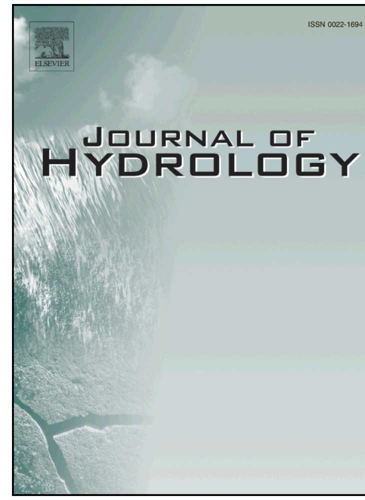
Accepted Manuscript



Research papers

Chronic groundwater decline: a multi-decadal analysis of groundwater trends under extreme climate cycles

Andrew F. Le Brocque, Jarrod Kath, Kathryn Reardon-Smith

PII: S0022-1694(18)30312-3
DOI: https://doi.org/10.1016/j.jhydrol.2018.04.059
Reference: HYDROL 22762

To appear in: *Journal of Hydrology*

Received Date: 6 December 2017
Revised Date: 13 March 2018
Accepted Date: 25 April 2018

Please cite this article as: Le Brocque, A.F., Kath, J., Reardon-Smith, K., Chronic groundwater decline: a multi-decadal analysis of groundwater trends under extreme climate cycles, *Journal of Hydrology* (2018), doi: https://doi.org/10.1016/j.jhydrol.2018.04.059

Chronic groundwater decline: a multi-decadal analysis of groundwater trends under extreme climate cycles

Andrew F. Le Brocque[a]*, Jarrod Kath[a,b], and Kathryn Reardon-Smith[b]

[a.] Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia, 4350.

[b.] Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia, 4350.

* Corresponding author:

Faculty of Health, Engineering and Sciences, University of Southern Queensland, Baker St, Darling Heights, Queensland, Australia 4350.

Ph. +617 4631 1529; Email: Andrew.LeBrocque@usq.edu.au

Declarations of Interests (all authors): None

Author Contributions:

A.F. Le Brocque: Study conceptualisation and design; Data visualisation and graphics; Article preparation

J. Kath: Study conceptualisation and design; Data collation and analysis; Article preparation

K. Reardon-Smith: Study conceptualisation and design; Article preparation

All authors have approved the final article

Abstract

Chronic groundwater decline is a concern in many of the world's major agricultural areas. However, a general lack of accurate long-term *in situ* measurement of groundwater depth and analysis of trends prevents understanding of the dynamics of these systems at landscape scales. This is particularly worrying in the context of future climate uncertainties. This study examines long-term groundwater responses to climate variability in a major agricultural production landscape in southern Queensland, Australia. Based on records for 381 groundwater bores, we used a modified Mann-Kendall non-parametric test and Sen's slope estimator to determine groundwater trends across a 26-year period (1989–2015) and in distinct wet and dry climatic phases. Comparison of trends between climatic phases showed groundwater level recovery during wet phases was insufficient to offset the decline in groundwater level from the previous dry phase. Across the entire 26-year sampling period, groundwater bore levels (all bores) showed an overall significant declining trend ($p<0.05$) of an average 0.06 metres year^{-1}. Fifty-one bores (20%) exhibited significant declining groundwater levels ($p<0.05$), 25 bores (10%) exhibited significant rising groundwater levels ($p<0.05$), and 175 bores (70%) exhibited no significant change in groundwater levels ($p>0.05$). Spatially, both declining and rising bores were highly clustered. We conclude that over 1989–2015 there is a significant net decline in groundwater levels driven by a smaller subset of highly responsive bores in high irrigation areas within the catchment. Despite a number of targeted policy interventions, chronic groundwater decline remains evident in the catchment. We argue that this is likely to continue and to occur more widely under potential climate change and that policy makers, groundwater users and managers need to engage in planning to ensure the sustainability of this vital resource.

Key Words: groundwater decline; groundwater extraction; temporal trend; drought; aquifer recharge/depletion; climate extremes

1. Introduction

Chronic groundwater decline from unsustainable extraction is a significant issue in many agricultural landscapes (Gleeson et al., 2012; Konikow, 2014; Cheema et al., 2014). Groundwater is often seen as a reliable water source during drought and periods of reduced surface water availability (Kath and Dyer, 2017). While extraction rates under such conditions may exceed recharge, these are borne as a temporary deficit (Vaux, 2011), which assumes adequate recharge to restore groundwater levels during periods of higher rainfall. While this may be a reasonable assumption under a stable climate model and sustainable rates of extraction, there is increasing concern that under climate change, or unsustainable rates of extraction, this may not be the case for many regions across the globe (e.g. Döll, 2009; Taylor et al., 2013) and in Australia (Crosbie et al., 2010; Crosbie et al., 2013).

There is a growing body of research suggesting groundwater recharge at landscape scales is vulnerable to land use and climate change (Barron et al., 2012; Flint et al., 2012; Mair et al., 2013; Kuss & Gurdak, 2014; Russo and Lall, 2017). Under even moderate future climate change scenarios, inland eastern Australia is expected to experience increased average temperatures, increased occurrence and severity of heatwaves, decreased average winter rainfall, increased intensity of extreme rainfall events, increased potential evapotranspiration, and importantly, increased duration and severity of drought (CSIRO and Bureau of Meteorology, 2015). As water resources decline, the interplay between climate and groundwater dynamics could be particularly important for groundwater-linked ecological systems (Kath et al., 2014). In addition, groundwater provides more than 30% of Australia's total water consumption (Simmons, 2016) and the potential increased dependency on groundwater, particularly for agriculture (irrigated cropping and livestock production systems), places increased importance on understanding trends in groundwater decline and recharge in relation to climate.

Although limited, a number of recent studies have examined the relationships between trends in climate and groundwater decline and recharge. Correlations between climate and long term groundwater levels have been observed for agricultural areas in Manitoba, Canada (Chen et al., 2004), southwestern United States (Zektser et al., 2005), Central Taiwan (Jan et al., 2007), Orissa region, India (Panda et al., 2007), Daegu, Korea (Lee et al., 2007), Bangladesh (Shahid and Hazarika, 2010; Shamsudduha et al., 2009), northern Iran (Tabari et al., 2012; Daneshvar Vousough et al., 2013), New England region, United States (Weider and Boutt, 2010), Canning Basin, Western Australia (Richey et al., 2015) and the southern Murray-Darling Basin, Victoria, Australia (Chen et al., 2016) and broader Murray-Darling Basin, southeast Australia (Leblanc et al., 2009). While some of these studies showed sufficient groundwater recharge during high rainfall periods, some studies (e.g. Panda et al., 2007; Shahid and Hazarika, 2010; Daneshvar Vousough et al., 2013; Richey et al., 2015) showed a lack of adequate recharge and hence, chronic groundwater decline.

There have been recent attempts to model climate-groundwater relationships at regional and national scales largely using indirect methods, such as satellite gravity (e.g. GRACE) and hydrological and water resources modelling approaches, to estimate groundwater pumping and recharge fluxes (e.g. Leblanc et al., 2009; Crosby et al., 2010; Crosbie et al., 2013; Döll et al., 2014; Richey et al., 2015; Chen et al., 2016; Wada, 2016). Such approaches may be advantageous where there are limited or missing data (Wada, 2016). However, recent reviews warn of the potential of overestimating groundwater decline by indirect approaches (e.g. Wada, 2016; Long et al., 2016), while Sahoo et al, (2016) report significant underestimation of groundwater depletion by indirect techniques such as GRACE and suggest that they do not explicitly account for irrigation and water stored in the unsaturated zone. Döll et al. (2014) also note that the low spatial resolution of such approaches is a concern given the often highly localised nature of groundwater decline. Despite increased understanding of climate-groundwater dynamics in some regions, a lack of reliable *in situ* data and consistent measurement at landscape scales over long periods means that, for many agricultural systems, there is little understanding of the combined effects of groundwater extraction and potential climate change (although see Gurdak et al., 2007; Weider and Boutt, 2010; Daneshvar Vousough et al., 2013; Russo and Lall, 2017). Furthermore, Fekete et al. (2015) claim that, for effective management of groundwater resources, *in situ* observations are needed to provide continuous, long-term, high-frequency and accurate data.

In recent years, groundwater trend analysis has become an effective approach to investigating the patterns and trends of groundwater dynamics at multiple temporal and spatial scales. Daneshvar Vousoughi et al. (2013) recently reviewed the use of non-parametric methods for examining groundwater trends. One of the most frequently used procedures is the Mann-Kendell (MK) trend test statistic (Sen, 2017) that measures the significance of monotonic trends in time series data. This rank-based approach has been effectively used to analyse trends in the time series of hydrogeological parameters (e.g. Jan et al., 2007; Tabari et al., 2012; Daneshvar Vousoughi et al., 2013; Abdullahi et al., 2015; see Dinopashoh et al., 2011, 2014 for reviews of MK variants and procedures). Tabari et al. (2012) found similar trends in groundwater levels in northern Iran when comparing across annual and seasonal time periods; however, the magnitude of trends was more pronounced in summer and spring. Abdullahi et al. (2015) identified both significant positive and negative trends for the north-eastern region of Peninsula Malaysia for different time periods, suggesting overall trends across an entire sampling period may mask significant trends within distinct climatic phases. Similarly, Tirogo et al. (2016) found different significant MK groundwater trends in multi-year climatic phases in West Africa. These studies suggest that an approach that includes overall trend analysis and trend analysis within distinct climatic phases may provide more insightful information about potentially stressed groundwater systems.

The Murray-Darling Basin in south-eastern Australia covers an area of 1.06 million km^2, 14% of Australia's total surface area, and accounts for about 40% of Australia's agricultural production value (Swirepik et al., 2016). The region has recently experienced one of the most severe and prolonged droughts on record (Leblanc et al., 2011). The Condamine catchment, in the northern headwaters of the Murray-Darling Basin, provides an ideal model system for investigating groundwater decline, having a development trajectory of substantial land use change and intensification of water extraction for irrigation that began in the late 1950s comparable to that in many other agricultural landscapes throughout the world. The region also has reliable continuous groundwater monitoring data dating from the 1960s (Queensland Government, 2015).

