Runoff and groundwater responses to climate change in South West Australia

DON MCFARLANE [1*], RICHARD GEORGE [2], JOHN RUPRECHT [3], STEVE CHARLES [4] & GEOFF HODGSON [4]

[1] *School of Agriculture and Environment, University of Western Australia, Perth, WA, Australia*

[2] *Department of Primary Industries and Regional Development, Bunbury, WA, Australia*

[3] *School of Energy, Water and Waste, Murdoch University, Perth, WA, Australia*

[4] *Land and Water, CSIRO Floreat Laboratories, Perth, WA, Australia*

[*] *Corresponding author: ✉ don.mcfarlane@outlook.com*

ABSTRACT

A warming and drying climate in the South West of Australia since about 1975, and especially from 2000, has reduced flooding and lessened salinisation risks, but also has reduced fresh water supplies. As well as continuous trends, there have been abrupt changes in hydrological processes as groundwater levels have receded from valleys.

In some cleared inland wheatbelt areas, saline groundwaters are still rising where the watertable is deep, clearing has been recent and/or the reduction in rainfall has been limited. Over time, groundwater level changes will better reflect the drying climate. The reduction in rainfall and higher potential evaporation rates has dried catchments overall, and greatly reduced runoff and major flooding, even in catchments where salinity is still expanding across valley floors. Major flooding after rare storms may occur, but now is more likely in summer than winter. It is now driven by infiltration-excess rather than saturation-excess runoff processes, depending on landscape position, and rainfall amount and duration. Episodic events, such as occurred in 2017, may increase salinity and flooding for a period despite the overall decreasing trend in such risks.

In the largely cleared Zone of Rejuvenated Drainage and vegetated Darling Range, groundwater levels in cleared areas are close to reaching a new equilibrium, with the drier climate reducing salinisation risks. In the largely forested Darling Range, groundwater levels are falling below stream beds thereby substantially reducing runoff into dams in the western part of the zone where groundwaters are fresh. As a result, Perth (population two million) has transitioned from being almost entirely dependent on such runoff for its drinking water, to not having any usable runoff in some years.

In the Perth Basin, groundwater levels are falling within sedimentary strata as the predominantly perennial vegetation uses a high proportion of incoming rainfall. The less intense and more intermittent rainfall is also increasing canopy interception and unsaturated-zone water losses. Cleared areas with high watertables are least affected because a reduction in recharge may be offset by less rejected runoff, lower drain flows and evaporation from vegetation tapping into groundwater. This buffering will continue until groundwater levels fall beneath drain inverts and plant rooting depths. The impact of the drying climate on groundwater levels has been masked to date by increasing recharge due to clearing and urbanisation. Streams connected to strata in the Perth and Collie basins usually gain fresher water from unconfined aquifers. With falling groundwater levels drainages are transitioning from gaining- to losing-streams, with reducing surface water flows and increasing risk of aquifer salinisation where the cross-cutting streams are saline.

Climate projections indicate a continuing drying trend is likely with increased temperatures and possibly a greater proportion of annual rainfall, and therefore flood risks, in summer. Water yields in dams and aquifers will continue to decline if these projections are correct. However, risks associated with too much water (salinisation, flooding, soil waterlogging) will probably continue to abate unless the amount and/or intensity of rainfall increases in the future.

KEYWORDS: Runoff, groundwater, recharge, climate change, salinity, Mediterranean climate, South West, Australia

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INTRODUCTION

The South West region of Australia (Fig. 1) is much wetter than expected for a west coast between latitudes 28° and 34°S. Deserts are common at similar locations in South America and southern Africa because of the cold, north-flowing Humboldt and Benguela currents, respectively, which flow up each coastline. The Indian Ocean has a similar anti-clockwise cold current flowing along the west coast of Australia, the West Australian Current, but its effect on rainfall is offset by the warm southerly flowing Leeuwin Current (Feng *et al*. 2003). This current arises from the alignment of islands in the Indonesian archipelago, and a difference in oceanic levels between the Pacific and Indian oceans. Because of the Leeuwin Current, annual rainfalls are 400 mm higher in the South West than for equivalent latitudes in the other two continents (Table 1).

