer systems in some areas, making it unusable for most agricultural activities. This is because other recharge sources such as surface water- or rainfall recharge have ceased during these extended dry periods.

Although all catchments have their own physical characteristics, some general lessons and ideas can be transferred from this study to catchments elsewhere. Firstly, the complex spatial and temporal patterns of connections between alluvium and streams, likely to be similar in mid-reaches of other catchments with dynamic climates dominated by droughts and flooding elsewhere, highlights the challenge in defining where groundwater-surface water interaction occur (and thus, whether river reaches are gaining, losing or disconnected). Secondly, this study also demonstrates that it should not be automatically assumed that there is no hydraulic connection between sedimentary bedrock and alluvial aquifers and streams, as this relationship can be very complex and variable both spatially and temporarily. Monitoring networks generally sample the subsurface at a limited number of locations, and in many catchments in Australia (and likely elsewhere), they are often designed to assess the water quantity (i.e. water levels) of the uppermost (often alluvial) aquifers rather than the hydraulic connection between shallow and deep aquifers. They may therefore not capture the hydraulic connection between bedrock and alluvial aquifers. Although it may sound trivial, it is important to reinforce that approaches that integrate multiple lines of geoscientific evidence and honour all available hydrochemical, hydraulic, lithological and stratigraphic records help to reduce the likelihood of misconceptions or oversimplifications in catchment hydrological and hydrogeological investigations. Insights gained from such multi-disciplinary approaches can support future water resource planning and management through an improved conceptual understanding of the hydrogeology and surface water – groundwater interactions, as well as through a more robust model structure and framework to apply in groundwater flow and catchment hydrological simulations.

Declaration of interests

None.

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Appendix 1

Hierarchical Cluster Analysis (HCA) is a multivariate statistical technique, which is commonly adopted in groundwater hydrochemical studies to identify patterns within a dataset to enhance the understanding of physical and chemical processes that underpin groundwater evolution (e.g. Stetzenbach et al., 1999; Güler et al., 2002; Menció and Mas-Pla, 2008; Daughney et al., 2010; Raiber et al., 2012). Ideally, a large number of variables should be included in HCA to capture spatial and temporal processes that control groundwater chemical evolution. In the DNRM (2015) groundwater database, hydrochemical data exist for a large number of variables including both major and minor ions. However, in this study, only ten variables were selected (Ca, Mg, Na, K, HCO_3, Cl, F, $SO_{4,}$ pH and electrical conductivity) as they were measured across most sites whereas variables such as Fe, Mn and NO3 were excluded to their relatively poor spatial coverage. Prior to the multi-variate statistical analysis, data quality checks were performed on all hydrochemical records. Sample records with charge balances outside ± 5%, or where the aquifer at the screened interval was unknown, were excluded from further analysis; this resulted in a hydrochemical dataset with 3155 complete hydrochemical records (i.e.

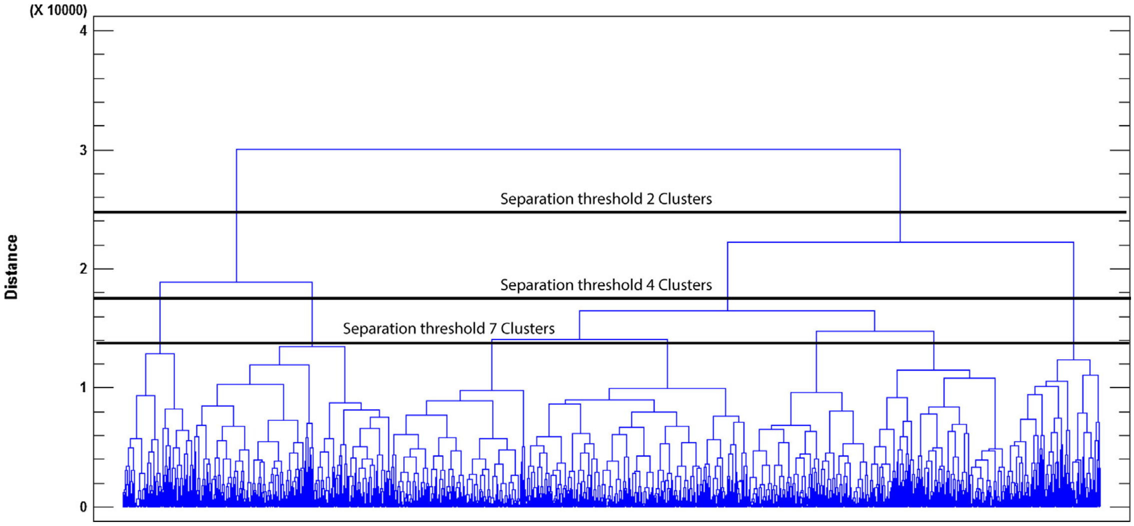

Fig. A1. Dendrogram for 3155 groundwater chemistry samples in the Lockyer Valley.