It has been estimated that between 1.26 and 2.09 $m^3 s^{-1}$ of groundwater is extracted from the shallow Condamine alluvial and sub-artesian aquifers for irrigation (Dafny and Silburn, 2014; Office of Groundwater Impact Assessment, 2016). Current groundwater extraction exceeds water recharge over much of the Central Condamine Alluvium (White et al., 2010), with extraction often being up to five times the average potential rainfall recharge (CSIRO, 2008). Kelly and Merrick (2007) report groundwater depth declines of up to 15 to 25 m in Central Condamine Alluvium groundwater levels over a longer period (1967–2007). The Queensland Department of Natural Resources and Mines report groundwater declines of more than 20 m across much of the Condamine alluvium from 1940 to 2010 (Office of Groundwater Impact Assessment, 2016).

Evidence of chronic groundwater decline in the Central Condamine Alluvium has driven changes in groundwater policy and management. In 1978, the metering of production bores (for irrigation) was introduced and reductions in existing entitlements (currently 50% of entitlements for production bores in the Central Condamine Alluvium) was instigated in 1995 (Tan et al., 2012). In 2008, a moratorium on new groundwater production bore licences was also established (Queensland Government, 2012) and extensive modelling of groundwater flows, sustainable yields and condition reports have since been conducted.

In this study, we investigate groundwater responses to climatic variability from 1989 to 2015 in the agricultural landscape associated with the Condamine floodplain alluvium and associated tributaries alluvium in southern Queensland where there are high rates of groundwater extraction (White et al., 2010), and a history of climatic extremes (prolonged drought and intense flooding). The study period (1989−2015) includes a prolonged and severe drought, the 'Millennium Drought' (2001–2009), as well as significant widespread flooding (1990, 1996, 2010–2011). This model region provides an opportunity to investigate groundwater responses during periods of extreme drought and following intense rainfall, as indicative of possible responses to future climatic extremes under climate change (e.g. Vos et al., 2008; Aghakouchak et al., 2014). Specifically, our aim was to determine the direction and magnitude of trends in groundwater levels over the 26-year period and in wet and dry climatic phases. Under sustainable levels of groundwater extraction, it would be expected that groundwater would be responsive to climatic phases (i.e. groundwater levels decline during drought and recover during wet phases). Groundwater levels showing recovery in wet phases over longer term climatic cycles would suggest some resilience of the system to extreme climate variability. This research will inform the future management of groundwater resources in the region and will provide a basis for the modelling of the effects of climate extremes on agricultural production and biodiversity (for example, groundwater dependent ecosystems).

2. Materials and Methods

2.1. Study area

The Condamine catchment, southern Queensland, covers an area of approximately 25000 km^2 at the headwaters of the Murray-Darling Basin (Fig. 1). The Condamine catchment has undergone significant agricultural development since the 1940s. In 2014–2015, the region contributed AUD$1.32 billion in agricultural value to Australia’s GDP, representing 11% of Queensland’s total agricultural value (Australian Bureau of Statistics, 2016).

The floodplains associated with the Condamine River and its tributaries are characterised by predominantly basalt-derived alluvial sediment, with Tertiary basalt substrates dominating in the south east and Tertiary-Jurassic sediments in the northwest (Searle et al., 2007). The most common soils are highly fertile black, brown, grey and red Vertisols (cracking clays), with some red non-cracking clay soils in the eastern catchment (Biggs and Carey, 2006). Approximately 8500 km^2 of the central area of the catchment is dominated by alluvial floodplain (Searle et al., 2007), extending to 130 m in depth (Kelly and Merrick, 2007).

[Fig. 1]

The region occupies a climate transition zone, with both tropical northern and temperate southern climatic influences and is characterised by a variable sub-tropical to semiarid climate (Hutchinson et al., 2005). Annual rainfall averages range from 952 mm in the east (Toowoomba) to 673 mm in the west of the catchment (Chinchilla) (Australian Bureau of Meteorology, 2017). Mean annual stream flow for the catchment varies from 3.01 $m^3 s^{-1}$ at Warwick (1961–2016) to 19.44 $m^3 s^{-1}$ downstream at Chinchilla (1976–2016) (Queensland Department of Natural Resources and Mines, 2017). Although rainfall is summer dominant (December to February), significant falls may occur at any time throughout the year (Australian Bureau of Meteorology, 2017). Mean rainfall, minimum and maximum ambient temperatures for Dalby (approximate geographical centre of study area) are shown in Figure 2. Rainfall is also highly variable with occasional widespread floods under the influence of tropical monsoonal activity and droughts influenced by El Niño weather patterns (Australian Bureau of Meteorology, 2017). Since 1983, the region has experienced major summer/autumn floods (>1250 $m^3 s^{-1}$) in 1983, 1988, 1990, 1996, and 2011 (Australian Bureau of Meteorology, 2017; Fig. 3). Widespread prolonged moderate drought (5-10% of driest years on record) occurred in 1990–1995, and severe drought (<5% of driest years on record) occurred in 2000–2009 (‘Millennium Drought’) (van Dijk et al., 2013; Fig. 3).

[Fig. 2] [Fig. 3]

The Condamine catchment has undergone significant landscape transformation, with the highly fertile soils and access to water resources being a significant driver of agricultural and regional development over the past 100 years (Walker and Thoms, 1993). Extensive tree clearing and alteration of hydrological flows have resulted in significant eco-hydrological changes throughout the Murray-Darling Basin (e.g. Walker and Thoms, 1993), including the Condamine catchment, where there have been substantial hydrological and land use changes as a result of agricultural development (Biggs and Carey, 2006; Kath et al., 2014). Cropping for agriculture and grazing dominate the landscape of the Condamine catchment and comprise approximately 62% and 30% of the floodplain, respectively (Queensland Department of Environment and Resource Management, 1999).

The Condamine catchment contains substantial groundwater reserves in both the shallow unconfined alluvial aquifers and the underlying confined Great Artesian Basin (GAB). The shallow alluvial aquifers are of generally high water quality and low salinity (Searle et al., 2007), and largely used by agriculture (irrigation and livestock), industry, and domestic water supply, often to augment variable surface water supplies. Groundwater pollution is of a minor concern in the area, and has recently been reviewed by Dafny and Silburn (2014); with most of the management focus being on the management of groundwater extraction. There are an estimated 3800 active bores accessing the Condamine alluvial groundwater across the floodplains and a further 2700 bores accessing the nearby Main Range Volcanics and upland alluvium associated with tributary streams (Office of Groundwater Impact Assessment, 2016).

2.2. Climatic phases defined by rainfall anomalies

Extensive groundwater monitoring data are available for the Condamine catchment for the 26-year period from 1989 to 2015, during which several significant flooding and drought events occurred (Fig. 3). Rainfall anomalies for the period were calculated against mean annual rainfall across Warwick, Dalby and Chinchilla rainfall recording stations (Australian Bureau of Meteorology, 2017) to provide an aggregated rainfall measure for the Condamine catchment. These three main rainfall recording stations encompass the broad range of climatic conditions from the north-west (Chinchilla), centre (Dalby) and south-east (Warwick) of the catchment. These values were compared to the widely accepted long-term (1961–1990) rainfall average (Hundecha and Bárdossy, 2005) to provide annual anomalies for the period 1989–2015. To account for lag effects of previous years—which are likely to be important for groundwater dynamics (Chen et al., 2004)—weighted rainfall anomalies were calculated for each year by adding the current year's rainfall anomaly to that of the previous four years (weighted by years since). Letting the rainfall anomaly (relative to the mean) in year i = $R(y_i)$, $R(y_{i-1})$ represents the anomaly in the previous year and so on, then the 5 year weighted annual rainfall anomaly for each rainfall recording station was:

$$R(5\text{yr}, \text{wtd}) = R(y_i) + \frac{R(y_{i-1})}{(1+y_i - y_{i-1})} + \frac{R(y_{i-2})}{(1+y_i - y_{i-2})} + \frac{R(y_{i-3})}{(1+y_i - y_{i-3})} + \frac{R(y_{i-4})}{(1+y_i - y_{i-4})} \quad (1)$$

Aggregated annual anomalies (j) across the three recording stations (n) were then calculated as:

$$CatchRainAnom(5\text{yr}, \text{wtd}) = \frac{1}{n}\sum_{i=1}^{n} R_{ij}(5\text{y}, \text{wtd}) + \mathrm{R}(y_{ij}) \qquad (2)$$

For our study system, we defined climatic phase (wet or dry) on the basis of the occurrence of two or more extreme wet years (greater than the 90th percentile of the long-term 1961–1990 anomaly) or extreme dry years (less than the 10th percentile of the long-term 1961–1990 anomaly). Hundecha and Bárdossy (2005) use this approach to identify extreme periods in extensive climate data. Climatic phase boundaries were identified where there was a change from positive to negative anomalies (or *vice versa*) and the magnitude of change was approximately 50% or greater. Using this approach, we identified four distinct climatic (wet/dry) phases: Dry 1989–1994; Wet 1994–1999; Dry 1999–2009; Wet 2009–2015 (Fig. 3).

2.3. Groundwater data

All groundwater data (in metres) was extracted from the Queensland groundwater database (Queensland Government 2015), hence quality assured, and restricted to government monitoring bores accessing the unconfined alluvial aquifers. The groundwater depth reference point for these data was taken as the top of bore casing or casing protector to the water surface. The dataset contained data for a total of 445 monitoring bores for the study area over the 27 year period, from which we extracted groundwater level data to carry out trend analysis in each of the climatic phases (overall and wet/dry phases, as above). Data were aggregated to mean yearly depths and in total there were 11,060 observations and 955 missing values. Within each of the climatic phases analysis was only carried out on bores that had sufficient data to justify time series based trend analysis (see section 2.4 for details). The total number of bores analysed in each phased is given in Table 1.