Many areas around the world with a Mediterranean climate have experienced a hotter, drier climate in recent decades—a trend projected to increase and affect both water resources (Arnell 2004) and nature conservation values (Klausmeyer & Shaw 2009). Southwestern Australia has experienced a particularly abrupt and severe reduction in rainfall since about 1975 with this reduction being attributed, in part, to additional greenhouse gases (Hope *et al*. 2006; Cai & Cowan 2006; Frederiksen *et al*. 2017).

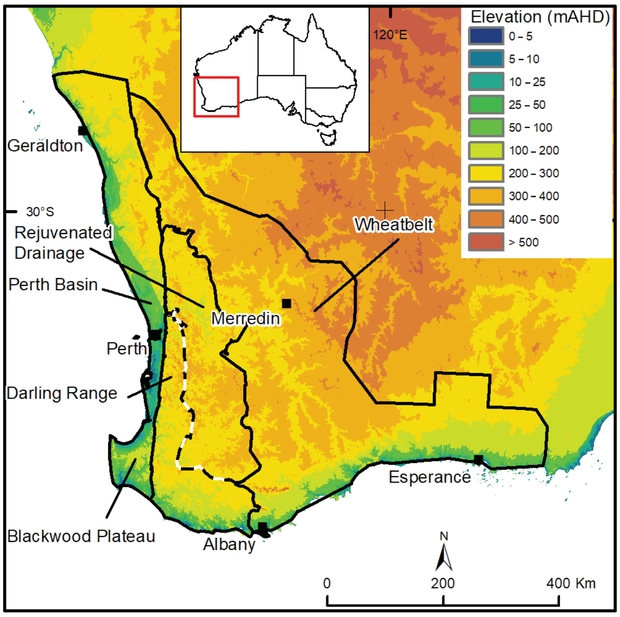

Figure 1. Location of Wheatbelt, Zone of Rejuvenated Drainage and Darling Range (separated by dashed line), and Perth Basin relative to topography in the South West, Western Australia. Background Landsat image from the National Aeronautics and Space Administration archive.

The region is unusual in that it has experienced little tectonic, glaciation or volcanic activity for hundreds of millions of years. As a result, it is flat, rivers are broad and ill-defined, weathering profiles are deep, and soils are infertile. This has allowed the accumulation of cyclic salts and, where native vegetation in inland areas was cleared, the rapid development of dryland salinity (Clarke *et al*. 2002). Shallow sand-over-clay (texture-contrast or duplex) soils are also common in inland areas. These profiles can fill with water and cause crops and pastures to be waterlogged in an otherwise water-limiting environment (McFarlane *et al*. 1992).

This paper examines the different impacts of this climate shift on the region's surface water and groundwater hydrology in the past four decades. It examines recorded trends in salinisation, flooding and water resource availability that are likely to intensify in the future. We also comment on what may happen if these trends continue, as have been largely correctly projected by Global Climate Models in the past 20 or more years.

PHYSIOGRAPHY OF THE SOUTH WEST

Both soil landscape and land cover affect how the hydrology of the South West has responded to the drying climate. For this overview, the area has been divided into three broad east-to-west regions, the Zone of Ancient Drainage (the cleared portion being the Wheatbelt), the Zone of Rejuvenated Drainage and the Perth Basin. The Zone of Rejuvenated Drainage has been sub-divided based on whether it has been largely cleared (in the east) or not (the Darling Range).

The Wheatbelt consists of a plateau covered by deeply weathered clay-rich profiles on Archaean granite and gneiss, over which native vegetation has been mostly cleared. Mulcahy & Bettenay (1972) called the larger region extending well beyond the Wheatbelt the 'Zone of Ancient Drainage'. Its valleys are wide and contain saline lakes and ephemeral rivers that predate progressive clearing in the last 175 years (Fig. 1). The regolith is often over 30 m deep and stores cyclic salts that have not been

Table 1. Comparison of annual average rainfall for areas on the west coasts of Australia, South America and Africa.

