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REPORT

Response of groundwater level and surface-water/groundwater interaction to climate variability: Clarence-Moreton Basin, Australia

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Abstract Understanding the response of groundwater levels in alluvial and sedimentary basin aquifers to climatic variability and human water-resource developments is a key step in many hydrogeological investigations. This study presents an analysis of groundwater response to climate variability from 2000 to 2012 in the Queensland part of the sedimentary Clarence-Moreton Basin, Australia. It contributes to the baseline hydrogeological understanding by identifying the primary groundwater flow pattern, water-level response to climate extremes, and the resulting dynamics of surface-water/groundwater interaction. Groundwater-level measurements from thousands of bores over several decades were analysed using Kriging and nonparametric trend analysis, together with a newly developed three-dimensional geological model. Groundwater-level contours suggest that groundwater flow in the shallow aquifers shows local variations in the close vicinity of streams, notwithstanding general conformance with topographic relief. The trend analysis reveals that climate variability can be quickly reflected in the shallow aquifers of the Clarence-Moreton Basin although the alluvial aquifers have a quicker rainfall response than the sedimentary bedrock formations. The Lockyer Valley alluvium represents the most sensitively responding alluvium in the area, with the highest declining (−0.7 m/year) and ascending (2.1 m/year) Sen's slope rates during and after the drought period, respectively. Different surface-water/groundwater interaction characteristics were observed in different catchments by studying groundwater-level fluctuations along hydrogeologic cross-sections. The findings of this study lay a foundation for future water-resource management in the study area.

Keywords Climate change · Australia · Trend analysis · Kriging · Baseline study

Introduction

The Clarence-Moreton Basin (CMB) is a Mesozoic intracratonic basin in north-eastern New South Wales (NSW) and south-east Queensland (Fig. 1; Wells and O'Brien 1994). Substantial coal, coal seam gas (CSG, also referred to as coal bed methane) and conventional gas resources have been discovered in the basin (e.g. Wells and O'Brien 1994; Ingram and Robinson 1996; Doig and Stanmore 2012; Geoscience Australia and BREE 2014; Raiber et al. 2015). Although coal mining activity has ceased and current CSG exploration has halted in many parts of the basin, the identification of commercially viable resources means that there remains potential for future developments of coal or CSG resources; furthermore, multiple catchments within the CMB form important agricultural areas.

Prior to the impact assessment of potential future CSG development activities and other developments on adjacent aquifer systems and groundwater dependent ecosystems, it is important to have a good baseline understanding of the sedimentary basin hydrodynamics in potential areas of potential resource development (Nieto et al. 2005; CAFTA-DR and US Country EIA and Mining Experts 2011; Hamawand et al. 2013; Davies et al. 2015). This requires knowledge of the past and current groundwater levels, the hydraulic connection between shallow aquifers (i.e. alluvium, volcanics, and unconfined part of the bedrock aquifers) and deeper sedimentary

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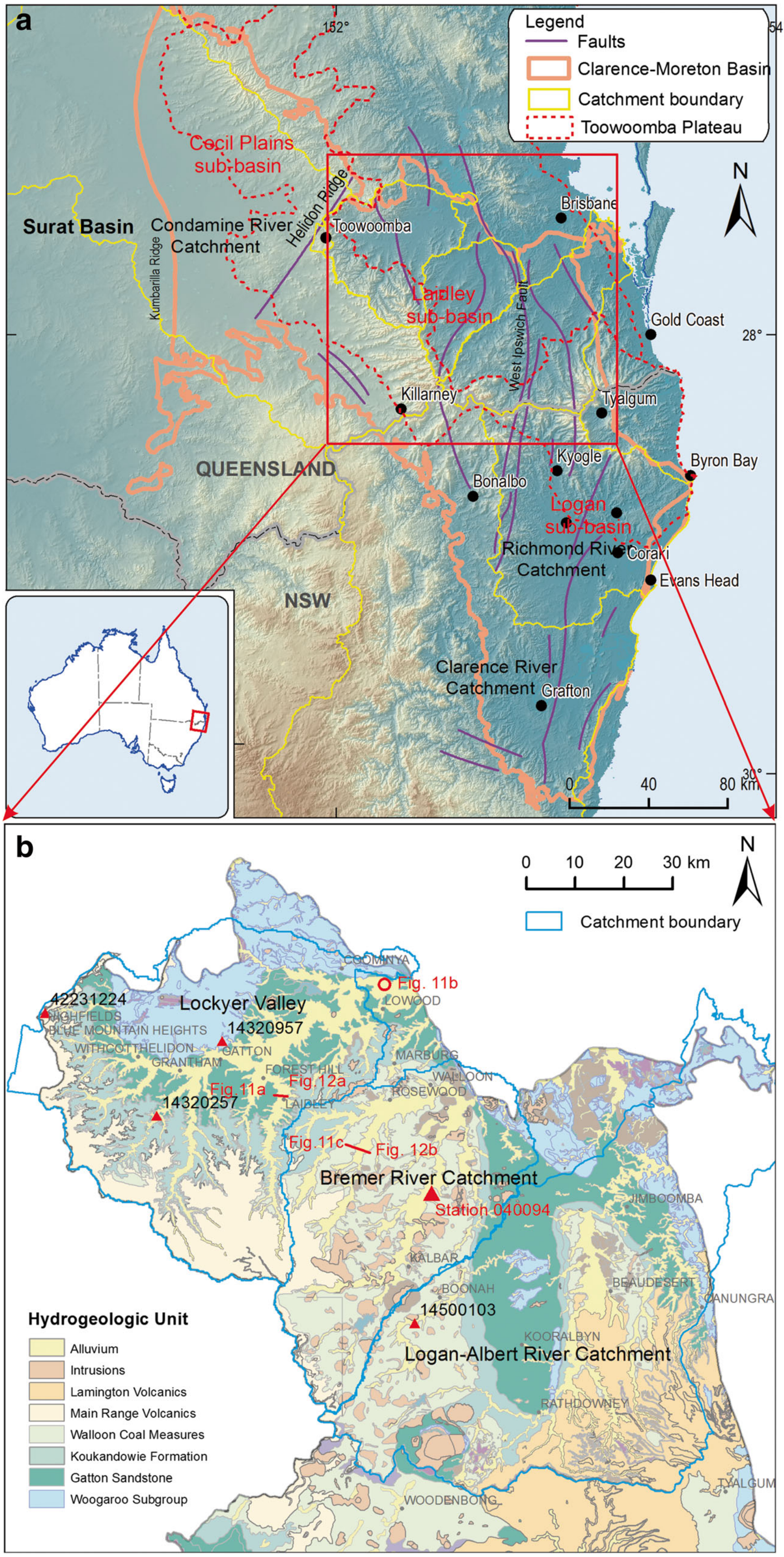
Fig. 1 **a** The location of the Clarence-Moreton Basin in eastern Australia and its main structures. The study area is highlighted by the *red square* in (**a**) and shown in more detail in (**b**). The locations of bores and cross-sections discussed later in *Fig. 11* and *Fig. 12*, respectively, are also indicated



bedrock aquifers and between aquifers and streams (Dafny and Silburn 2013; Duvert et al. 2015).

Groundwater levels are among the most fundamental and critical baseline data that underpin the understanding of groundwater systems. They are used to infer groundwater flow pattern and aquifer inter-connectivity. The response of water levels to precipitation is an important indicator of the connectivity between the surface water and groundwater systems (Sophocleous 2002; Scibek et al. 2007; Duvert et al. 2015; Barthel and Banzhaf 2016; Hocking and Kelly 2016; Martinez et al. 2017). In addition, groundwater levels (together with fluxes) are the most typical observations used to calibrate numerical groundwater models (Anderson et al. 2015).

At the regional scale, depth to groundwater table is primarily driven by topography and climate (Fan et al. 2013). Climatic extremes such as extended droughts and floods can cause significant fluctuations in water-table depths that can potentially reverse the connection between rivers and underlying alluvial aquifers (King et al. 2014). These factors, which are projected to increase in fluctuating extremes due to climate change, greatly influence the hydrology of alluvial aquifers (Parry et al. 2007) since flooding is a major source for their recharge (Hughes et al. 2011). Climate change directly controls recharge through determining the magnitude of precipitation and evapotranspiration. It also impacts the mechanisms, pathways, and the spatial variability of recharge (Taylor et al. 2012). The direction and magnitude of recharge change under a future climate is highly uncertain; hence, decisions on water future allocations are associated with a high degree of uncertainty (Crosbie et al. 2013). Groundwater resources needs to be managed in the context of the future intensity and frequency of dry periods combined with warming trends (Green et al. 2011).

Baseline data assessment has become an integral part of CSG and other large resource development in Australia. Under the Queensland Government's Water Act 2000, petroleum tenure holders are required to conduct baseline assessment for the bores within their tenures (Queensland Government 2000). In NSW, a groundwater baseline project was announced in August 2014 to monitor and map the baseline data within the major catchments (NSW Government 2014).

Despite their significance, baseline groundwater-level studies have not yet been conducted in the CMB at a regional scale with previous studies mainly focusing on storage and quality evaluations at the river catchment scale. The Lockyer Valley in southeast Queensland is one of the most-studied areas within the CMB with a number of evaluations quantifying the groundwater resources of the alluvial aquifers (e.g. Durick and Bleakley 2000; Hair 2007; Moore et al. 2011; Chee et al. 2012; Wolf 2013). Helm et al. (2009) provides a comprehensive assessment for the aquifer storage and recovery ability in South East Queensland. The water quality in the Queensland part of the CMB was also investigated as part of the National Action Plan for Salinity and Water Quality (e.g. Pearce et al. 2007a; Pearce et al. 2007b). Raiber and Cox (2012) tested the usage of 3D geological modelling and multivariate statistics in defining groundwater chemistry baseline and identifying connectivity across aquifers.

For the NSW part of the CMB, Ogier (2005) conducted a comprehensive analysis of groundwater quality and quantity to test the vulnerability of major aquifers. The analysis was mainly underpinned by the available data in the NSW state database, although 27 additional groundwater samples were collected and tested. Drury (1982) provided a comprehensive investigation of the groundwater system in the Quaternary sediments within the Richmond River valley using geology, hydrogeology, and chemistry data. Brodie and Green (2002) assessed the fractured basalt aquifer, which is part of the Lamington Volcanics on the Alstonville Plateau. They divided the basalt into a shallow unconfined aquifer within the regolith and a deep confined aquifer below the weathered part of the basalt. They also found that the shallow aquifer has a rapid rainfall response and also provides significant baseflow to plateau streams.

This study shows how the simultaneous application of multiple statistical techniques (Delhomme 1978; Delhomme 1979; Hoeksema et al. 1989; Tonkin and Larson 2002; Desbarats et al. 2002), including Kriging, Variogram fitting and trend analysis, to groundwater level time-series data can provide insights into the response of aquifers in sedimentary basins to mid-term climate variations. The assessments of water-table depth identify patterns to help understand the effects of groundwater on terrestrial ecosystems (Fan et al. 2013). Kriging was used to construct the groundwater level contours to describe the primary groundwater flow pattern. Multiple variograms were fitted and assessed in order to find an optimal variogram to be used in Kriging interpolation. Nonparametric trend analysis and representative hydrographs were constructed and compiled to identify the response of groundwater levels to climate variation. Finally, groundwater level fluctuations along two bore transects were visualized and assessed with the assistance of a 3D geological model to help understand the dynamic nature of the interactions between surface water and groundwater, and between different aquifers, and how these interactions change during droughts, at the break of drought and in response to flooding.