[Table 1]

2.4. Groundwater level trend analyses

Trends in groundwater levels for each bore, across and within each of the four climatic phases, were calculated using the Mann–Kendall test. The nonparametric Mann–Kendall test quantifies trends in time-series data (Kendall, 1955), and has been used to assess environmental trends (e.g. Dinopashoh et al., 2011; Dinopashoh et al., 2014) and groundwater trends in particular (e.g. Tabari et al., 2012; Abdullahi et al., 2015; Tirago et al., 2016). We used Sen's slope estimator in association with the Mann-Kendall test to detect trends in the hydrological time series (after Tabari et al., 2012). The 'Zhang' method (Zhang et al., 2000) for computing trends was used to determine pre-whitened nonlinear trends (i.e. detrended for serial autocorrelation [e.g. seasonality], which can bias analysis) and conducted using the ZYP (Bronaugh and Werner, 2013) and Kendall (McLeod, 2011) packages in R (R Core Development Team 2016). Bores with time series that had insufficient data (i.e. where, after removing autocorrelation, the valid proportion of data was less than 40%) were excluded from analysis (after Bronaugh and Werner, 2013). Two hundred and fifty-one bores were analysed across the entire sampling period (1989–2015), with the mean valid fraction across all bores of 0.96. We restricted analysis to the period 1989−2015 because this aligned with the identified wet and dry climatic phases (Fig. 3) and because the Condamine alluvium groundwater level data is less extensive and more temporally sparse prior to this period. The number of bores analysed in each climatic phase ranged from 356 to 377 and the mean valid fraction across all bores in each climatic phase ranged from 0.95 to 0.99 (Table 1). These analyses identified significant negative or positive trends (at $p<0.05$), or otherwise no trend, for each bore in each climatic phase. Changes in groundwater level (as metres year^{-1}) were mapped for each bore showing a significant negative or positive trend across the Condamine alluvium. We classified bore responses into three categories; those that showed: (a) a significant negative trend ('declining'); (b) a significant positive trend ('rising'); and, (c) no trend ('stable').

3. Results

3.1. Groundwater level trends (1989–2015)

The overall net response across the entire time period (1989–2015) for groundwater monitoring bores in the Condamine alluvium was a significant decline in groundwater levels (Fig. 4; Mann-Kendell Test, $p<0.05$), with an average overall reduction in groundwater level of 0.06 m year^{-1} (Table 1). This average is based on the depth change across all monitoring bores. Across the entire sampling period, 51 bores (20%) exhibited significant negative groundwater level trends ($p<0.05$), 25 bores (10%) exhibited significant positive groundwater level trends ($p<0.05$), and 175 bores (70%) exhibited no significant tends in groundwater levels ($p>0.05$; Table 1).

[Fig. 4]

There is a cluster of monitoring bores exhibiting negative groundwater level trends at moderate magnitudes in the central floodplain between Dalby and Millmerran, although bores exhibiting negative trends also occur elsewhere in the catchment, including in the southeast near Warwick (Fig. 5). There is also a cluster of bores exhibiting positive trends around Dalby in the central part of the catchment, with the majority of positive trending bores located within approximately 30 km of the town (Fig. 5). Monitoring bores exhibiting no significant trend were spread throughout the catchment (Fig. 5).

[Fig. 5]

3.2. Groundwater level trends within climatic phases

In the first dry climatic phase (1989–1994), there was an overall significant decline (from 1989 base level) in mean groundwater level, with an overall magnitude of groundwater level change of -0.30 m year^{-1} (Fig. 4; Table 1). In the subsequent wet phase (1994–1999), mean groundwater level increased significantly ($p<0.05$), by a magnitude of 0.08 m year^{-1} (Fig. 4; Table 1). In the second dry phase

(1999–2009), mean groundwater level decreased significantly (Fig. 4; $p<0.05$), with a magnitude of groundwater decline of -0.16 m $year^{-1}$ (Table 1). In the final wet phase (2009–2015), mean groundwater level increased significantly ($p<0.05$), with a magnitude of groundwater level increase of 0.21 m $year^{-1}$ (Table 1).

Trends in groundwater level changes in each dry and wet phase were spatially heterogeneous, with some areas showing much stronger changes in groundwater levels than others (Fig. 6). In the first dry phase (1989–1994), 233 bores showed significant declines in groundwater level (Mann-Kendall, $p<0.05$; Table 1). The magnitude of declining bores was highest in the central floodplain around Dalby, Cecil Plains and Jondaryan, although high magnitude declining bores were also evident in the southeast near Warwick and east of Allora (Fig. 6a). Five bores in the north of the catchment showed significant positive trends in groundwater level (Mann-Kendall, $p<0.05$; Table 1); one bore located near the town of Chinchilla exhibited a high magnitude of rising groundwater (Fig. 6a). Other rising bores during this climatic phase were located northeast of Dalby (Fig. 6a). One hundred and forty-nine bores, spread across the catchment (Fig. 6a) exhibited no significant trends (Mann-Kendall, $p>0.05$).

[Fig. 6]

In the following wet phase (1994–1999), 280 bores exhibited no significant trends in groundwater level (Mann-Kendall, $p>0.05$; Table 1), 72 bores exhibited significant positive trends (Mann-Kendall, $p<0.05$; Table 1), and 25 bores showed significant negative trends in groundwater levels (Mann-Kendall, $p<0.05$; Table 1). Bores exhibiting rising groundwater levels during this phase were spread across the catchment, although bores exhibiting high magnitudes of increase were primarily located south of Jondaryan, east of Allora and east of Warwick (Fig. 6b). Declining trends were restricted to bores between Dalby and Millmerran, with two high magnitude declining bores near Kaimkillenbun (Fig. 6b).

In the second dry phase from 1999–2009, 197 monitoring bores exhibited significant negative groundwater level trends (Mann-Kendall, $p<0.05$; Table 1) and 168 bores showed no trend (Mann-Kendall, $p>0.05$; Table 1). Only seven bores exhibited significant positive trends (Mann-Kendall,

$p<0.05$; Table 1). Bores with declining trends were spread across the entire catchment; however, the magnitude of declines were greatest between Dalby and Millmerran in the central part of the floodplain, near Jondaryan and northeast of Allora (Fig. 6c). The bores exhibiting positive trends were located near Warra, east of Dalby, northeast of Bowenville, and south of Jondaryan, although these were only of low to moderate magnitude (Fig. 6c),

In the second wet phase from 2009–2015, 33 bores showed significant positive groundwater level trends (Mann-Kendall, $p<0.05$; Table 1); three bores showed significant negative groundwater trends (Mann-Kendall, $p<0.05$; Table 1), and 221 bores showed no positive trend (Mann-Kendall, $p<0.05$; Table 1). Two bores with low magnitude declining trends were located around Dalby and one bore of very low magnitude declining trend was located at Jondaryan (Fig. 6d). Bores with rising trends were spread across the catchment and ranged in magnitude from low to high, with one bore south of Toowoomba of very high magnitude (Fig. 6d).

Examples of individual bore time series within each of the broad type of groundwater response are shown in Figure 7. Bores exhibiting no significant trends typically showed great variability across the 1989–2015 period (Fig. 7c).

[Fig. 7]

4. Discussion

In this study we assessed *in situ* groundwater level changes over a 26-year period (1989–2015) in the Condamine catchment, an agricultural landscape subject to significant levels of groundwater extraction and periodic climate extremes. We defined climate extremes on the basis of significant departure of annual rainfall anomaly from the long term (1961–1990) average rainfall anomaly and identified four distinct climatic phases. We categorised monitoring bore responses in groundwater level as ‘declining’ (significant negative trends), ‘rising’ (significant positive trends), or ‘stable’ (no significant trend) over the entire time period and within climatic phases. Overall, we found that average groundwater levels declined by 0.06 m year^{-1} across Condamine catchment over the entire 26 year study period and that, within climatic phases, groundwater recovery in wet phases was insufficient to offset decline in dry phases.

This study was based on the premise that under a sustainable level of extraction, groundwater levels in monitoring bores would be responsive to climatic phases (i.e. decline during drought and recover during wet phases). If groundwater levels declined in drought, but showed recovery in wet phases, this would suggest some long-term resilience of the system to climate variability. Conversely, lack of recovery in groundwater levels during wet phases (i.e. further groundwater decline or no significant positive trend) would suggest that the system is experiencing chronic groundwater decline and has poor resilience to climate variability. ‘Stable’ bore responses might then represent a system which, while potentially in equilibrium in terms of recharge and extraction/leakage, was either not greatly exposed to extraction pressure or unresponsive to climate phases.

The overall groundwater decline in our study area was driven by a smaller subset of highly responsive bores that were mostly clustered around the central Condamine floodplain. Previous studies have suggested a higher degree of groundwater decline in the study area of between 0.29 and 0.63 m year^{-1} (Kelly and Merrick, 2007; Office of Groundwater Impact Assessment, 2016). However, these reports have focussed on a small number of bores in the central floodplain where there is high groundwater extraction for agriculture over longer time periods, which may explain the discrepancy in the magnitude of overall decline with the current study. Dafny and Silburn (2014) similarly found this central area of the catchment to be experiencing significant groundwater decline and attributed this to over-extraction for irrigation.

Over the last 40 years or so, there have been changes in groundwater policy (a moratorium on new bores and reduced allocations) and the management (e.g. metering of extraction in the Condamine Groundwater Management Area) of groundwater resources in this catchment (Queensland Government, 2012; Tan et al., 2012). However, the overall decline in groundwater levels and, importantly, lack of substantial recovery during extreme high rainfall events and wetter phases found in this study, suggests continued chronic groundwater decline for these parts of the Condamine alluvium despite groundwater policy and management changes.

Analysis of distinct climatic phases in this study reveal further important patterns. As might be expected, the dry phase of 1989–1994 showed the majority of monitoring bores exhibiting a significant decrease in groundwater level. The subsequent positive groundwater level trend during the 1994–1999 wet phase, which included two extreme rainfall years, was not sufficient to offset the magnitude of the negative trend during the preceding dry phase (1989–1994). Furthermore, the high magnitude (0.21 m year^{-1}) positive trend during the 2009–2015 wet phase, while significantly greater than that of the negative trend in the preceding dry phase (1999–2009), was insufficient to offset the longer term (1989–2015) decline in groundwater levels. However, we acknowledge that the temporal response to wet and dry climatic phases may not be the same and may not account for any lags in recharge or extraction. Future analyses examining shorter-term responses to extreme rain events and/or annual rainfall cycles and potential groundwater recovery are needed.

The overall declining groundwater level trend observed for the Condamine alluvium is of significance to the continued drought resilience of both agricultural systems and groundwater-linked ecosystems in this landscape. Chronic groundwater decline will leave these systems increasingly vulnerable to future drought and broader climatic variability. This will likely be further compounded with the projected increase in the magnitude of droughts and increased evapotranspiration in the region over the next century (CSIRO and Bureau of Meteorology, 2015). Furthermore, Crosbie et al. (2010) modelled groundwater recharge in the Murray-Darling Basin under low, medium and high global-warming scenarios and suggest that recharge for the Condamine catchment is predicted to reduce or remain the same under medium or high warming scenarios. These scenarios of climate change, coupled with no further action to reduce extraction rates (through policy change), could be expected to exacerbate the groundwater declines identified in this study.