Western Australian location	Annual rainfall (mm)	South American location	Annual rainfall (mm)	South West African location	Annual rainfall (mm)
Geraldton 28°47'S	460	Vallenar 28°36'S	32	Alexander Bay 28°35'S	46
Lancelin 31°01'S	599	Coquimbo 29°57'S	106	Lambert Bay 31°40'S	140
Perth 31°96'S	868	Canela 31°23'S	170	Elands Bay 32°18'S	170
Bunbury 33°33'S	871	Valparaiso 33°10'S	462	Cape Town 33°55'S	515

leached over tens of thousands of years because of poor flushing (McFarlane & George 1992). Fresh water is limited in this region because of saline runoff and most groundwater salinities exceed 10 000 mg/L.

To the west of the Wheatbelt the regolith is thinner and the valleys more incised in the Zone of Rejuvenated Drainage (Mulcahy & Bettenay 1972) including the Darling Range sub-region. Whereas the soils are also clayey, especially below about 1 m, salt storage is less, and there are almost no saline lakes in the valleys.

The Darling Range has retained its cover of native forests whereas most of the Zone of Rejuvenated Drainage has been cleared for dryland agriculture (Fig. 2). Because of improved natural flushing, the western, higher-rainfall part of the Darling Range has lower salt storage in the regolith and groundwater is fresher than farther inland. Although groundwater salinities progressively increase to the east with reduced rainfall and flushing within the region, they are less than in the Wheatbelt. Consequently, forest clearing in the eastern parts can lead to increased stream salinities, whereas clearing in the higher-rainfall western part increases the runoff yield of fresh water.

The thick sedimentary succession in the Perth Basin is overlain by sandy soils and unconfined aquifers especially where there are sand dunes. The soils are mostly too permeable to generate sufficient runoff to develop defined drainage lines, except where the soils are clayey on the Blackwood Plateau and around floodplains where major inland drainages from the hinterland cross the basin and have deposited fine-grained material.

As salt storages are low, fresh groundwater is present in most coastal areas. Almost all the flat and low-lying Swan Coastal Plain along the westernmost part of the Perth Basin has been cleared of perennial vegetation, whereas elevated parts in the south (Blackwood Plateau) have retained their native vegetation (Fig. 2).

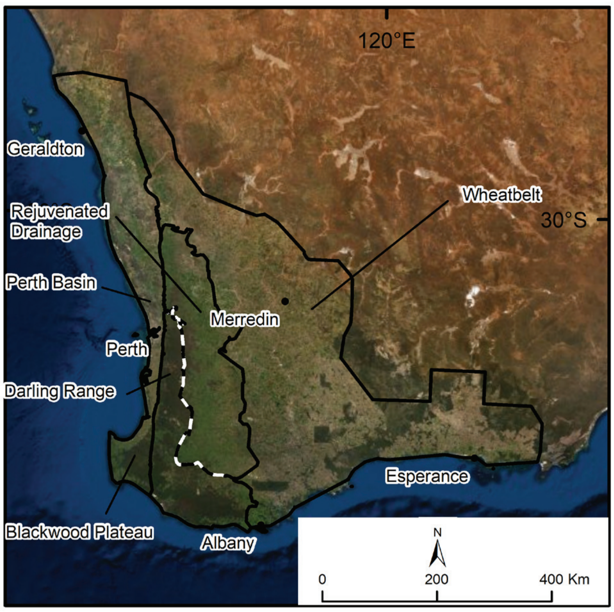

Figure 2. Land cover in the South West of Australia. Background Landsat image from Google Earth.

CLIMATE

The annual rainfall in the South West has reduced by 10–25% in its western parts since 1975 with a small area in the east and southeast recording an increase (Fig. 3). At first the decline in the western area was thought to be natural variability. It was not until the mid-1990s, when runoff into the dams that supply Perth became unreliable, that climate change was considered a factor (Bates *et al*. 2008, 2010).

Cool-season rainfall is far more effective than summer rain in generating runoff because evaporation rates are lower. Soils remain wetter for longer and profiles can become saturated leaving no room for further rain to infiltrate. Soils with sandy topsoils and clayey subsoils are common outside the Perth Basin. These ‘duplex’ soils are very effective in retaining water in their profiles because the sandy topsoil increases infiltration and decreases evaporative losses while the clay subsoil inhibits deep drainage. These soil types are therefore very susceptible to winter runoff and waterlogging. Figure 4 shows that cool season rainfall has decreased by 10 to 30% since 1975 over almost the entire South West.