Study area

The expanding of CSG or coal mining industry in Australia can raise environmental concerns, particularly in a water-stressed area (Towler et al. 2016). In order to strengthen the science used to inform decisions on CSG and large coal mining developments, the Bioregional Assessment Programme was established by the Australian Government (Barrett et al. 2013). These assessments are undertaken for six bioregions across eastern Australia. The CMB bioregional assessment was undertaken primarily to understand the potential impact of future coal resource developments on water resources and water-dependent assets such as wetlands and groundwater bores.

As a component of the entire CMB bioregional assessment, the work presented in the current paper focuses on the Queensland part of the CMB, where most available baseline monitoring data are located. In south-east Queensland, it covers the mid and upper parts of the Logan-Albert River Catchment, parts of the Brisbane River Catchment (mainly the Bremer River Catchment and Lockyer Valley; Fig. 1b). The region contains large areas of steep ranges and forests. Grazing and cropping is undertaken in the large valley floor areas. The Lockyer Valley also supports a large irrigated cropping and vegetable industry. Note that the Condamine River alluvium is not considered since it is outside the defined bioregion, and extensive studies for the Condamine River alluvial groundwater system have already been conducted (Dafny and Silburn 2013; Hocking and Kelly 2016).

Climate and geography

The CMB spans several catchments in north-east New South Wales (NSW), and south-east Queensland. South-east Queensland has a subtropical climate that is dominated by dry/mild winters, and hot/humid summers. The climate is classified into three groupings (ABARES 2017): mostly “subtropical distinctly dry summer”, with “temperate no dry season: hot summer” and “temperate no dry season: warm summer” in smaller areas in the higher elevation parts along the western and south-western edges.

The mean annual rainfall in the south-east Queensland part of the CMB varies from ~800 to ~2,400 mm (BOM 2017), with pronounced gradients (lower rainfall moving away from the coast, and higher rainfall at higher elevations). The highest mean annual rainfall zone is in the east of the study area in the high elevation area around the state border, while parts of the Lockyer Valley have the lowest mean annual rainfall. In the headwaters of the Lockyer Valley, total annual rainfall is ranging from approximately 366 to 1,418 mm/year (BOM Station number 040205), although the mean annual rainfall is 839 mm/year (BOM 2017). Gatton, located in the central Lockyer Valley, has a mean annual pan evaporation rate of 1,809 mm (Harms and Pointon 1999), which significantly exceeds the mean annual rainfall (775 mm/year).

Comparison of the cumulative deviation from the mean monthly rainfall for stations in the Lockyer Valley and the Bremer River Catchment highlights that there were some very distinct climatic events during the last decades in the study area (Fig. 2). These are:

- Above average rainfall from 1988 to 1989
- A severe and prolonged drought from ~2000 to 2007
- Break of drought in late 2008
- Extreme rainfall events resulting in very severe flooding in December 2010 and January 2011.

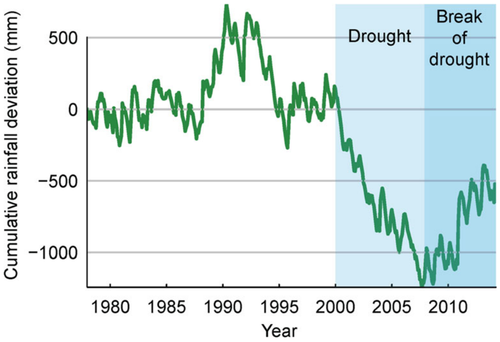


Fig. 2 Cumulative deviation from mean monthly rainfall based on data from the Bureau of Meteorology at Harrisville Post Office (station *040094*) about 25 km south of Ipswich, highlighting severe droughts that lasted until 2007 followed by the break of drought commencing in 2008. The location of the station is shown in Fig. 1b

This rainfall variability has been particularly evident since 2000, when below average rainfall from 2000 to 2008 resulted in very low creek flow (Fig. 2), especially from mid-2006 until early 2008 when flow in the creek ceased completely. This period of drought was then followed by two wet years, which generated significant flooding in January 2011.

Physiographically, the CMB is part of the New England-Moreton Uplands Province, within the broader Eastern Uplands Division (Pain et al. 2011). The Queensland part of the CMB is mostly covered by the “Bunya-Burnett Ranges” (mountain ranges, rugged and dissected on granitic and metamorphic rocks in east, broader uplands and upland basins, partly on sedimentary rocks, in west), with the western and southern edges covered by the “Toowoomba Plateau” (basaltic plateau terminating southeast in dissected volcanic pile, forming part of the Main Range Volcanics; Fig. 1a; Pain et al. 2011).

Geology and hydrogeology

The CMB is an elongated intracratonic sag basin that overlies the mid to late- Paleozoic rocks of the New England Orogen in south-east Queensland and north-east New South Wales (Fig. 1a) (Korsch et al. 1989). It covers approximately 38,000 km^2 on-shore, and contains sedimentary sequences of Middle and Late Triassic to Lower Cretaceous age with a combined thickness of up to approximately 3,000 m. The basin extends from the Kumbarilla Ridge in the west to the coast in south-east Queensland and into northern New South Wales (Fig. 1a). It is the youngest of a series of linked Mesozoic basins in the region (Johnstone et al. 1985). The formation of the CMB and adjoining Mesozoic basins is closely related to large-scale tectonic processes associated with the development of the New England Orogen and the reorganization of tectonic plates which began in the Late Carboniferous (Korsch et al. 1989). Structures and faults (presented in Fig. 1a) divide the region into three sub-basins: the Cecil Plains sub-basin, Laidley sub-basin, and Logan sub-basin (Fig. 1a).

The groundwater-bearing formations in the CMB include shallow water-bearing aquifers formed by the alluvia along river courses, floodplains and volcanic rocks, and deeper formations composed of sedimentary rocks. The important alluvial aquifers in the CMB include the Condamine River alluvium, Lockyer Valley alluvium, Bremer River/Warrill Creek alluvia, Logan/Albert River alluvia, Clarence River alluvium and the Richmond River alluvium. Some of these aquifers are economically important, for example, the Condamine River and Lockyer Valley alluvial aquifers are seasonally pumped for irrigation. The major bedrock units below the alluvial aquifers and their corresponding generalized hydraulic characteristics are listed in Fig. 3.

The thicknesses of the alluvial systems in the study area observed from bore logs vary within a relatively small margin (15–40 m), whereas the widths of the floodplain are highly variable (approximately from 500–5,000 m; Raiber et al. 2017a). This is in strong contrast to other alluvial systems further to the west such as the Condamine River alluvium, which is approximately up to 130 m thick and more than 30 km wide (Dafny and Silburn, 2013). The thickness of the Main Range Volcanics that overlie the CMB sedimentary bedrocks ranges from 100 to 200 m; however, locally the Main Range Volcanics, composed of vesicular and massive olivine basalts, can be considerably thicker in topographically elevated areas or close to the eruptive centres of volcanoes (Raiber et al. 2017a). The sedimentary bedrock stratigraphic units in the study area include the Walloon Coal Measures, the Koukandowie Formation, the Gatton Sandstone and the Woogaroo Subgroup (Figs. 1b and 3). The Koukandowie Formation and the Gatton Sandstone together form the Marburg Subgroup (Fig. 3).

Data and methodology

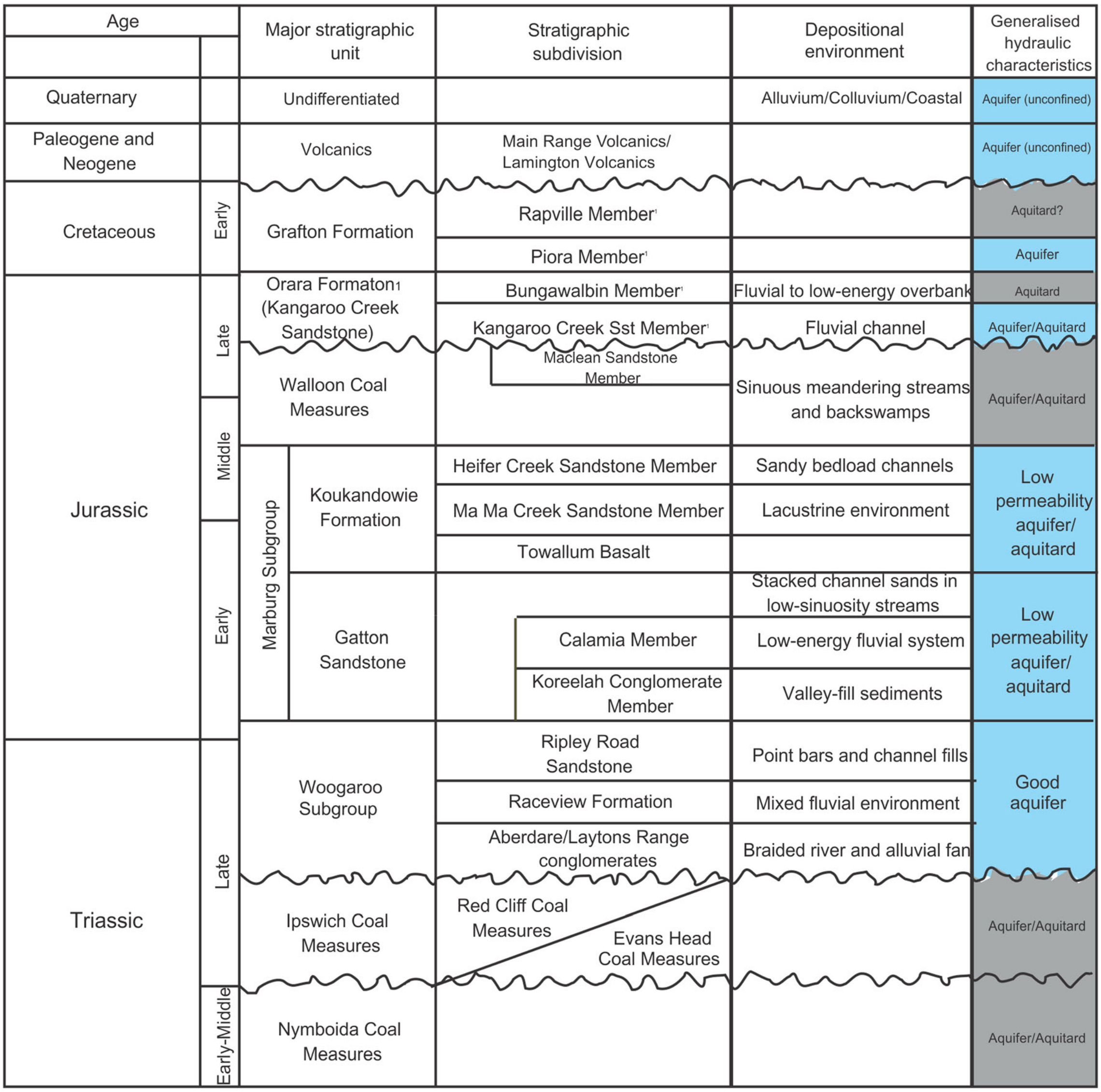
Data

Groundwater level data for the study area (up to November 2013) were sourced from the Queensland state groundwater database (Department of Natural Resources and Mines, Accessed November 2013). After the integrity of the data was confirmed through a rigorous quality check and standardization process (Raiber et al. 2017b), only those bores with sufficient information on bore-depth screen intervals were used to inform the assignment of a bore to a particular aquifer. For this purpose, all bores and their screened intervals were imported into the 3D geological model, where the stratigraphic unit at the screened interval was queried using the 3D geological model. As the 3D geological models are subject to uncertainty, the screen assignments were also compared to the original bore stratigraphy where available. For bores that lacked screen data, the assignment was based on bore depth provided that the lithological and stratigraphic information confirmed that the entire bore path was located within a single aquifer. Statistical analyses in this paper required a single datum to be used, the elevation of natural ground surface around a bore or the reference point in the state database was recorded using different references including AHD (Australian height datum), STD (state datum), and ASS (assumed datum). Due to inconsistencies in datum conversion and the unknown quality and source of the elevations, the Australian one-second DEM derived from the Shuttle Radar Topography Mission (SRTM) dataset (Gallant et al. 2011) was used for referencing all ground surface elevation instead of the originally recorded elevation in the state database. When compared with a total of 1,198 permanent survey marks (PSM) across Australia, the mean and median height differences are 1.287 and 1.668 m, respectively (Gallant et al. 2011).