Understanding the drivers of groundwater dynamics is also complicated by multiple climate variables such as carbon dioxide concentration, temperature, solar radiation and rainfall intensity (e.g.

McCallum et al., 2010; Barren et al., 2012; Crosbie et al., 2012). Similarly, land uses (e.g. native vegetation, irrigated and dryland agriculture, plantation forests, etc.) and management practices, including extraction rates, can all impact groundwater discharge/recharge rates, hence groundwater levels (Willis and Black, 1996). We identified a number of bores exhibiting rising groundwater level trends over the entire sampling period, albeit at lower magnitudes. These bores appear to be located in areas where local water storages and/or flood irrigation of crops may result in localised input into the alluvium (Dafny and Silburn, 2014). In the Lower Macquarie Valley of New South Wales, irrigation has been linked to local groundwater rises from 0.04 to 0.52 m year^{-1} (Willis and Black, 1996). One bore adjacent to the town of Chinchilla exhibited a very strong rising groundwater trend in the first dry phase (1989–1994) and most likely represents the influence of urban infrastructures such as the local weir.

In many cases, a broader set of climate variables and land use and management practices will interact with climatic conditions and these warrant further investigation to adequately account for their influence on groundwater use and recharge (Smerdon, 2017). Our understanding of the drivers of groundwater decline would also benefit from access to accurate long term and high spatial resolution measures of groundwater extraction in the Condamine catchment and Australia more broadly (Harrington and Cook, 2014). Dafny and Silburn (2014) report estimated groundwater extraction rates from the Condamine Alluvium of between 1.46 and 2.12 m^3 s^{-1} since the early 1980s, exceeding the estimated sustainable yield of between 0.48 and 0.95 m^3. s^{-1} (Kelly and Merrick, 2007), but time series data sets for individual production bores is not openly available. While the demand for groundwater extraction may be expected to reduce during wetter climatic phases with increased availability of both soil moisture and surface water, the continued decline in groundwater levels observed in the majority of bores in this study suggests that extraction in parts of the Condamine is unsustainable. These trends also indicate that changes in policy settings over this time period do not appear to have adequately redressed this ongoing decline.

Similar trends indicating chronic groundwater decline has been observed in other agricultural regions, based on direct *in situ* measurement (e.g. Shamsudduha et al., 2011; Tabari et al., 2011; Daneshvar

Vousoughi et al., 2013), and studies using satellite gravity data (e.g. Crosbie et al., 2013; Döll et al., 2014; Richey et al., 2015). Chronic groundwater decline due to over-exploitation of groundwater resources for both agricultural and domestic uses has also been observed in the Ardabil plain agricultural landscape in northwest Iran (Daneshvar Vousoughi et al., 2013). Non-seasonal chronic groundwater decline observed in parts of the Indo-Gangetic Basin has been strongly associated with high extraction rates, particularly during low rainfall periods (Shamsudduha et al., 2011; MacDonald et al., 2016). However, while there is widespread reporting of seasonal and inter-annual trends in groundwater (e.g. Shamsudduha et al., 2009), few studies have previously examined groundwater response to longer climatic cycles (although see Tirogo et al., 2016). In addition, extraction and subsequent lowering of groundwater tables has substantially reduced groundwater storage in many regions (Steward et al., 2013; Döll et al., 2014). Global groundwater storage depletion from 2000–2009 is estimated at 113 km^3 yr^{-1}, with highest rates of change in India, the US, Iran, Saudi Arabia and China (Döll et al., 2014). Reductions in groundwater storage are also likely to have occurred in the Condamine alluvium from the declines in groundwater level observed in this study. We are not aware of studies quantifying storage changes in the Condamine, but this would be an important avenue of future research with important implications for the sustainability of groundwater resources in the area.

Overall decline in groundwater levels across longer climate cycles—despite some recovery in wetter phases as indicated in this study—provides a strong indication that a sustainable groundwater management regime is yet to be achieved and there are grounds for further policy adjustment. However, policy settings are unlikely to change unless there is strong evidence of chronic groundwater decline, based on reliable data and rigorous analysis. Further, unless policy is subject to regular review and adaptation over time, under climate change—in regions where dry and wet extreme events are predicted to be become more prominent (CSIRO and Bureau of Meteorology, 2015)—this situation will likely continue to contribute to even greater groundwater decline over time.

4.1. Resilience of Agricultural Landscapes and Groundwater

Our premise in this study was that groundwater levels showing recovery in wet periods would suggest some degree of resilience of the agricultural system of the Condamine catchment to extreme climate variability. Ecological resilience (*sensu* Holling 1974), has been extensively researched and debated in community ecology, and increasingly considered in more interdisciplinary studies (e.g. Standish et al., 2014; Thoms et al., 2018) to describe non-equilibrium systems. Walker et al. (2004) define resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change to retain the same function, structure, identity, and feedbacks. We extend the approach of Colloff and Baldwin (2010), who developed a model of resilience for semi-arid (250-500 mm rainfall per year) floodplain and wetland ecosystems, to the temperate/sub-tropical (670-950 mm rainfall per year) floodplain agricultural system of the Condamine catchment. Colloff and Baldwin (2010) regard semi-arid floodplain social-ecological systems as existing in a single state, alternating between dry and wet phases driven by episodic floods (recharge) and droughts (drawdown). Colloff and Baldwin (2010) maintain that the stability of these systems is conferred by the capacity to alternate between these phases. While any one cycle (dry/wet phase combination) may not see complete recovery of groundwater, it could be expected that over a number of cycles, groundwater recharge would represent a relatively steady-state system. Our study suggests incomplete recovery over multi-decadal scales, which may indicate a transitioning (unstable) state for the agricultural system of the Condamine catchment in response to a shift in climate and/or groundwater extraction practises. While this may not yet be a catastrophic shift (e.g. Scheffer et al., 2001), failure of policy to address unsustainable groundwater extraction rates in the context of climate change may prove disastrous.

In our study, the proportion of declining bores during both dry climatic phases was much greater than the proportion of rising bores in the following wet phases despite a number of policy interventions on groundwater extraction during this period. Under climate change, where dry and wet extreme events are predicted to be become more prominent (CSIRO and Bureau of Meteorology, 2015), this pattern could intensify leading to even greater decline and less recovery than we have observed.

We conclude that over 1989–2015, there is evidence of a significant net decline in groundwater levels in the important agricultural landscape of the Condamine catchment, southern Queensland. Analysis of trends within distinct climatic phases further reveals that recharge during intense wet periods does not offset the decline in groundwater levels during prolonged drought. While this decline in groundwater levels is restricted to a smaller subset of highly responsive bores within the catchment, it is indicative of the chronic groundwater decline likely to occur more widely with increasing reliance on groundwater systems to supplement variable rainfall and reduced availability of surface water resources. Future extraction policy, and water resource management practises more broadly, will need to carefully consider the heterogeneity of groundwater system responses and the potential impacts of climate change on groundwater dynamics.

Acknowledgements

The authors would like to acknowledge Ernest Dunwoody for fruitful discussions on groundwater data. We also thank the International Centre for Applied Climate Sciences (ICACS) at the University of Southern Queensland for logistic support. We thank Anthony O'Grady for suggestions that have improved the manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abdullahi, M.G., Toriman, M.E., Gasim, M.B., and Garba, I., 2015. Trends Analysis of Groundwater: Using Non-Parametric Methods in Terengganu Malaysia. J. Earth. Sci. Clim. Change 6. doi: 10.4172/2157-7617.1000251

Aghakouchak, A., Feldman, D., Stewardson, M.J., Saphores, J.D., Grant, S., Sanders, B., 2014. Australia's drought: lessons for California. Science 343, 1430–1431. doi: 10.1126/science.343.6178.1430

Australian Bureau of Meteorology, 2017. Australian Bureau of Meteorology Climate Data Online. Commonwealth of Australia, Canberra [cited 17 April 2017.] Available from http://www.bom.gov.au/climate/data/index.shtml

Australian Bureau of Statistics, 2016. Value of Agricultural Commodities Produced, Australia, 2014-15. Australian Bureau of Statistics, Canberra. [cited 17 April 2017.] Available from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7503.02014-15?OpenDocument

Barron, O.V., Crosbie, R,S., Dawes, W.R., Charles, S.P., Pickett, T., Donn, M.J., 2012. Climatic controls on diffuse groundwater recharge across Australia. Hydrol. Earth Syst. Sci. 16 (12), 4557–4570. doi: 10.5194/hess-16-4557-2012

Biggs, A., Carey, B., 2006. The Condamine Catchment. Queensland Natural Resources and Water, Queensland.

Bronaugh, D., Werner, A., 2013. zyp: Zhang + Yue-Pilon trends package. R package version 0.10-1. http://CRAN.R-project.org/package=zyp.

Cheema, M.J.M., Immerzeel, W.W., Bastiaanssen, W.G.M., 2014. Spatial Quantification of Groundwater Abstraction in the Irrigated Indus Basin. Ground Water 52, 25–36. doi: 10.1111/gwat.12027.

Chen, Z., Grasby, S., Osadetz, K.G., 2004. Relation between climate variability and groundwater level in the upper carbonate aquifer, south Manitoba, Canada. J. Hydrol. 290, 43–62.

Chen, J.L., Wilsona, C.R., Tapley, B.D., Scanlon, B., Güntner, A., 2016. Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. Glob. Plan. Change 139, 56–65. doi: 10.1016/j.gloplacha.2016.01.002

Colloff, M.J., Baldwin, D.S., 2010. Resilience of floodplain ecosystems in a semi-arid environment. The Rangeland Journal 32, 305–314. doi: 10.1071/RJ10015

Crosbie, R.S., McCallum, J.L., Walker, G.R., Chiew, F.H.S., 2010. Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. Hydrogeol. J. 18, 1639–1656. doi: 10.1007/s10040-010-0625-x

Crosbie, R.S., McCallum, J.L., Walker, G.R., Chiew, F.H.S., 2012. Episodic recharge and climate change in the Murray-Darling Basin, Australia. Hydrogeol. J. 20, 245–261. doi: 10.1007/s10040-011-0804-4

Crosbie, R.S., Pickett, T., Mpelasoka, F.S., Hodgson, G., Charles, S.P., Barron, O.V., 2013. An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. Climatic Change 117, 41–53. doi: 10.1007/s10584-012-0558-6

CSIRO, 2008. Water Availability in the Condamine-Balonne. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO, Canberra.

CSIRO and Bureau of Meteorology, 2015. Climate Change in Australia Information for Australia’s Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia.