where all ten selected parameters had a measured value) from 1190 groundwater bores.

Many of these groundwater bores were only sampled once, although some bores were sampled multiple times (the largest number of time series hydrochemical records for a single groundwater bore included in the cluster analysis is 16). In contrast to other studies where the median was used as a representative of time-series data from particular groundwater bores (e.g. Guggenmos et al., 2011), all sampling records that passed the data quality checks were included in this study to evaluate temporal patterns and understand the influence of droughts and flooding on groundwater chemistry.

All variables except pH were log-transformed to approximate a normal distribution before the multivariate statistical analysis was conducted.

The HCA presented in this work was carried out using the StatGraphics Centurion software (Manugistics Inc., USA). Prior to the clustering, the variables were standardized by subtracting its sample mean and then dividing by its sample standard deviation. Two linkage rules were adopted: (1) the nearest neighbour rule was applied to identify sites with significantly different hydrochemical signatures; these were removed as outliers/ residuals from the data set, and, (2) the Ward's rule, which allowed the generation of distinct clusters based on analysis of variance; this resulted in grouping of all non-residuals into separate clusters. Dissimilarities across all variables were assessed using the square of the Euclidean distance (E). The transformed input data together with linkage rules and the dissimilarity measure are described as the most appropriate techniques for identifying patterns in hydrochemical data sets (Güler et al., 2002; Daughney et al., 2012; Raiber et al., 2012). The outcome of this process is a dendrogram (Cloutier et al., 2008) (Fig. A1).

HCA is considered a semi-objective technique as it involves an element of judgment when determining the number of clusters that are representative of the sample population (e.g. Daughney et al., 2012). In this study, the dendrogram was visually inspected, and centroid concentrations (represented by the median) for different input variables and clusters at different separation thresholds (Fig. A1) and the spatial distribution of clusters were compared to decide on an appropriate separation threshold or phenon line which determines the number of clusters (Güler et al., 2002; Cloutier et al., 2008; Daughney et al., 2012; Raiber et al., 2012). The median was used for the comparison as it is considered as a better indicator of central tendency than the mean as the median is less sensitive to extreme values (Helsel and Hirsch, 2012).

Surface water data were not integrated into the HCA, as there are a very large number of measurements available at some sites (up to 170 hydrochemical time-series records at a single monitoring station). Using all of these data could potentially skew the dataset, but there are different ways of dealing with such extensive time-series data. For example the median of all time-series data can be included to represent surface water monitoring datasets (e.g. Martinez et al., 2015). In the present study, however, we have conducted a discriminant analysis (DA) for this purpose. This approach provides insights into the similarity between groundwaters and surface waters without skewing the groundwater chemistry dataset, and it also allows assessment of temporal variabilities within the surface water time series data. DA is a multivariate statistical technique that predicts into which of two or more categories an observation is most likely to fall based on a set of classification functions and a certain combination of input variables (e.g. Daughney et al., 2010; Raiber et al., 2012). The discriminant analysis is designed to develop a set of discriminating functions which can help predict the cluster membership of the surface water chemistry records based on the values of other quantitative variables. All complete groundwater chemistry cases ($n = 3155$) were used to develop a model to discriminate among the seven clusters from the HCA. Ten predictor variables (the hydrochemical parameters listed above) were entered, and the derived six discriminating functions with P-values less than 0.05 are statistically significant at the 95.0% confidence level. Amongst the 3155 observations (the groundwater chemistry records) used to fit the model, 2643 (84%) were correctly classified. Surface water chemistry cluster memberships were then predicted as new observations to assess their similarity with groundwater chemistry records and predict to which groundwater chemistry cluster they would be most likely assigned.

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