The statistical and trend analysis covered two periods, a period representing drought conditions (from 2000 to 2007) and a subsequent period during which the drought broke (from 2008 to 2012; Fig. 2); hence, only bores with records between 2000 and 2012 were used in this study. The spatial distribution of bores used in the analysis is shown in Fig. 4. For the alluvial bores, the Lockyer Valley had the highest data density. The bedrock bores are scattered across the study area. The Woogaroo Subgroup bores are mainly located in the northern part of the Lockyer Valley, whereas the Marburg Subgroup bores are mainly located in the Lockyer Valley. Most bores screened in the Walloon Coal Measures bores are located in the Bremer River Catchment. There are only five volcanic bores within the study area with three of them located along the margin of the study area. The bedrock bores are mostly screened in the unconfined part of the bedrock aquifers. There are not enough data to compile groundwater level contours for each bedrock aquifer separately. In the current study, all the bedrock bores were considered to belong to a lumped shallow bedrock aquifer for the purpose of Kriging interpolation.

Kriging and variogram fitting

Kriging was used to interpolate water levels to create water level contour maps. This method has been widely used by many researchers to study the spatial and temporal variations of groundwater levels (Delhomme 1979; Hoeksema et al. 1989; Ta'any et al. 2009). Kitanidis (1997) provided a detailed theoretical background for Kriging and variogram fitting, and their application in hydrogeology. In this section, only the



Age		Major stratigraphic unit		Stratigraphic subdivision	Depositional environment	Generalised hydraulic characteristics
Quaternary		Undifferentiated			Alluvium/Colluvium/Coastal	Aquifer (unconfined)
Paleogene and Neogene		Volcanics		Main Range Volcanics/ Lamington Volcanics		Aquifer (unconfined)
Cretaceous	Early	Grafton Formation		Rapville Member[1]		Aquitard?
				Piora Member[1]		Aquifer
Jurassic	Late	Orara Formaton[1] (Kangaroo Creek Sandstone)		Bungawalbin Member[1]	Fluvial to low-energy overbank	Aquitard
				Kangaroo Creek Sst Member[1]	Fluvial channel	Aquifer/Aquitard
	Middle	Walloon Coal Measures		Maclean Sandstone Member	Sinuous meandering streams and backswamps	Aquifer/Aquitard
	Early	Marburg Subgroup	Koukandowie Formation	Heifer Creek Sandstone Member	Sandy bedload channels	Low permeability aquifer/ aquitard
				Ma Ma Creek Sandstone Member	Lacustrine environment	
				Towallum Basalt		
			Gatton Sandstone		Stacked channel sands in low-sinuosity streams	Low permeability aquifer/ aquitard
				Calamia Member	Low-energy fluvial system	
				Koreelah Conglomerate Member	Valley-fill sediments	
Triassic	Late	Woogaroo Subgroup		Ripley Road Sandstone	Point bars and channel fills	Good aquifer
				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
	Early-Middle	Nymboida Coal Measures				Aquifer/Aquitard

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

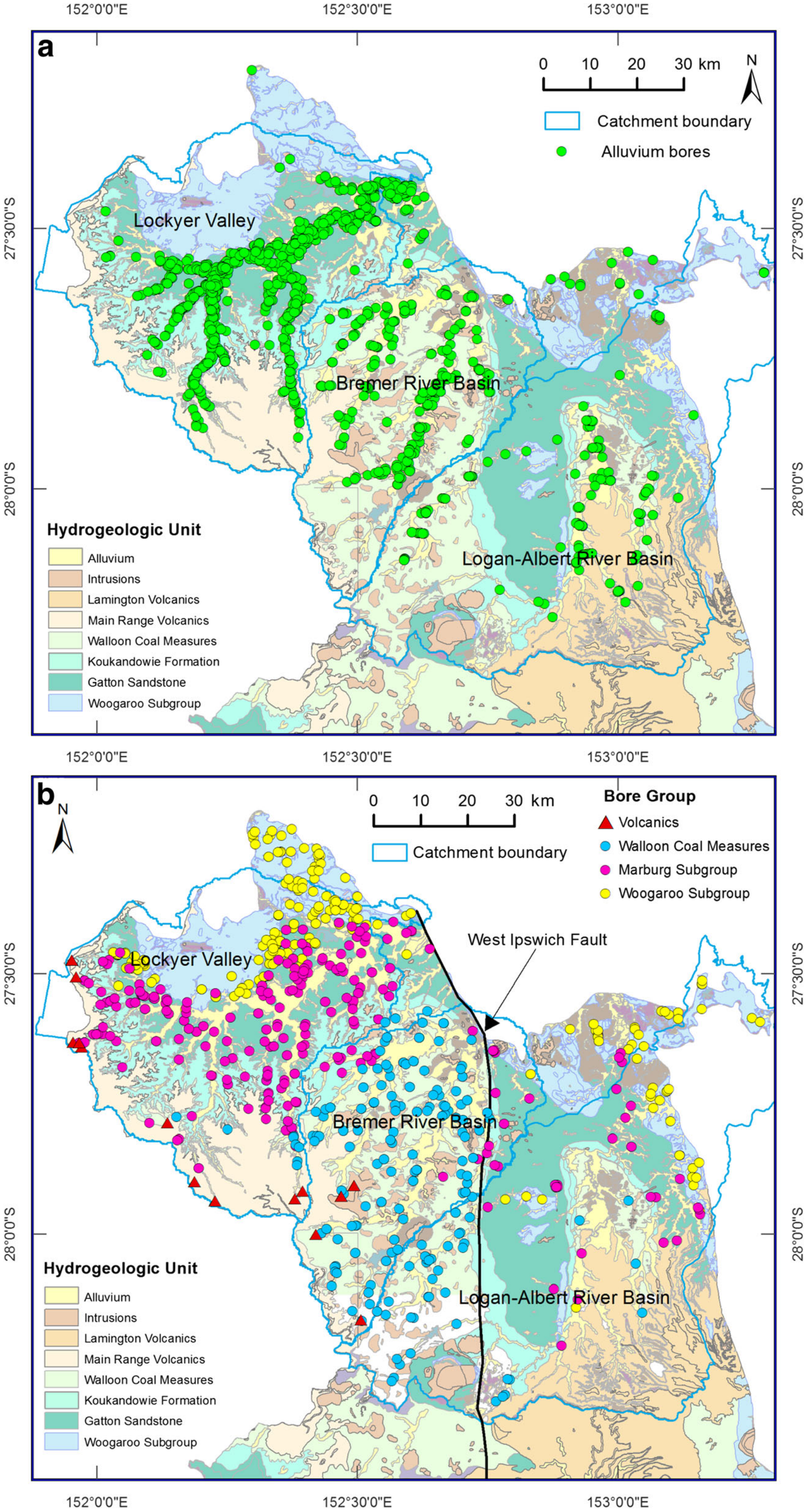
Fig. 3 The main stratigraphic units and their generalized hydraulic characteristics in the Clarence-Moreton Basin. The major aquifers present in the study area are highlighted by *blue color*

procedure for selecting the optimal variogram for the collected data is described.

Groundwater level data, especially in shallow aquifers, usually show a regional trend controlled by the topography elevation. It is believed that this kind of regional trend usually overwhelms the local variations when a variogram based on raw data is used in Kriging (Kitanidis 1997). The study area generally shows a SW–NE groundwater flow direction due to the impact of high topography elevation in the SW margin of the study area. This is demonstrated by directional experimental variogram curves (Fig. 5). The black and blue curves of Fig. 5 show the directional variograms in the mean longitudinal and transverse direction of groundwater flow in the alluvial aquifer, respectively. The variogram based on raw data shows an infinite growth of the variogram as the separation distance grows (Fig. 5a). However, after the raw data was detrended with the aid of a linear model, the experimental variogram no longer shows significant anisotropy (Fig. 5b). A more detailed discussion about detrending data can be found in Kitanidis (1997). The data for the shallow bedrock aquifer exhibit a similar anisotropic characteristic as shown in Fig. 5c,d; therefore, variogram models based on de-trended data need to be tested.

Semi-variogram fitting is a key step of geostatistical analysis (Kitanidis 1997), which expresses the spatial dependence of the hydraulic heads at different sites. Linear and Gaussian models based on raw data and a spherical model based on detrended data were assessed in order to find the optimal variogram model for the available groundwater level data. The regional trend was simulated by anisotropic parameters

Fig. 4 The distribution of the bores in **a** the alluvium and **b** the shallow bedrock aquifers, with groundwater level records between 2000 and 2012. Note that most bores screened in bedrock are located in the outcrops of the corresponding bedrock aquifers



in the linear and Gaussian model based on the raw data. Three statistics, including the median absolute deviation, standard deviation, and rank correlation between the observed data and the prediction, were used to assess these fitted models. Table 1 summarizes the performance of the afore-mentioned models. Although it is believed that the regional trend in the observed data usually dominated the impact of local variability on the experimental variogram (Kitanidis 1997), the