Dafny E., Silburn D.M., 2014. The hydrogeology of the Condamine River Alluvial Aquifer, Australia: a critical assessment. Hydrogeol. J. 22, 705–727. doi: 10.1007/s10040-013-1075-z

Daneshvar Vousoughi, F., Dinpashoh, Y., Aalami, M.T., Jhajharia, D., 2013. Trend analysis of groundwater using non-parametric methods (case study: Ardabil plain). Stoch. Environ. Res. Risk Assess. 27, 547–559. doi: 10.1007/s00477-012-0599-4

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V.P., Kahya, E., 2011. Trends in reference crop evapotranspiration over Iran. J. Hydrol. 399, 422–433. doi: 10.1016/j.jhydrol.2011.01.021

Dinpashoh, Y., Mirabbasi, R., Jhajharia, D., Abianeh, H.Z., Mostafaeipour, A., 2014. Effect of short-term and long-term persistence on identification of temporal trends. Journal of Hydrologic Engineering, 19, 617–625. doi: 10.1061/(ASCE)HE.1943-5584.0000819

Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett. 4 (3), 35006–35006. doi: 10.1088/1748-9326/4/3/035006

Döll, P., Müller Schmied, H., Schuh, C., Portmann, F.T., Eicker, A., 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. Water Resour. Res. 50, 5698–5720. doi: 10.1002/2014WR015595.

Fekete, B.M., Robarts, R.D., Kumagai, M., Nachtnebe, H-P., Odada, E., Zhulidov, A.V., 2015. Time for in situ renaissance. Science 349, 685–686. doi: 10.1126/science.aac7358.

Flint, L.E., Flint, A.L., Stolp, B.J., Danskin, W.R., 2012. A basin-scale approach for assessing water resources in a semiarid environment: San Diego region, California and Mexico. Hydrol. Earth Syst. Sci. 16 (10), 3817–3833. doi: 10.5194/hess-16-3817-2012

Gleeson, T, Wada, Y., Bierkens, M.F.P. van Beek, L.P.H., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488, 197–200. doi:10.1038/nature11295

Gurdak, J.J., Hanson, R.T., McMahon, P.B., Bruce, B.W., McCray, J.E., Thyne, G.D., Reedy, R.C., 2007. Climate variability controls on unsaturated water and chemical movement, high plains aquifer, USA. Vadose Zone J., 6, 533–547. doi: 10.2136/vzj2006.0087

Harrington, N., Cook, P., 2014. Groundwater in Australia. National Centre for Groundwater Research and Training, Adelaide, Australia.

Holling, C.S., 1974. Resilience and stability of ecological systems. Annu Rev. Ecol. Syst. 4, 1–23.

Hundecha, Y., Bárdossy, A., 2005. Trends in daily precipitation and temperature extremes across western Germany in the second half of the 20th century. Int. J. Climatol. 25, 1189–1202. doi: 10.1002/joc.1182

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S., Kinloch, J., 2005. Integrating a global agro-climatic classification with bioregional boundaries in Australia. Glob. Ecol. Biogeo. 14, 197–212.

Jan, C.D., Chen, T.H., Lo, W.C., 2007. Effects of rainfall intensity and distribution on groundwater level fluctuations. J. Hydrol. 332, 348–360. doi: 10.1016/j.jhydrol.2006.07.010

Kath, J., Dyer, F.J., 2017. Why groundwater matters: an introduction for policy-makers and managers. Policy Studies 38, 447–461. doi: 10.1080/01442872.2016.1188907

Kath, J., Reardon-Smith, K., Le Brocque, A.F., Dyer, F. J., Dafny, E., Fritz, L., Batterham, M., 2014. Groundwater decline and tree change in floodplain landscapes: identifying non-linear threshold responses in canopy condition. Glob. Ecol. Conser. 2, 148–160. doi: 10.1016/j.gecco.2014.09.002

Kelly, B., Merrick, N., 2007. Groundwater knowledge and gaps in the Condamine Alliance area. National Centre for Groundwater Management (NCGM), University of Technology, Sydney.

Kendall, M.G., 1955. Rank Correlation Methods. 2nd edn. Griffin, London.

Konikow, L.F., 2014. Long-Term Groundwater Depletion in the United States. Groundwater 53, 2–9. doi: 10.1111/gwat.12306.

Kuss, A.J.M., Gurdak, J.J., 2014. Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO. J. Hydrol., 519, 1939–1952. doi: 10.1016/j.jhydrol.2014.09.069

Leblanc, M.J., Tregoning, P., Ramillien, G., Tweed, S.O., Fakes, A., 2009. Basin-scale, integrated observations of the early, 21st century multiyear drought in southeast Australia. Water Resour. Res. 45, W04408. doi: 10.1029/2008WR007333.

Leblanc, M., Tweed, S., Ramillien, G., Tregoning, P., Frappart, F., Fakes, A., Cartwright, I., 2011. Ch 10: Groundwater change in the Murray basin from long- term in- situ monitoring and GRACE estimates In, Climate Change Effects on Groundwater Resources Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations (Eds. Holger Treidel, Jose Luis Martin-Bordes, Jason J. Gurdak) Taylor & Francis Group, Boca Raton. pp. 169-187.

Lee, J.Y., Yi, M.J., Moon, S.H., Cho, M., Won, J.H., Ahn, K.H., Lee, J.M. 2007. Causes of the changes in groundwater levels at Daegu, Korea: the effect of subway excavations. Bull. Eng. Geol. Environ. 66, 251–258. doi: 10.1007/s10064-006-0074-x

Long, D., Chen, X., Scanlon, B.R., Wada, Y., Hong, Y., Singh, V.P., Chen, Y., Wang, C., Han, Z., Yang, W., 2016. Have GRACE satellites overestimated groundwater depletion in the Northwest India Aquifer? Scientific Reports 6, 24398. doi: 10.1038/srep24398

MacDonald, A.M., Bonsor, H.C., Ahmed, K.M., Burgess, W.G., Basharat, M., Calow, R.C., Dixit, A., Foster, S.S.D., Gopal, K., Lapworth, D.J., Lark, R.M., Moench, M., Mukherjee, A., Rao, M.S., Shamsudduha, M., Smith, L., Taylor, R.G., Tucker, J., van Steenbergen, F., Yadav, S.K., 2016. Groundwater quality and depletion in the Indo-Gangetic Basin mapped from *in situ* observations. Nature Geoscience 9, 762–766. doi: 10.1038/ngeo2791

Mair, A., Hagedorn, B., Tillery, S., El-Kadi, A.I., Westenbroek, S., Ha, K., Koh, G-W., 2013. Temporal and spatial variability of groundwater recharge on Jeju Island, Korea. J. Hydrol. 501, 213–226. doi: 10.1016/j.jhydrol.2013.08.015

McCallum, J.L., Crosbie, R.S., Walker, G.R., Dawes, W.R., 2010. Impacts of climate change on groundwater in Australia: A sensitivity analysis of recharge Hydrogeol. J. 18, 1625–1638. doi: 10.1007/s10040-010-0624-y

McLeod, A.I., 2011. Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2. http://CRAN.R-project.org/package=Kendall.

Office of Groundwater Impact Assessment, 2016. Groundwater connectivity between the Condamine Alluvium and the Walloon Coal Measures: A hydrogeological investigation report. Office of Groundwater Impact Assessment, Queensland Department of Natural Resources and Mines. Brisbane, Australia.

Panda, K., Mishra, A., Jena, S.K., James, B.K., Kumar, A., 2007. The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. J. Hydrol. 343, 140–153.

Queensland Department of Natural Resources and Mines, 2017. Water Monitoring Information Portal. Department of Natural Resources and Mines, Queensland Government, Brisbane, Australia. Available from https://water-monitoring.information.qld.gov.au/

Queensland Department of Environment and Resource Management, 1999. Land Use Mapping Data, Queensland. Queensland Government, Brisbane, Australia.

Queensland Government, 2012. Water Management Plan for the Upper Condamine Alluvium Sustainable Diversion Limit Area. Interim water resource plan for the Commonwealth Water Act 2007. Department of Natural Resources and Mines, Queensland Government, Brisbane, Australia.

Queensland Government, 2015. Groundwater Database – Queensland. Queensland Government, Brisbane, Australia. Available from https://data.qld.gov.au/dataset/groundwater-database-queensland.

R Core Development Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria http://www.R-project.org/.

Richey, A.S., Thomas, B.F., Lo, M.-H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S., Rodell, M., 2015. Quantifying renewable groundwater stress with GRACE, Water Resour. Res. 51, 5217–5238. doi: 10.1002/2015WR017349

Russo, T.A.; Lall, U., 2017. Depletion and response of deep groundwater to climate-induced pumping variability. Nature Geo. 10, 105–108. doi: 10.1038/NGEO2883

Sahoo, S., Russo, T., Lall, U., 2016. Comment on “Quantifying renewable groundwater stress with GRACE” by Alexandra S. Richey et al., Water Resour. Res., 52, 4184–4187. doi: 10.1002/2015WR018085

Searle, R.D., Walting, K.M, Biggs, A.J.W., Secombe, K.E., 2007. Strategic Salinity Risk Assessment in the Condamine Catchment. Queensland Department Natural Resources and Water, Brisbane.

Sen, Z., 2017. Hydrological trend analysis with innovative and over-whitening procedures. Hydrol. Sci. J. 62, 294–305. doi: 10.1080/02626667.2016.1222533

Shahid, S. Hazarika, M.K., 2010. Groundwater drought in the north-western districts of Bangladesh. Water Res. Manage. 24, 1989–2006. doi: 10.1007/111269-009-9534-y

Shamsudduha, M., Chandler, R.E., Taylor, R.G., Ahmed, K.M., 2009. Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges–Brahmaputra–Meghna delta. Hydrol. Earth Syst. Sci. 13, 2373–2385.

Shamsudduha, M., Taylor, R., Ahmed, K.M., Zahid, A., 2011. The impact of intensive abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol. J. 19, 901–916.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B.. 2001. Catastrophic shifts in ecosystems. Nature, 413 (6856), 591−596. doi: 10.1038/35098000

Simmons, C.T., 2016. Groundwater down under. Groundwater 54, 459–460. doi: 10.1111/gwat.12433

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge J. Hydrol. 555, 125–128. doi: 10.1016/j.jhydrol.2017.09.047

Standish, R.J., Hobbs, R.J., Mayfield, M.M., Bestelmeyer, B.T., Suding, K.N., Battaglia, L.L., Eviner, V., et al., 2014. Resilience in ecology: Abstraction, distraction, or where the action is? Biological Conservation, 177, 43–51. doi: 10.1016/j.biocon.2014.06.008

Steward, D.R., Bruss, P.J., Yang, X., Staggenborg, S.A., Welch, S.M., & Apley, M.D., 2013. Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. Proceedings of the National Academy of Sciences, 110, 3477-3486. doi: 10.1073/pnas.1220351110

Swirepik, J.L., Burns, I.C., Dyer, F.J., Neave, I.A., O'Brien, M.G., Pryde, G.M., Thompson, R.M., 2016. Environmental Water Requirements for the Murray–Darling Basin, Australia's Largest Developed River System. River Res. Applic. 32, 1153–1165. doi: 10.1002/rra.2975

Tabari, H., Nikbakht, J., Shifteh Some'e, B., 2012. Investigation of groundwater level fluctuations in the north of Iran. Environ. Earth Sci. 66, 231–243. doi:10.1007/s12665-011-1229-z

Tan, P-L., Baldwin, C., White, I., Burry, K., 2012. Water planning in the Condamine Alluvium, Queensland: Sharing information and eliciting views in a context of overallocation. J. Hydrol. 474, 38–46. doi:10.1016/j.jhydrol.2012.01.004

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.-F., Holman, I., Treidel, H., 2013. Ground water and climate change. Nature Clim. Change 3 (4), 322–329.

Thoms, M.C., Piegay, H., Parsons, M., 2018. What do you mean, ‘resilient geomorphic systems’? Geomorphology, 305, 8–19. doi: 10.1016/j.geomorph.2017.09.003

Tirogo, J., Jost, A., Biaou, A., Valdes-Lao, D., Koussoubé, Y., Ribstein, P., 2016. Climate Variability and Groundwater Response: A Case Study in Burkina Faso (West Africa). Water 8, 171.

van Dijk, A.I.J.M., Beck, H.E., Crosbie, R.S., de Jeu, R.A.M., Liu, Y.Y., Podger, G.M., Timbal, B., Viney, N.R., 2013. The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. Water Resour. Res. 49, 1040–1057. doi: 10.1002/wrcr.20123.

Vaux, H., 2011. Groundwater under stress: the importance of management. Environ. Earth Sci. 62, 19–23. doi: 10.1007/s12665-010-0490-x

Vos, C.C., Berry, P., Opdam, P., Baveco, H., Nijhof, B., O'Hanley, J., Bell, C., Kuipers, H., 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. J. Appl. Ecol. 45, 1722–1731.

Wada, Y., 2016. Modeling Groundwater Depletion at Regional and Global Scales: Present State and Future Prospects. Surv. Geophys. 37, 419–451. doi: 10.1007/s10712-015-9347-x

Walker, K.F., Thoms, M.C., 1993. Environmental-effects of flow regulation on the lower River Murray, Australia. Regulated Rivers-Res. .Manage. 8, 103–119.

Walker, B.H., Holling, C.S., Carpenter, S.R., Kinzig, A.S., 2004. Resilience, adaptability and transformability in Social–ecological Systems. Ecol. Soc. 9: 5.

Weider, K., Boutt, D., 2010. Heterogeneous water table response to climate revealed heterogeneous water table response to climate revealed by 60 years of ground water data. Geophys. Res. Lett. 37, L24405. doi: 10.1029/2010GL045561

White, I., Burry, K., Baldwin, C., Tan, P., George, D., Mackenzie, J., 2010. Tools for water planning: lessons, gaps and adoption. PART 3: Condamine groundwater: from over allocation to sustainable extraction. Rep. Water Line 37, National Water Commission, Canberra.

Willis, T.M., Black, A.S., 1996. Irrigation increases groundwater recharge in the Macquarie Valley. Soil Res. 34 (6), 837–847.

Zektser, S., Loáiciga, H.A., Wolf, J.T., 2005. Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States. Env. Geol. 47, 396–404. doi: 10.1007/s00254-004-1164-3

Zhang, X., Vincent, L.A., Hogg, W.D., Niitsoo, A., 2000. Temperature and Precipitation Trends in Canada During the 20th Century. Atmosphere-Ocean 38, 395–429. doi: 10.1080/07055900.2000.9649654

Table 1. Summary of groundwater level responses showing Sen's slope estimators, number and proportion of bores and mean groundwater level changes within response types across the entire sampling period (1989–2015) and within climatic phases.

Trend (Response)	Mean Sen's slope (trend)			Mean linear trend	Number of bores	Proportion of bores	Groundwater level change (m year^{-1})	
	Mean per year	Mean over period/phase	Mean intercept				Mean	Standard error
Entire period (1989–2015)					*251*	*1.00*	*-0.06*	*0.01*
Negative (Declining)	-0.16	-4.41	-21.77	-0.16	51	0.20	-0.14	0.01
Positive (Rising)	0.13	3.68	-17.00	0.06	25	0.10	0.04	0.02
No trend (Stable)	0.03	0.90	-15.92	-0.06	175	0.70	-0.06	0.01
Dry phase (1989–1994)					*363*	*1.00*	*-0.30*	*0.02*
Negative (Declining)	-0.55	-3.32	-12.57	-0.45	233	0.64	-0.35	0.02
Positive (Rising)	0.22	1.30	-19.49	0.22	5	0.02	0.17	0.09
No trend (Stable)	-0.35	-2.07	-13.02	-0.29	125	0.34	-0.22	0.03
Wet phase (1994–1999)					*377*	*1.00*	*0.08*	*0.01*
Negative (Declining)	-0.17	-1.05	-21.48	-0.20	25	0.07	-0.17	0.02
Positive (Rising)	0.35	2.11	-14.11	0.30	72	0.19	0.22	0.03
No trend (Stable)	0.07	0.43	-15.58	0.10	280	0.74	0.07	0.01
Dry phase (1999–2009)					*372*	*1.00*	*-0.16*	*0.01*
Negative (Declining)	-0.24	-2.62	-15.60	-0.23	197	0.53	-0.19	0.01
Positive (Rising)	0.12	1.29	-19.53	0.13	7	0.02	0.10	0.04
No trend (Stable)	-0.08	-0.85	-15.66	-0.18	168	0.45	-0.13	0.01
Wet phase (2009–2015)					*257*	*1.00*	*0.21*	*0.02*
Negative (Declining)	-0.08	-0.58	-16.21	-0.08	3	0.01	-0.06	0.03
Positive (Rising)	0.26	1.79	-24.37	0.24	33	0.13	0.18	0.03
No trend (Stable)	-0.07	-0.52	-15.13	0.28	221	0.86	0.22	0.02

All negative and positive trends are significant at $p<0.05$ (Mann-Kendall test). Values in italics are across the specified period and are either totals (number of bores, proportion of bores) or means (groundwater level change) and associated standard errors.

Figure 1. Map of Condamine River Sub-basin, southern Queensland, showing major tributaries, towns (solid circles), and distribution of alluvium.

Figure 2. (a) Mean monthly rainfall and (b) mean maximum (solid line) and minimum (dashed line) daily ambient temperatures for Dalby recording station for the period of analysis (1989–2015).

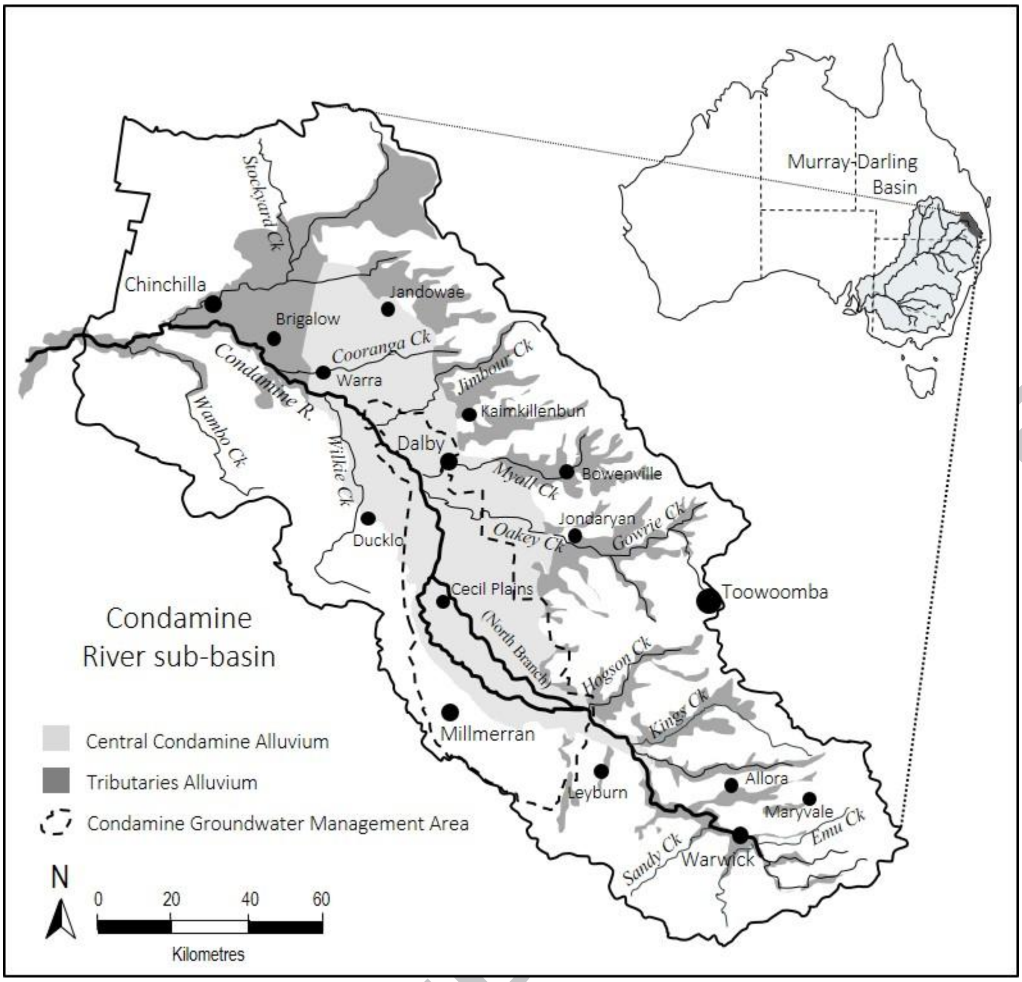
Figure 3. Weighted rainfall anomaly (5 year) for the Condamine catchment (1983–2015) with respect to long-term rainfall anomaly (1961–1990). 90th and 10th percentiles for long term anomaly (1961–1990) shown as dashed horizontal lines. Rainfall anomalies were calculated against mean annual rainfall across Warwick, Dalby and Chinchilla recording stations. Dry and wet phases for the period of analysis (1989 to 2015) are shown.