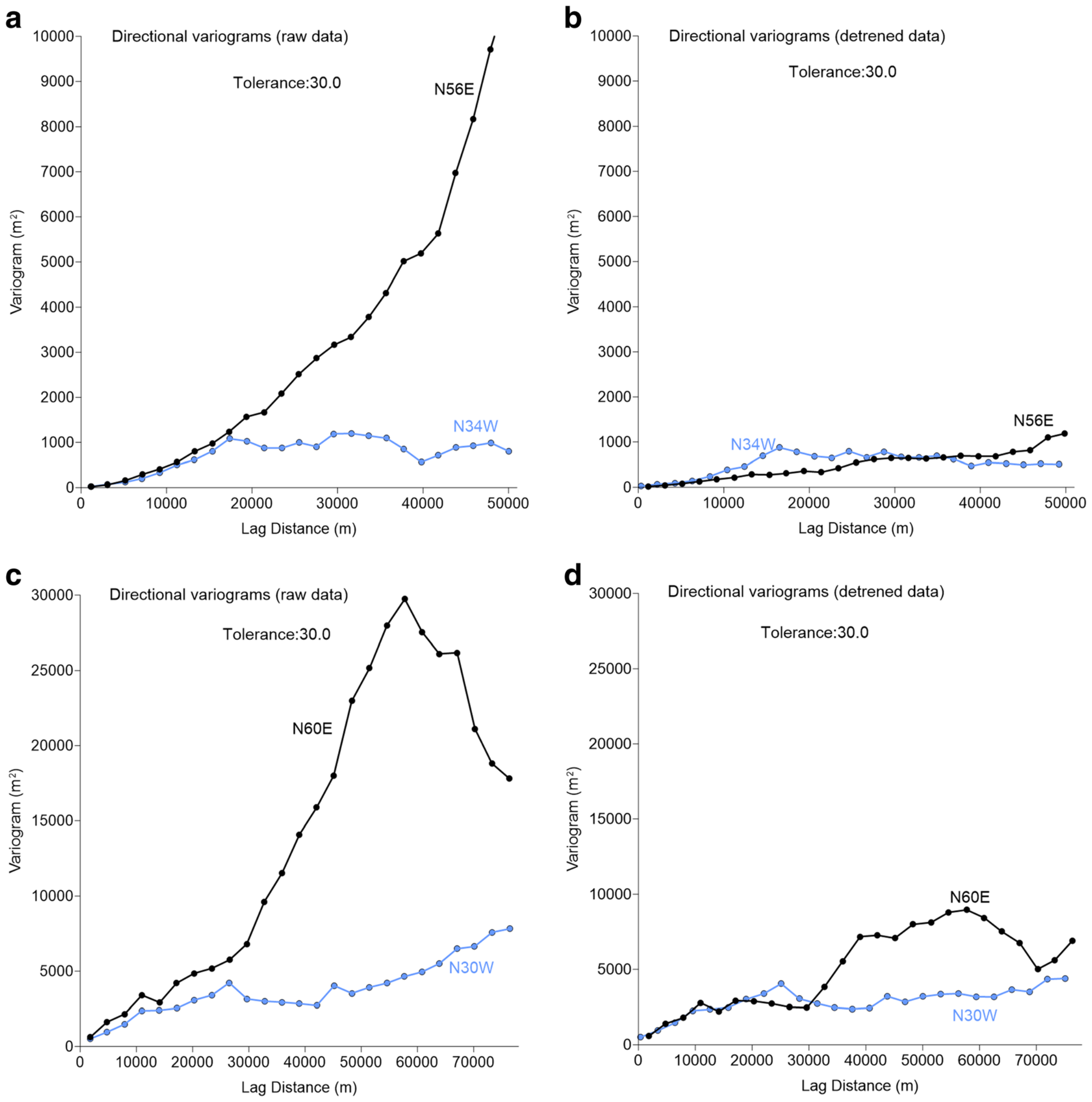


Fig. 5 Directional experimental variograms of the mean groundwater level in the alluvia (**a**–**b**) and shallow bedrock aquifers (**c**–**d**) during the dry spell (2000–2007). **a** and **c** Based on the raw observed data, while **b** and **d** use the detrended data. The *black and blue curves* show the directional variograms in the mean longitudinal and transverse direction of groundwater flow respectively

spherical model fitted for the de-trending data shows a similar performance with the simple linear model for the current raw data in the study area. An assessment of the data after the drought period was also conducted with similar results observed; thus, the linear model was used during the Kriging interpolation for simplicity.

Trend analysis

Monotonic trends in hydraulic heads were examined for the low-rainfall period (2000–2007) and the high-rainfall period (2008–2012) using non-parametric statistical methods. For the nonparametric trend analyses, the Mann-Kendall tau statistic and Theil-Sen estimator were used to identify and quantify the presence of trends in the observed data. Both of these methods have been used extensively in statistical analyses of hydrological and water quality data (e.g. Hirsch et al. 1991; Hipel and McLeod 1994; Batlle-Aguilar et al. 2007). For bores with sufficient records (at least three observations) during these two periods, the direction of the trend (increasing or decreasing hydraulic head) and the statistical significance was assessed using the Mann-Kendall tau statistic (Mann 1945). This statistical test is based on differences between all pairs of observations in a time series. The tau statistic is equal to the difference between the proportion of all data pairs that are increasing with time and the proportion of all data pairs that are decreasing with time. If all pairs of observations in the series are increasing or decreasing, then the tau statistic is assigned a value of 1.0 or

Table 1 Summary for the performance of various fitted variogram models using three statistical parameters based on a cross validation analysis

	Gaussian	Linear	Spherical (de-trended)
Alluvium (2000–2007)			
SD	23.95	8.23	8.6
MAD	2.16	1.87	1.81
RC	0.98	0.99	0.99
Bedrock (2000–2007)			
SD	52.02	29.22	28.84
MAD	12.93	8.96	8.97
RC	0.88	0.93	0.94

SD standard deviation of the predication residual; *MAD* median absolute deviation of the prediction residual; *RC* rank correlation between the estimated values and the observed data. Note that the standard deviation of the prediction for the shallow bedrock is higher due to its sparse sampling

−1.0, respectively. Values between −1.0 and 1.0 correspond to less monotonic trends, with the zero occurring when there are equal numbers of increases and decreases among all data pairs. *P*-values for the tau statistic were also calculated to determine whether upward or downward trends were statistically significant (the two-sided test; Helsel and Hirsch 2002). For this analysis, any *p*-value of less than 0.05 is considered to be significant. The tau-statistic was calculated as follows:

$$\tau = \frac{2\left(n_{\mathrm{up}} - n_{\mathrm{down}}\right)}{n(n-1)} \qquad (1)$$

where n is the number of observations in the time series; n_{up} is the number of pairs of observations for which there is an increase in the quantity of interest with time; and n_{down} is the number of pairs of observations for which there is a decrease in the quantity of interest with time. *P*-values for the test statistic were computed using the "Kendall" package for R (The R Core Team 2013).

For bores in each period where a statistically significant trend was detected, the rate of change (measured in m/year) was quantified using the Theil-Sen estimator (Sen 1968; Theil 1992) which is also known as Sen's slope estimator. It provides a robust estimate of the slope of the trends identified under the Mann-Kendal tau statistic and is computed using the median slope among lines fitted to all pairs of sample points in the time series.

Results

Mean water level and primary groundwater flow direction

Water level maps (Fig. 6) were generated using Kriging interpolation to identify the primary groundwater flow pattern in the study area. These maps were created for a drought period (2000–2007) and a period after the drought (2008–2012) using the mean measured hydraulic heads at monitoring bores over the two spells. Since the recovery of groundwater levels after the drought was not very obvious at the regional scale, only the dry period is shown on the map (Fig. 6).

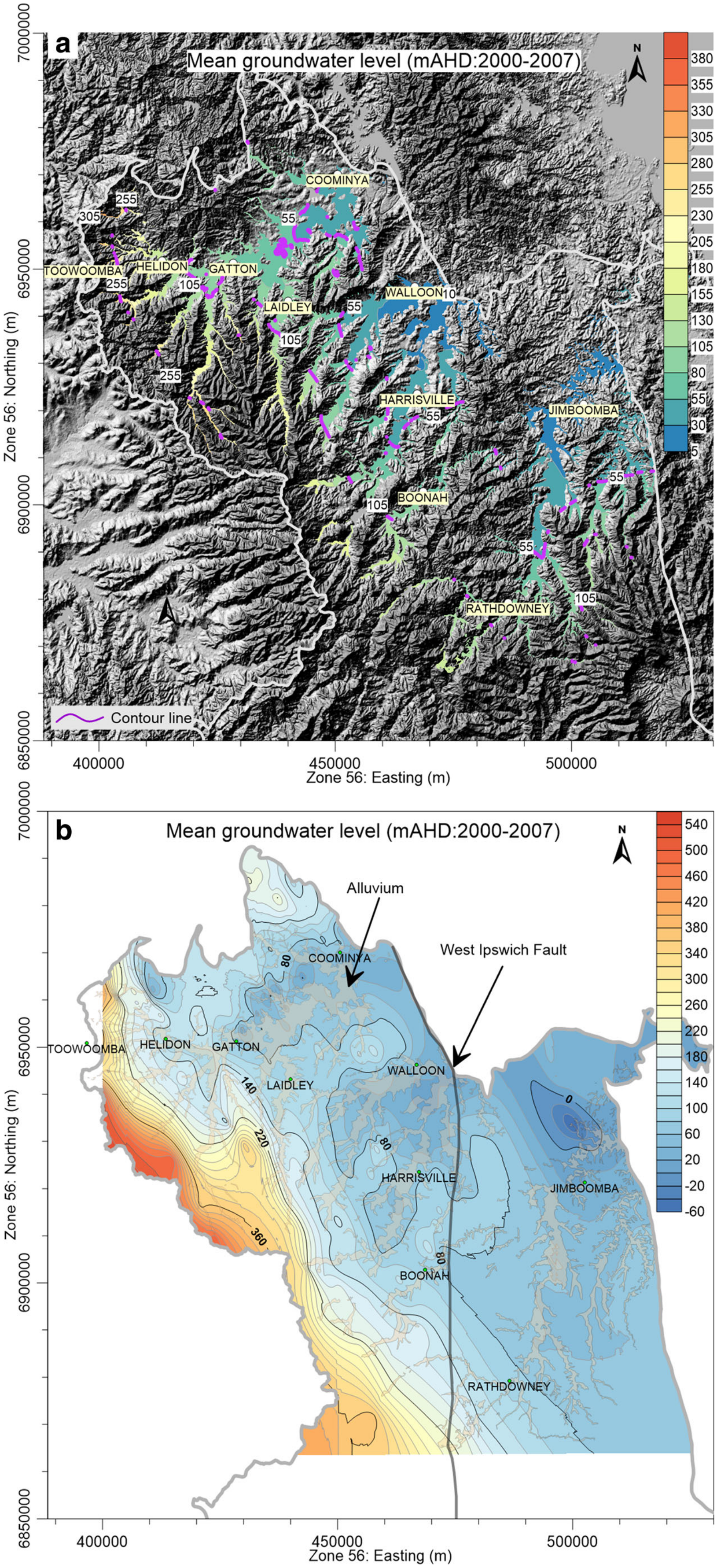
As expected, water tables in the alluvia generally follow the topographic relief along the stream flow direction (Fig. 6a). Hydraulic heads change from hundreds of meters AHD in the upland area to tens of meters AHD in the lowland segment. The lowest hydraulic head occurs in the lowland area of the Bremer River (~10 m AHD) southeast of Walloon (Fig. 6a). Groundwater flows generally from SW to NE within the Lockyer Valley and Bremer River alluvia, compared to a south–northerly direction in the Logan-Albert alluvium. The spatial distribution of measurement points is variable with more observations recorded in the Lockyer Valley compared to the other two alluvia (Fig. 4). This leads to a lower uncertainty for the Lockyer Valley results.

Hydraulic heads in the shallow bedrock also generally mimic the topographic elevation at the sub-basin scale (Fig. 6b); however, within the catchments, the hydraulic heads decrease towards the alluvium from the dividing ridge between river basins, resulting in local variations of flow patterns—for example, groundwater flows in a south-eastern direction in the Woogaroo Subgroup in the northern part of the Lockyer Valley, but changes to a north-westerly towards the central part of the alluvium in the southern part of the alluvial aquifer. In the Walloon Coal Measures at the eastern margin of the Laidley sub basin within the Bremer River Catchment, groundwater generally flows in the direction where the Bremer River, the Warrill Creek, and the Purga Creek exit the CMB west of Ipswich (Fig. 6b). Being bound by the West Ipswich fault, a major regional fault system, the units in this area are juxtaposed against low permeability basement rock at the margin of the sub basin. Consequently, groundwater from the Walloon Coal Measures and underlying formations can potentially flow in an upward direction, and hence discharge into nearby wetlands and alluvia. This is discussed further in section 'Hydraulic relationships between wetlands and aquifers'.