Figure 4. Mean proportional change in groundwater level relative to 1989 for all alluvial monitoring bores (1989–2015). Shading represents 95% confidence limits.

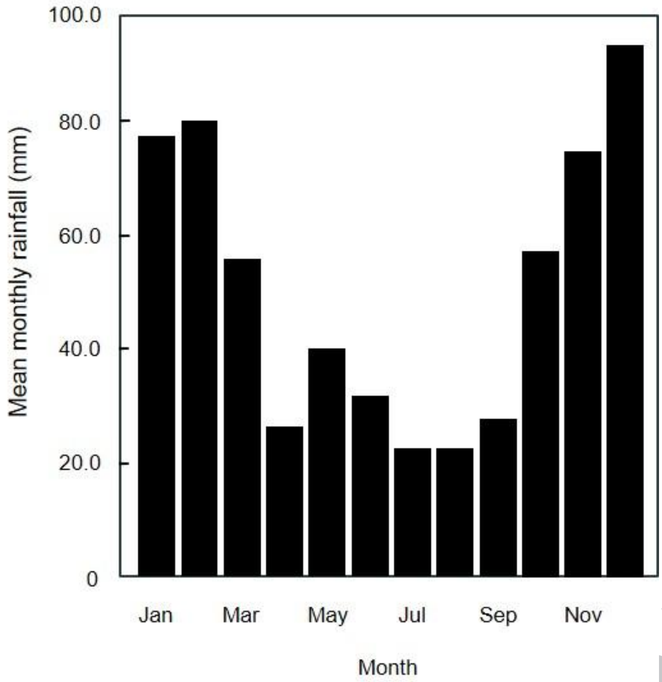
Figure 5. The spatial distribution and number of bores showing groundwater level trend responses during the period 1989–2015 (n = 251): positive trend (◯); negative trend (●); no trend (◯). The size of plotted circles is proportional to the change in groundwater level (magnitude) and is indicated by the scale.

Figure 6. Mean change in groundwater levels per year for the four different climatic phases analysed: (a) dry phase 1989–1994 (n = 363); (b) wet phase 1994–1999 (n = 377); (c) dry phase 1999–2009 (n = 371); and, (d) wet phase 2009–2015 (n = 356): positive trend (◯); negative trend (●); no trend (◯). The size of plotted circles is proportional to the change in groundwater level (magnitude) and is indicated by the scale.

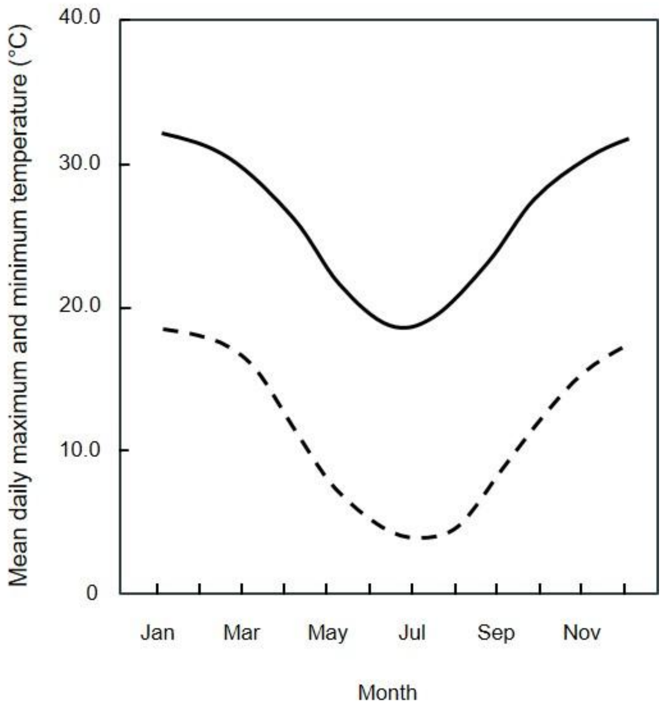
Figure 7. Examples of individual bore time series within broad types of groundwater responses identified: (a) negative trends (decline); (b) positive trends (rising); and, (c) no trend.

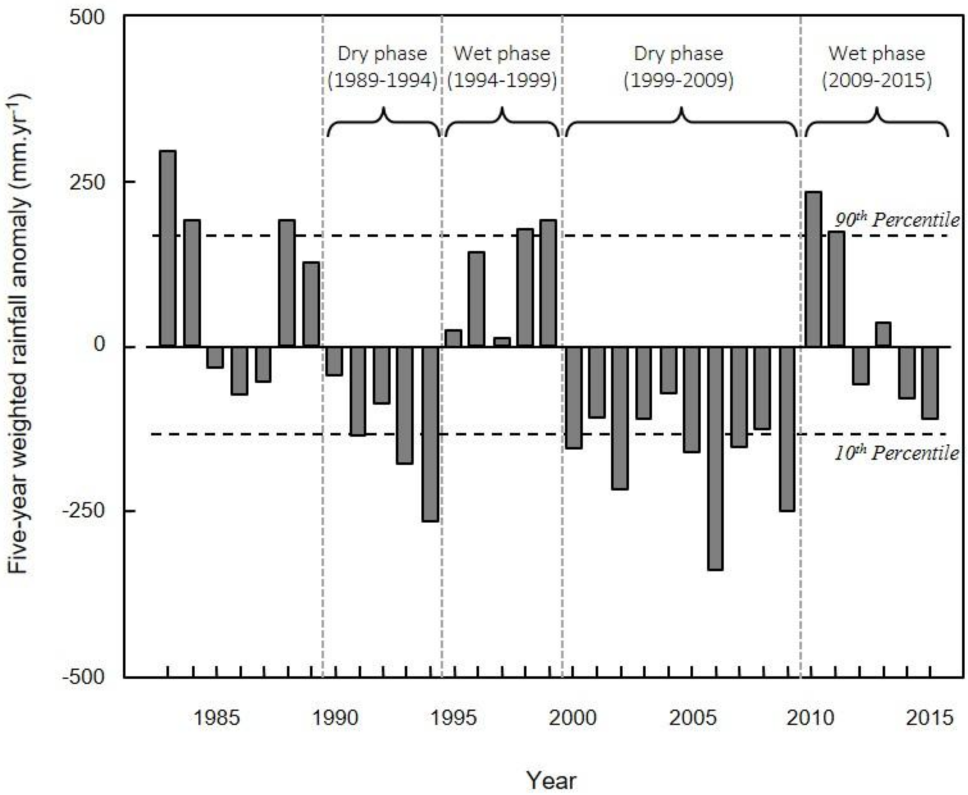

Murray-Darling Basin
Chinchilla
Stockyard Ck
Jandowae
Brigalow
Cooranga Ck
Warra
Condamine R.
Jimbour Ck
Kaimkillenbun
Wambo Ck
Wilkie Ck
Dalby
Bowenville
Myall Ck
Jondaryan
Gowrie Ck
Oakey Ck
Ducklo
Toowoomba
Cecil Plains
(North Branch)
Hogson Ck
Condamine River sub-basin
Kings Ck
Millmerran
Leyburn
Allora
Maryvale
Emu Ck
Sandy Ck
Warwick
Central Condamine Alluvium
Tributaries Alluvium
Condamine Groundwater Management Area
N
0
20
40
60
Kilometres

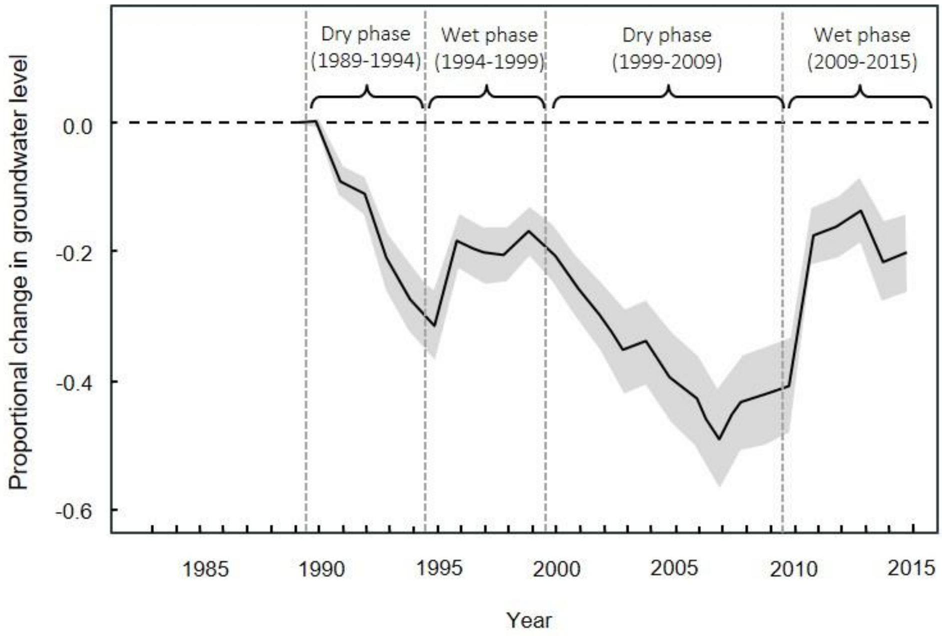
(a)

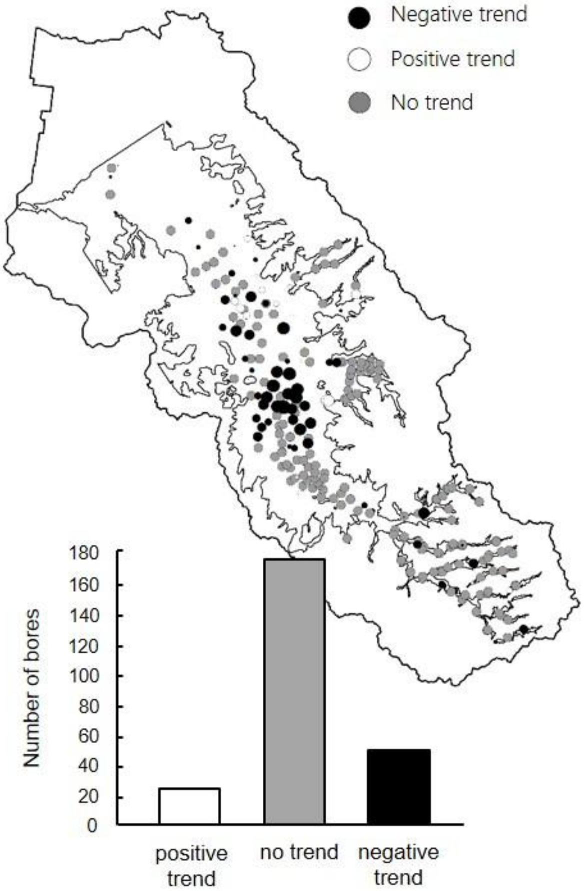

100.0
80.0
60.0
40.0
20.0
0
Mean monthly rainfall (mm)
Jan
Mar
May
Jul
Sep
Nov
Month

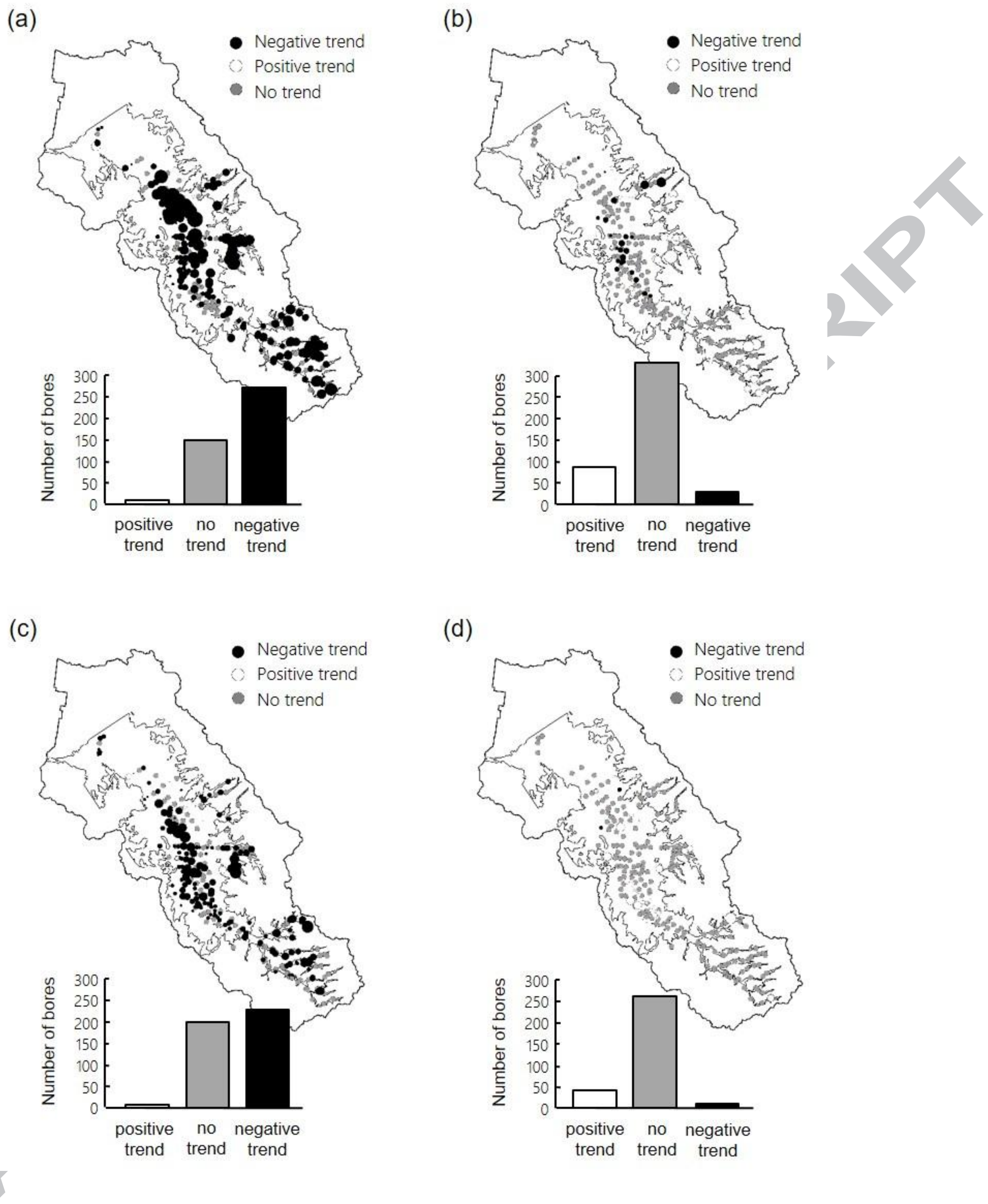
(b)

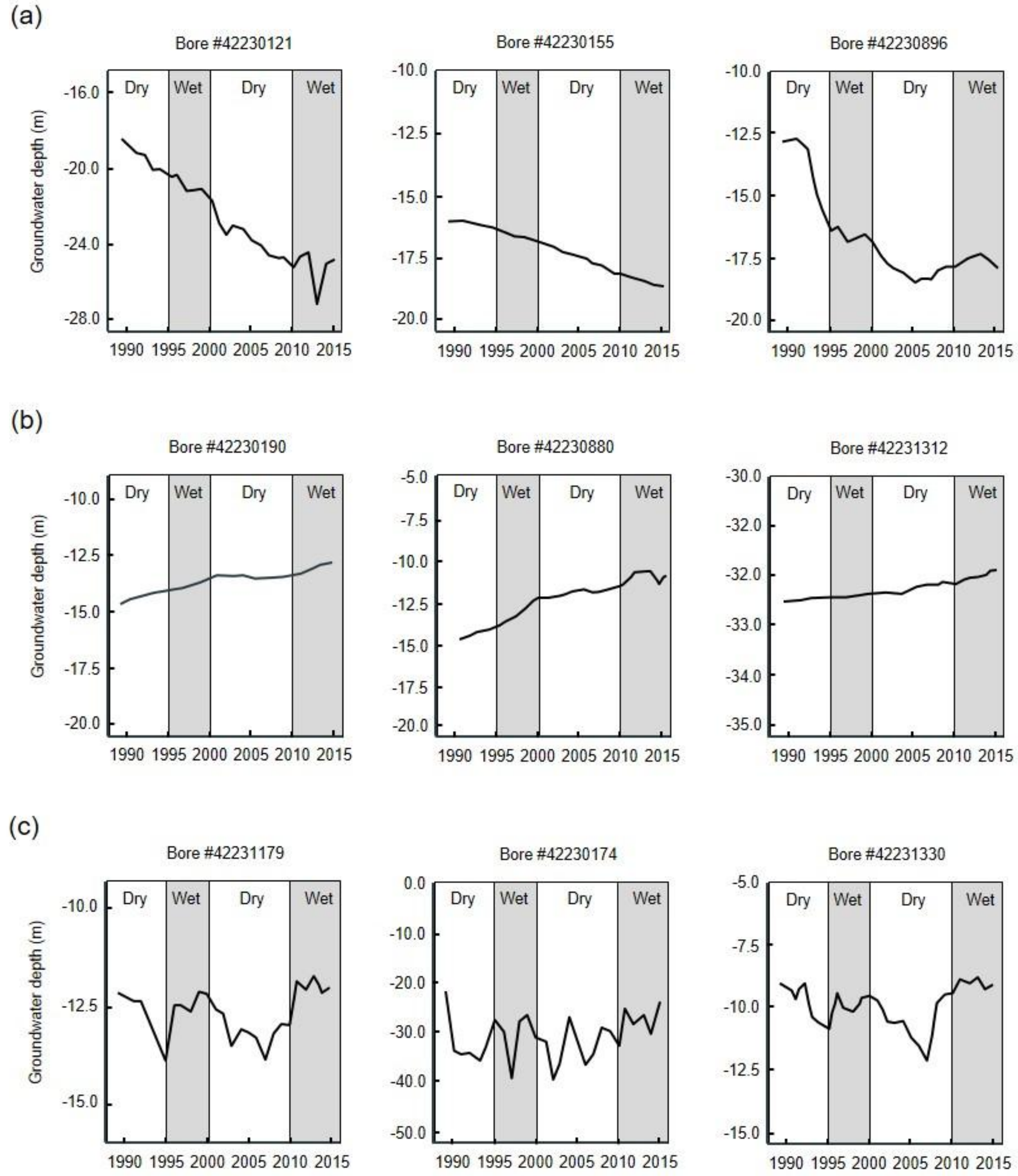

40.0
30.0
20.0
10.0
0
Mean daily maximum and minimum temperature (°C)
Jan
Mar
May
Jul
Sep
Nov
Month


500
250
0
-250
-500
Five-year weighted rainfall anomaly (mm.yr-1)
Dry phase
(1989-1994)
Wet phase
(1994-1999)
Dry phase
(1999-2009)
Wet phase
(2009-2015)
90th Percentile
10th Percentile
1985
1990
1995
2000
2005
2010
2015
Year


Dry phase
(1989-1994)
Wet phase
(1994-1999)
Dry phase
(1999-2009)
Wet phase
(2009-2015)
Proportional change in groundwater level
0.0
-0.2
-0.4
-0.6
1985
1990
1995
2000
2005
2010
2015
Year


Negative trend
Positive trend
No trend
Number of bores
180
160
140
120
100
80
60
40
20
0
positive trend
no trend
negative trend


(a)
Negative trend
Positive trend
No trend
Number of bores
300
250
200
150
100
50
0
positive trend
no trend
negative trend
(b)
Negative trend
Positive trend
No trend
Number of bores
positive trend
no trend
negative trend
(c)
Negative trend
Positive trend
No trend
Number of bores
positive trend
no trend
negative trend
(d)
Negative trend
Positive trend
No trend
Number of bores
positive trend
no trend
negative trend


(a)
Bore #42230121
Bore #42230155
Bore #42230896
(b)
Bore #42230190
Bore #42230880
Bore #42231312
(c)
Bore #42231179
Bore #42230174
Bore #42231330
Dry
Wet
Groundwater depth (m)
1990 1995 2000 2005 2010 2015

Highlights

- Groundwater decline occurred over a period of extreme climate variability.
- Groundwater levels declined an average of 0.06 m.year^{-1} over 26-year period.
- Groundwater decline was not offset by extreme wet climate periods.
- Spatially, both declining and rising bores were highly clustered.