Groundwater depth

Groundwater depth can be an indicator for potential surface-water/groundwater interactions. The mean depth to groundwater in the monitoring bores of the alluvium during the dry period is shown in Fig. 7a. Depth to groundwater depends on various factors, most notably the geometry and thickness of the alluvial aquifers and the distance from creeks; furthermore, the depth to groundwater across the alluvial floodplains varies considerably during droughts and following flooding. Shallower depths towards the edge of the alluvium and close

Fig. 6 Mean water level in **a** the alluvia and **b** the shallow bedrock aquifers during the drought period. The value is displayed in meters above Australian Height Datum (m AHD). The low groundwater level area north of *Jimboomba* is caused by a single water supply bore (ID: 138,684 in the state database). The low head is presumably due to abstraction in this region, but no further information is available



to the creeks can be observed. Shallower depth at the edge of the alluvium are associated with the generally smaller thickness of the alluvial aquifers at the catchment margins, but may also be the result of groundwater discharge from the underlying bedrock into the alluvial aquifers at the margin of the alluvium. The alluvial aquifers have a mean water-table depth that ranges from 8.5 to 17.5 m. Groundwater levels are generally deeper in the Lockyer Valley than in other alluvia, with a median depth 18.5 m during the dry period (Fig. 7a), which recovered to 13.8 m during the wet period. Extensive groundwater extraction adds significant pressure on water levels, especially during drought periods. The decline of groundwater levels during the drought also induces upward discharge from the underlying Gatton Sandstone into the alluvium. The median groundwater depths are 10.3 and 10.3 m during the dry period in the Bremer River and Logan-Albert alluvia, respectively, with a recovery to 8.5 and 8.4 m between 2008 and 2012.

Groundwater depths in the northern Lockyer Valley, where the Woogaroo Subgroup outcrops, are deeper than in other sedimentary bedrock aquifers with mean and a maximum depths of 33.2 and 92.5 m (Fig. 7b), respectively. The high quality of groundwater in the Woogaroo Subgroup in comparison to most other sedimentary bedrock units—the Woogaroo Subgroup contains very fresh groundwater with electrical conductivities typically <300 μS/cm (Raiber et al. 2017a)—means that this aquifer is very heavily exploited for agriculture (primarily intensive horticulture in the Lockyer Valley), which may have induced a substantial drawdown leading to deeper groundwater levels. In addition, the deeper potentiometric surface within the Woogaroo Subgroup might reflect that this formation dips very steeply towards the south-east at the northern basin margin and is confined by the shallower Gatton Sandstone.

The mean groundwater depth of the bedrock in the other catchments within the study area is shallower than that in the Lockyer Valley (Fig. 7b). The median groundwater depth in the Walloon Coal Measures is 13.9 m where it mainly outcrops into the Bremer River Catchment.

Response to climatic variability

The Mann-Kendall Tau statistic and Theil-Sen estimator provide a quantitative assessment of the temporal variability of groundwater levels as they respond to various stresses that are mainly driven by climate and/or extraction. The Mann-Kendall tau statistic provides an indicator of the strength of the monotonic trend of a groundwater head time series (Mann 1945). As mentioned in the methodology section, values of −1 and 1 indicate a monotonic decline or rise in all groundwater heads in the series, respectively. The results of the Mann-Kendall tau statistic for the alluvial and shallow bedrock aquifers show that water levels in most bores were declining during the drought period (2000–2007) with substantial recoveries in all systems after the drought period (Figs. 8 and 9). This implies a good connection between the shallow aquifers and the recharge sources. Furthermore, it also suggests that less water is abstracted during wet periods than during dry periods. However, very few bores show an opposite trend, such as the orange and red bores shown in Fig. 8, caused by un-representative sampling. For instance, bores 14320895A, 14310270A and 14310263A in Fig. 8b only have measurements from 2011 to 2012.

The Theil-Sen estimator (also referred to as Sen's slope) provides an insight into how rapidly the water level responds in different aquifers (Helsel and Hirsch 2002). For aquifers showing a statistically significant trend, box plots of the Sen's slope during the dry and wet periods were prepared (Fig. 10), confirming that the magnitude of change is variable throughout different parts of the alluvial aquifer systems. The steepest decline during the low-rainfall period was observed in the Lockyer Valley alluvium with a median of −0.7 m/year (Fig. 10a). More moderate declines were observed in the Bremer River/Warrill Creek and Logan-Albert River alluvia with medians of −0.3 and −0.2 m/year (Fig. 10a), respectively. Similarly, during the wetter period, the greatest magnitude of change was noticed in the Lockyer Valley alluvium bores with a median rate of 2.1 m/year (Fig. 10b), likely influenced by unprecedented flooding in 2011. The median rates for the Bremer and Logan-Albert alluvia during the wetter years were 0.5 and 0.3 m/year, respectively.

The rate and the magnitude of the response during and after the drought was generally less pronounced in the sedimentary bedrock aquifers compared to the alluvial aquifers (Fig. 10), despite the fact that the monitoring bores are mostly located in the unconfined part of the bedrock. During the high-rainfall period, the median ascent rate in groundwater levels observed in the Gatton Sandstone (lower part of the Marburg Subgroup) was 0.7 m/year (Fig. 10). Some bores in the Woogaroo Subgroup showed strong responses to climate variation, with a median descent rate of −0.9 m/year during the dry years and a median ascent rate of 1.3 m/year during the wet period. Changes in the Walloon Coal Measures were less pronounced, with a median descent rate of 0.1 m/year during the dry period and a median ascent rate of 0.3 m/year during the wet period (Fig. 10).

In addition to the trend analyses, water level hydrographs for different hydraulic units were compiled to enable a visual comparison between their responses to precipitation and extreme climate events such as droughts and floods. In order to provide a better comparison among different bores, hydraulic heads at a monitoring bore were normalized by subtracting their mean hydraulic heads between 1999 and 2013. The normalized heads were plotted in Fig. 11, with their locations shown in Fig. 1b. Water-level fluctuation is a result of a variety of hydrologic processes including natural events and

Fig. 7 Mean groundwater depth in **a** the alluvia and **b** the shallow bedrock aquifers during the drought period (2000–2007). The depth variation is indicated by the *size and colour of the circles*

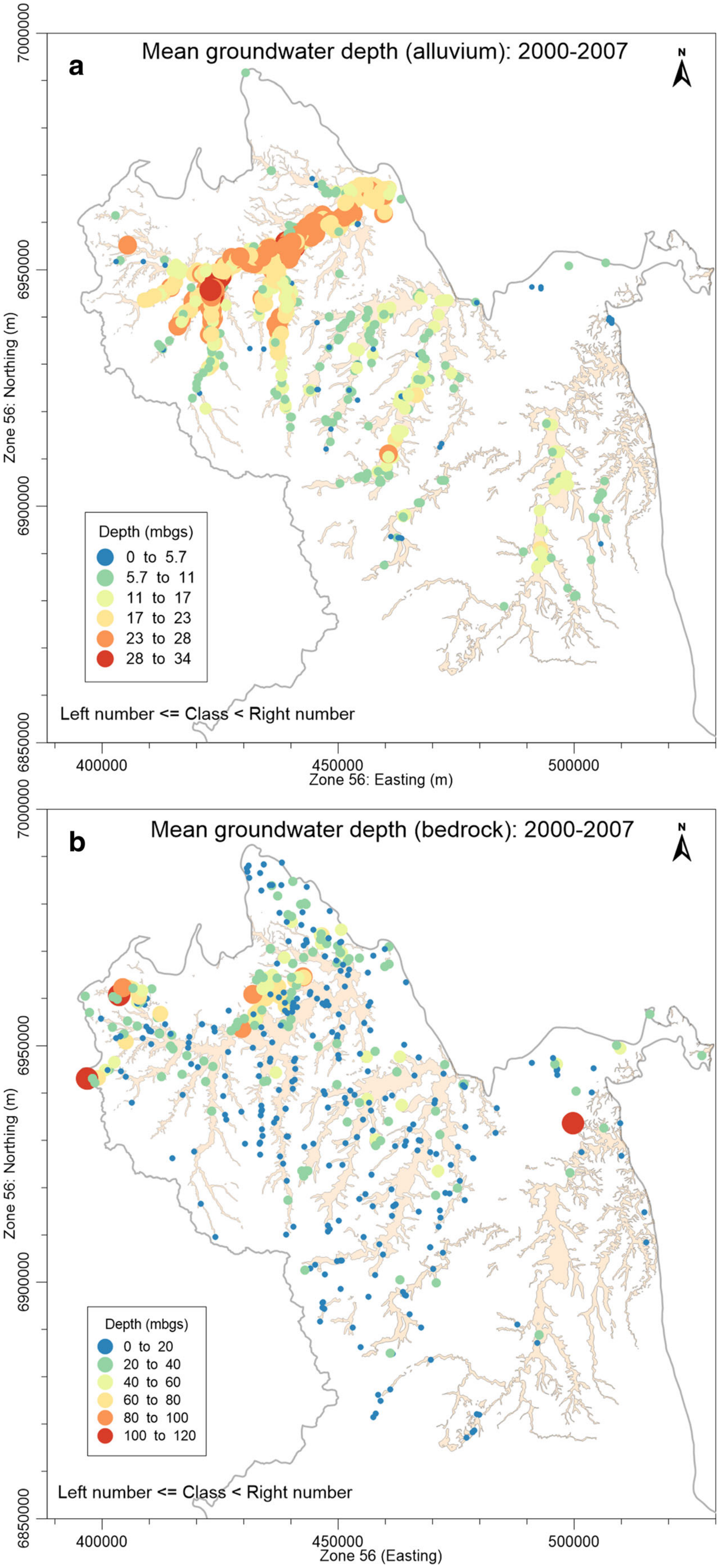


Fig. 8 Mann-Kendall trend analysis results of the alluvial groundwater level measurements **a** during and **b** after the drought. The change trend is indicated by a colour spectrum *from blue to red*. Note that fewer bores are presented in this figure than in Fig. 7a because the trend analysis requires at least three observations for a particular bore

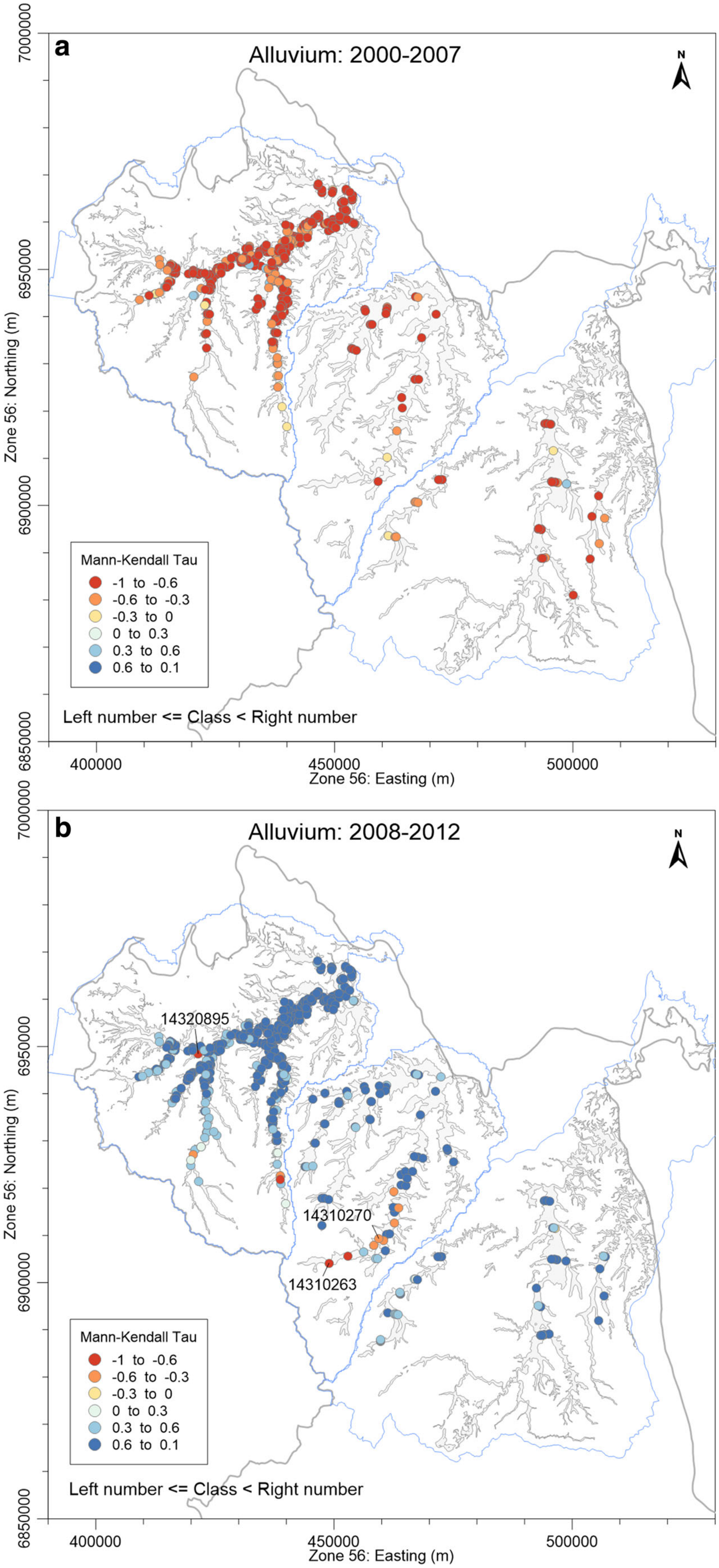
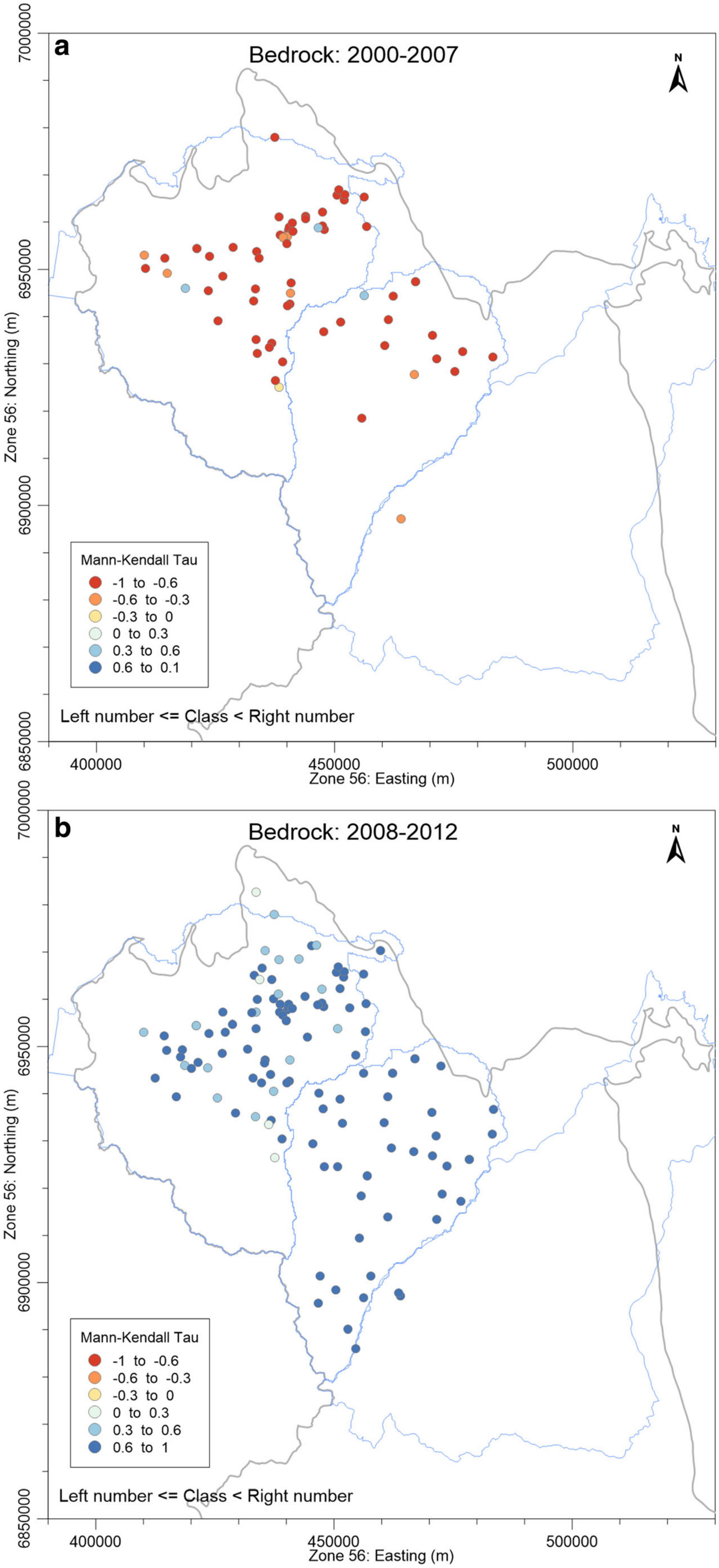


Fig. 9 Mann-Kendall trend analysis results for the groundwater levels in the shallow bedrock aquifers **a** during and **b** after the drought. The change trend is indicated by a colour spectrum *from blue to red*. Note that fewer bores are presented in this figure than in Fig. 7b because the trend analysis requires at least three observations for a particular bore



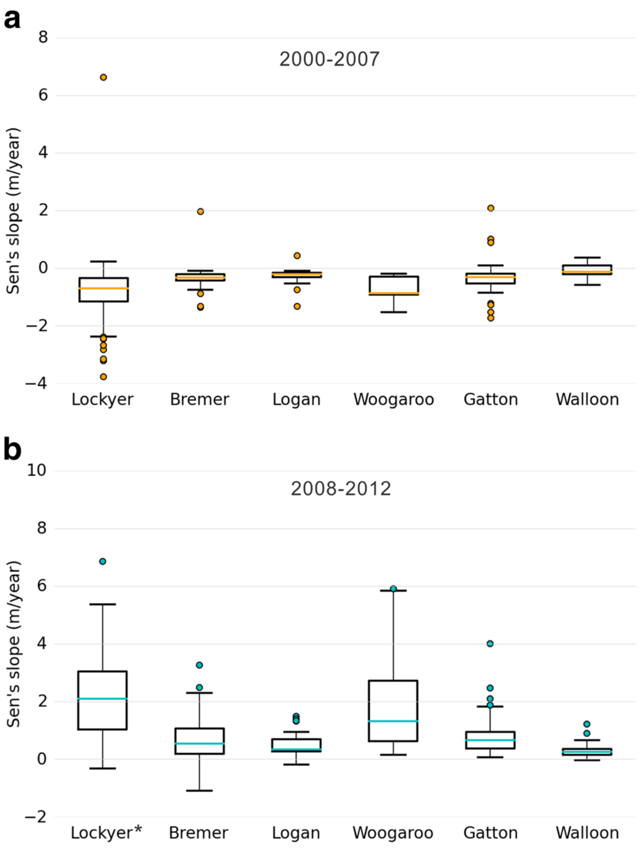


Fig. 10 Box plots of Sen's slope to show the average **a** declining and **b** recovering rates of groundwater levels in the main aquifers during (2000–2007) and after (2008–2012) the drought, respectively. The differences in terms of water-storage changes should be more extreme because the alluvium has a higher specific yield than the bedrock aquifers. * Note that two outliers for the Lockyer Valley Alluvium are not present in part **b** in order to gain a good resolution. The high values of the dropped outliers were caused by unrepresentative sampling of the groundwater level between 2008 and 2012

anthropogenic activities such as groundwater extraction. Even bores in the same aquifer can show different responses depending on screen depth, local hydrogeological condition or water usage; nevertheless, these hydrographs indicate some general patterns of response to rainfall.

The water level responses in different hydrogeological units vary significantly, both in terms of their sensitivity and magnitude. Figure 11a shows the hydrographs of four bores in the upland area of the Lockyer Valley alluvium with their respective distances to the Laidley Creek shown in Fig. 12a. These four alluvial bores exhibit a relatively rapid response to rainfall events with a clear seasonal pattern. They show a water level decline of approximately 15 m from 2000 to 2007. Following the break of the drought in 2008, the groundwater levels recovered to the pre-drought levels after several years. Although a similar response to rainfall events is observed among the four bores, bore 14320326 shows a weaker response, as it is located further away from the stream. A flat hydrograph segment from 2002 to 2009 is observed for this bore because it was completely dry during this period. The rapid response to rainfall suggests that the alluvium surrounding these bores is well connected to the surface-water system. The hydrographs also confirms the strong influence of the drought on groundwater levels in some parts of the alluvial aquifers.

Figure 11b includes several hydrographs from the lowland area of the Lockyer Valley alluvium. Although a seasonal response is still apparent, the magnitude of the response of −6 to 4 m is less than that shown in Fig. 11a. This may be attributed to different sedimentary environments across different stream segments. In the downstream stretch, there is usually a relatively thick clay layer at the bottom of the stream due to a declining flow velocity. Several bores in the Bremer River/Warrill Creek alluvia demonstrate an even weaker response (Fig. 11c). The magnitude of change here was less than 1.5 m between 2000 and 2012. With the exception of bore 14310050 that is located closest to the Bremer River, a seasonal signal cannot be observed due to different local hydrogeological conditions. Despite the variation, all of the selected bores experience a decline in water level during the drought and a recovery after the break of the drought, with water levels in most of the bores recovering to or exceeding pre-drought levels (Fig. 11a–c).

Only three bores screened in the Main Range Volcanics have sufficient data for constructing a water level hydrograph. Two of them show a strong response to rainfall variations (only one is shown in Fig. 11d), whereas the other one responds similarly to the sedimentary bedrock bores with changes dominantly driven by longer-term climatic variability rather than short-term rainfall events. Among the other sedimentary bedrock units, the Woogaroo Subgroup shows the strongest response to rainfall variations. The bores screened in the Marburg Subgroup and Walloon Coal Measures follow a similar trend with no response to minor rainfalls and a weak response to major rainfalls. Likewise, declining groundwater levels can be observed in the Marburg Subgroup and the Walloon Coal Measures from 2000 to 2007 as a consequence of the drought, although the decline in water levels occurs on a much smaller scale compared to that within the Woogaroo Subgroup.

Overall, groundwater levels in the shallow bedrock aquifers generally follow long-term or decadal patterns and are less affected by short-term (seasonal) climatic patterns. This also can be explained by the different groundwater depth configurations in the alluvia and the bedrock aquifers. In the alluvia where the water table is shallow (Fig. 7a), a hydrograph is characterized by a dynamic response to rainfall with relatively short recharge time lags (Fig. 11a,b). Conversely, the response in the sedimentary bedrock aquifers to individual rainfall events tends to be attenuated due to a time lag associated with the larger depth of groundwater and hydraulic property configuration (e.g. some parts of the bedrock aquifers are characterized by thick clay rich weathering

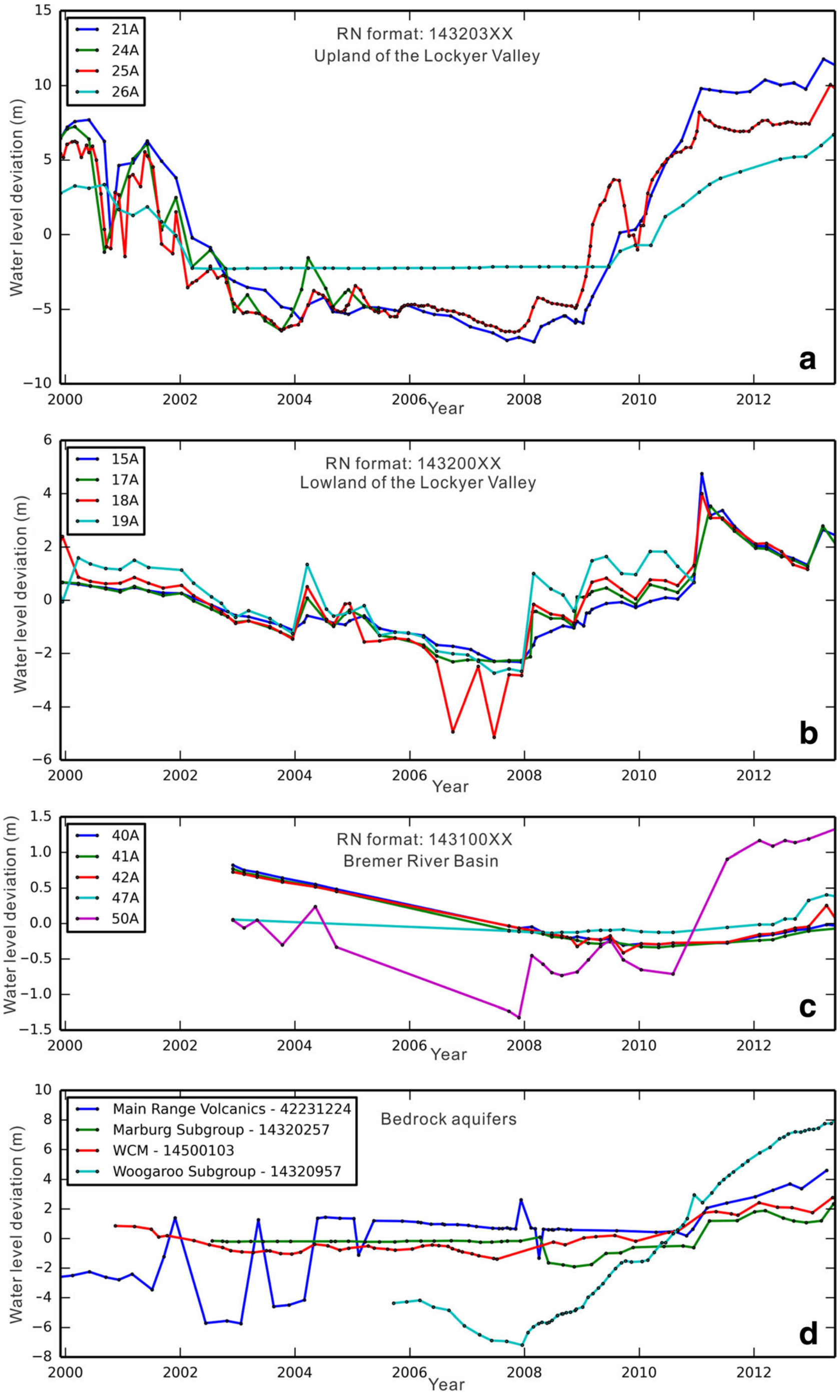


Fig. 11 Representative hydrographs from 2000 to 2012. The groundwater level in the y-axis is the deviation from the mean groundwater level from 1999 to 2013 of corresponding bores. The bore number is shorted in the legend except for part **d**. Note that bore 143203*26A* is completely dry from 2002 to mid-2009 resulting in a flat hydrograph segment (**a**). Bore locations can be found in Fig. 1b. **a**–**c** Bores are located in alluvial aquifers. **d** Bores are located in the shallow bedrock aquifers

profiles that do not allow much recharge), which results in a more uniform hydrograph (Fig. 11d) compared to its counterpart in the alluvium. In addition, this difference probably also reflects the fact that the alluvial aquifers within the study area are exploited more heavily than the bedrock aquifers due to the often poor groundwater quality of the latter. Pumping of alluvial groundwater during the drought due to a diminishing surface-water resource may be the major driver of declining groundwater levels within the alluvial systems.

Discussion

Groundwater levels as indicators of stream–aquifer connectivity

When augmented by a three-dimensional (3D) geological model, groundwater level observations can be used to assess hydraulic relationships between aquifers and streams. The collected water level measurements and their spatial

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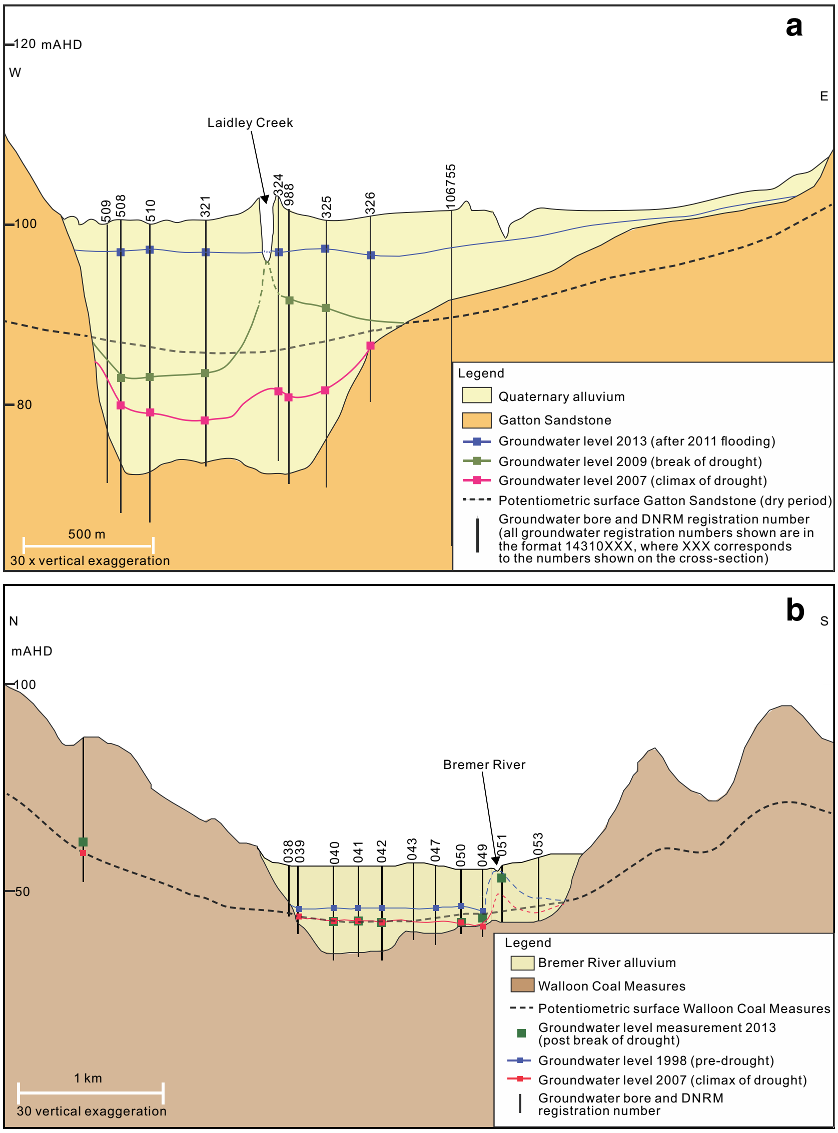

Fig. 12 Geological cross-section through **a** the Laidley Creek Catchment (sub-catchment of Lockyer Valley) and **b** the Bremer River Catchment. Note the spatial and temporal variability of the hydraulic relationships between the stream and the alluvial aquifer. The topographic surface is based on digital elevation model (DEM) data. With the exception of groundwater bore 106755, all groundwater registration numbers shown in **a** are in the format *14320XXX*, where *XXX* corresponds to the three numbers shown *on the cross-section*. For **b**, the registration numbers of bores are labelled in the format *14310XXX*

interpolations were imported into a 3D geological model in SKUA-GOCAD (Paradigm Geophysical Pty Ltd). Two-dimensional (2D) cross-sections were then created based on the 3D geological model at selected locations where time-series water level data existed along observation bore transects. Two examples are shown from different catchments within the study area (Lockyer Valley and Bremer River catchments) to demonstrate the dynamic nature of the stream-aquifer connectivity.

A cross-section from the Laidley Creek sub-catchment, a tributary system of the Lockyer Creek in the Lockyer Valley, demonstrates the dynamic interaction during the drought (represented by the 2007 data), the subsequent break of the drought (represented by the 2009 data), and following extreme flooding of 2011 (represented by the 2013 data; Fig. 12a). In addition, the cross-section also shows the relative vertical hydraulic gradient between the potentiometric surface of the Gatton Sandstone and the groundwater level surface of the alluvial aquifer.

During the drought in 2007, groundwater levels in the alluvial aquifer were generally low and well below the streambed level (around 15 m; Fig 12a) and close to the base of the alluvium. Under such conditions, a significant unsaturated zone is established under the stream bed where the stream constantly loses water to the underlying aquifer. The 2009 water levels indicate that Laidley Creek has recharged the underlying alluvial aquifer and caused a significant rise in water levels following the break of the drought, which has significantly reduced the thickness of the unsaturated zone underneath the creek, thus enhancing its hydraulic connection with the underlying alluvial aquifer (Fig. 12a). Following the extensive flooding of 2011, the groundwater levels continued to recover further, with the groundwater level observations from 2013 indicating that Laidley Creek has turned into a gaining stream (Fig. 12a). The comparison of the potentiometric surface of the Gatton Sandstone with the water levels within the alluvial aquifers shows that during the peak of the drought in 2007, the potentiometric surface of the Gatton Sandstone was considerably above the groundwater level of the alluvial aquifer. This implies that there was a strong potential for upwards discharge from the Gatton Sandstone into the alluvium particularly at the edge of the alluvium, which can be further investigated using water chemistry and isotopes.

Groundwater levels in the alluvial aquifer along with the potentiometric surface in the Walloon Coal Measures show that the response of the alluvial aquifer to drought and subsequent flooding and the nature of its hydraulic connection with the river are different in the Bremer River Catchment compared to the Laidley Creek case (Fig. 12b). During the drought, groundwater levels decreased substantially, likely reflecting a decrease of recharge and increased groundwater extraction due to ceasing of surface-water flows. In some instances (i.e. bores near the Bremer River such as bore number 14310051), the groundwater level in 2007 was very close to the base of the alluvium. Following the break of the drought, the groundwater levels in the Bremer alluvium recovered in bores near the Bremer River; however, in contrast to Laidley Creek, in 2013, groundwater levels in bores distant from the river showed little or no recovery in groundwater levels after the break of the drought and after the 2011 flooding. This suggests that stream recharge has a limited lateral extent and does not reach far across the floodplain at this location or that there are very substantial lag times for the lateral propagation of stream recharge across the floodplain. In addition, this also suggests that rainfall recharge has a very high lag time through the unsaturated zone.

The differences in groundwater level responses observed in the Laidley Creek and the Bremer River alluvia are probably linked to the geology and geomorphology of the area. The valley of the Laidley Creek tributary is considerably narrower than the broad valley of the Bremer River. In contrast to the Bremer River, Laidley Creek is deeply incised into the alluvial aquifer. As a result, Laidley Creek has penetrated the clay-rich floodplain sediments present at the top of the alluvial sequence acting as a seal that may limit groundwater recharge, as also observed elsewhere in south-east Queensland (e.g. King et al. 2014; Martinez et al. 2017).

Hydraulic relationships between wetlands and aquifers

In addition to stream–aquifer interactions, groundwater level data together with an assessment of the regional geology can also be used to identify the potential interactions between aquifers and wetlands, controlled primarily by regional-scale geological features pertaining to the geometry of bedrock aquifers or structural features. The thickness of the CMB sedimentary sequences in the Bremer River Catchment is likely to be more than 2,000 m with the Walloon Coal Measures comprising the uppermost 400–600 m. At the eastern edge of this depositional center, the CMB sedimentary sequences terminate against the basement controlled by the West Ipswich Fault. The potentiometric surface map of the Walloon Coal Measures in this area shows that groundwater flows generally towards the eastern margin of the basin (Fig. 13). As the basin sedimentary sequences thin from over 2,000 m to zero, and as groundwater is unlikely to penetrate the low-permeability basement rocks outside the basin, groundwater would likely discharge to the surface and is expressed either as discharge into the Bremer River or as wetlands and/or springs. The presence of wetlands in this area confirms the hypothesis that this area forms a regional discharge area for the sedimentary bedrock. Similar links between the structural framework of the sedimentary basin, the geometry of aquifers and shallow groundwater processes are likely to exist in other parts of the CMB near the basin margins—for example, in the Lockyer Valley, the Richmond and Clarence river catchments.

The relative contribution of climate variability and human pumping

Both climate variability and anthropogenic pumping can lead to groundwater level change (Earman and Dettinger 2011). Human groundwater demand and pumping is a reflection of change of human activities—as for example new industries and land use change and climate variability such as droughts and floods (Taylor et al. 2012). The latter is usually referred to as climate-induced pumping and its impact on groundwater levels has been highlighted by recent regional-scale studies (e.g. Gurdak 2017). The statistical analysis from Russo and Lall (2017) suggested that groundwater levels from shallow (less than 30 m deep) and deep (30–50 m deep) bores across the USA both show significant response to climate variability. The study also indicated that even water levels in deep bores respond to short-term climate variation over timescales of less than 1 year due to climate-induced pumping. Asoka et al.(2017) stated that variation in climate-induced pumping in irrigated agricultural areas has to be taken into account to explain the groundwater storage variability in northwester India. The different signals were not isolated in the current study due to lack of pumping data, which can lead to an overestimation of the direct effects of climate variability through precipitation and recharge. Pumping data have to be recorded to allow a more accurately investigation of the response of water level to climate variability. Except for the methods used in this study, the relationship between climate variability and water level change can also be further analysed by other techniques such as linear regression, wavelet analysis, vector autoregression and frequency analysis depending on data availability (Gurdak et al. 2007; Holman et al. 2011;

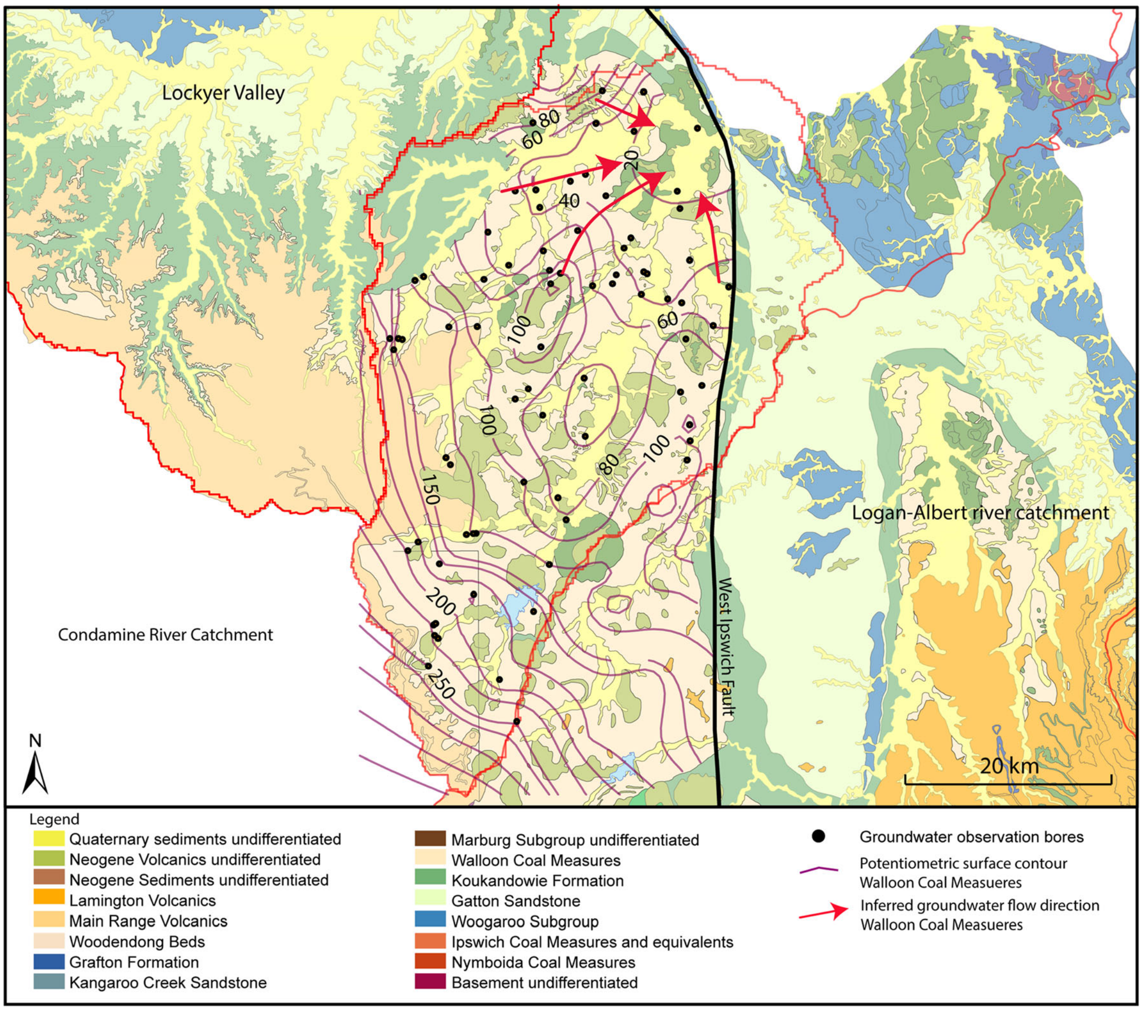

Fig. 13 Mean water-level contours of Walloon Coal Measures in the Bremer River Catchment and their relationship to the West Ipswich Fault

Duvert et al. 2015; Whittemore et al. 2016; Russo and Lall 2017).

Limitations and future research directions

While recognizing the benefits of applying statistical and geostatistical analyses for a groundwater level baseline assessment, it is important to also highlight some limitations in this study. Although there are a large number of groundwater observation bores in the study area, there is a general lack of deep groundwater observation bores, as most observation bores are less than 100 m deep and located either in or near areas where the bedrock outcrops. The existing groundwater monitoring network is likely to capture only a small component of the hydrodynamics of the CMB. This means that environmental impact assessment for potential developments would not be supported by sufficient monitoring data, especially when developments happen in the deep hydrogeological units such as CSG extraction; furthermore, there is a distinct lack of nested bore sites. More research is required to describe the fundamental hydrogeological characteristics such as deep groundwater flow direction or inter-aquifer head gradients and connectivity throughout much of the CMB, especially in the NSW part of the CMB where even shallow monitoring bores are insufficient. Another limitation of this study is the lack of baseline groundwater quality data (Edmunds and Shand 2009).

Conclusions

Understanding the response of groundwater levels in alluvial and sedimentary basin aquifers to climatic variability and human water resource developments is a key step in many hydrogeological investigations. In this study, statistical and geostatistical analyses were used to provide a baseline groundwater level assessment for different catchments within the Queensland part of the Clarence-Moreton Basin. This approach enabled us to determine the influence of droughts and flooding on shallow alluvial and adjacent sedimentary bedrock aquifers in this sedimentary basin where exploration for coal seam gas (CSG) has occurred over the last decade, and identify some of the major drivers that control the spatial and temporal variability.

The temporal trend of groundwater levels revealed by the Mann-Kendall tau statistic and the Sen's slope analyses highlights the system dynamics and shows how the alluvia and bedrock aquifers respond differently to contrasting climate conditions. While the sedimentary bedrock aquifers show a long-term response to climatic variability, the alluvial systems and volcanics respond rapidly to precipitation events. Of all aquifer systems assessed during this study, the Lockyer Valley alluvium is the most sensitive with the highest declining (−0.7 m/year) and ascending (2.1 m/year) rates, during and after the drought, respectively. Although all the plotted hydrographs have depicted a response to mid-term (years) and long-term (decades) climatic variability, the seasonal signal is hardly noticeable for some bores. The overall response to rainfall is highly variable even within the same aquifer depending on local hydrogeological settings and pumping. A further quantification of the impact of climate-induced pumping and the pumping due to human activity change on water level evolution is required to gain a more definitive understanding of the response of groundwater to climate variability.

The assessment of groundwater levels and streambed elevations enabled us to infer the degree of hydraulic connectivity between surface water and the underlying aquifers in key locations within the catchments. The comparison of an example from the Lockyer Valley (where no coal seam gas exploration has occurred) and the Bremer River Catchment (where coal seam gas development has occurred throughout the last decade) highlighted that there are some characteristic differences in the responses of different surface–water/groundwater systems to drought, the break of drought and subsequent flooding, with the local groundwater usage, hydrogeology and geomorphology being the major drivers. In addition to this local analysis of surface-water/groundwater interaction, there are also processes that are likely to be controlled by regional characteristics of the Clarence-Moreton Basin such as the geometry of aquifers or the presence of faults. This preliminary analysis indicates that there are areas where the presence of wetlands can be linked to the abutment of bedrock aquifers at the basin margins.

The findings of this study contribute to the baseline understanding of the hydrogeological processes in the Clarence-Moreton Basin at a regional scale, and lay a foundation for future water resource management in the study area. The groundwater flow pattern and its response rates to climate variability can serve as background information to compare with potential future variation as a result of human activities, climate change, and imposed environmental change. The results can be also used to inform the conceptualization of numerical groundwater models built to assess the sustainability of any future development activities within the Clarence-Moreton Basin such as coal, coal seam gas, and agricultural developments. A similar approach can also be used in other areas where water resource assessments are conducted.

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