Unlike eastern Australia, the South West is little influenced by the El Nino Southern Oscillation so the decline in rainfall has been progressive rather than punctuated by droughts followed by wet periods. This is shown in plots of normalised cumulative difference of mean (CDFM) annual rainfall for ten metrological stations across the South West (Fig. 5). Seven of the ten stations show periods of below average rainfall in recent decades. The year each decline started varies but the trends are clear. In contrast, rainfall at eastern stations (Lake Carmody, Welcome Downs and Codg Codgen) has been more consistent with a slight rising trend in recent years.

Although annual rainfall trends may vary, the proportion of rain falling in the wettest six months has shown a substantial decline at all stations except Cape Leeuwin in the South West (Fig. 6). The greatest declines have been at the three most eastern stations (Welcome Downs, Lake Carmody and Codg Codgen) where apparently more consistent total annual rainfall is due to increases in less-effective summer rain and decreasing winter rain.

Runoff is affected by the intensity as well as the amount of rainfall because soil infiltration rates can be exceeded (rainfall excess). Soils can also become saturated (saturation excess) after prolonged wet periods. Li *et al*. (2005) analysed daily rainfall for five stations in the Darling Range and Zone of Rejuvenated Drainage and found that post-1965 intensities were much lower. For example, in Manjimup (Darling Range sub-region) daily rainfalls with a 10% chance of being exceeded in any one year have reduced from about 78 to 40 mm. It is unclear how shorter duration rainfall events have changed, but rain comes more as showers interspersed with sun and wind rather than for extended periods (Hope *et al*. 2006). Under such conditions interception losses in tree canopies will be higher. The Bureau of Meteorology has also estimated that since 1975 daily temperatures in the South West have risen by about 0.5°C and pan evaporation by about 200 mm per annum (Bureau of Meteorology 2018).

In a water resource assessment using 15 Global Climate Models (GCMs) all projected less rainfall in the South West under three warming scenarios (Silberstein *et al*. 2012a). Under a Representative Concentration Pathway of 6.0 W/m^2, eight of 22 GCMs project no change in rainfall by 2040, ten project a decrease by 5–15% and four project a decrease of more than 15% (Climate Change in Australia 2018). A Representative Concentration Pathway (RCP) is the amount of radiative forcing produced by greenhouse gases in 2100. RPCs represent possible future emissions and concentration scenarios, with 6.0 W/m^2 being a mid-level of forcing. The decreases in winter and spring rainfall has a high confidence because of the agreement between GCMs (Hope *et al*. 2015). Therefore, decreased rainfall and increased temperatures and potential evaporation trends observed since the mid-1970s may continue in the future (Charles *et al*. 2010; IOCI 2012).

WHEATBELT AND ZONE OF REJUVENATED DRAINAGE

The accumulation of rainfall and dryfall salts, and lack of leaching from the deep clayey profiles in the Wheatbelt made it highly susceptible to dryland salination once deep-rooted native vegetation was replaced by annual crops and pastures. Surface outbreaks of salinity are greatly dependent on the time since clearing (i.e. the time needed to fill the unsaturated zones under valleys and hillslopes with shallow profiles), the frequency of wet years (especially in the 1950s and 1960s), and the annual rainfall zone (with low rainfall zones taking longer to fill).

By 2000 almost one million hectares (ha) of previously productive land was salt-affected to such an extent that it could not support non-halophytic plants (McFarlane *et al*. 2004). Land was being lost at a rate of about 14 000 ha per annum and an additional 2.8–4.5 million ha could be affected if watertables were to rise by a further 2 m above the valley floor area classified as being a salinity hazard. This extent was considered unlikely because of factors such as the drying climate (McFarlane *et al*. 2004). There were concerns that a four-fold increase in salt-affected land in valley floors could increase historic flood peaks by a similar amount (Hatton & Ruprecht 2001).

A network of groundwater monitoring bores established by the Western Australia Department of Agriculture (now the Department of Primary Industries and Regional Development) from the mid-1980s make it possible to determine how the drying climate mentioned in the previous section has affected recharge and discharge rates. About 700 bores across the South West

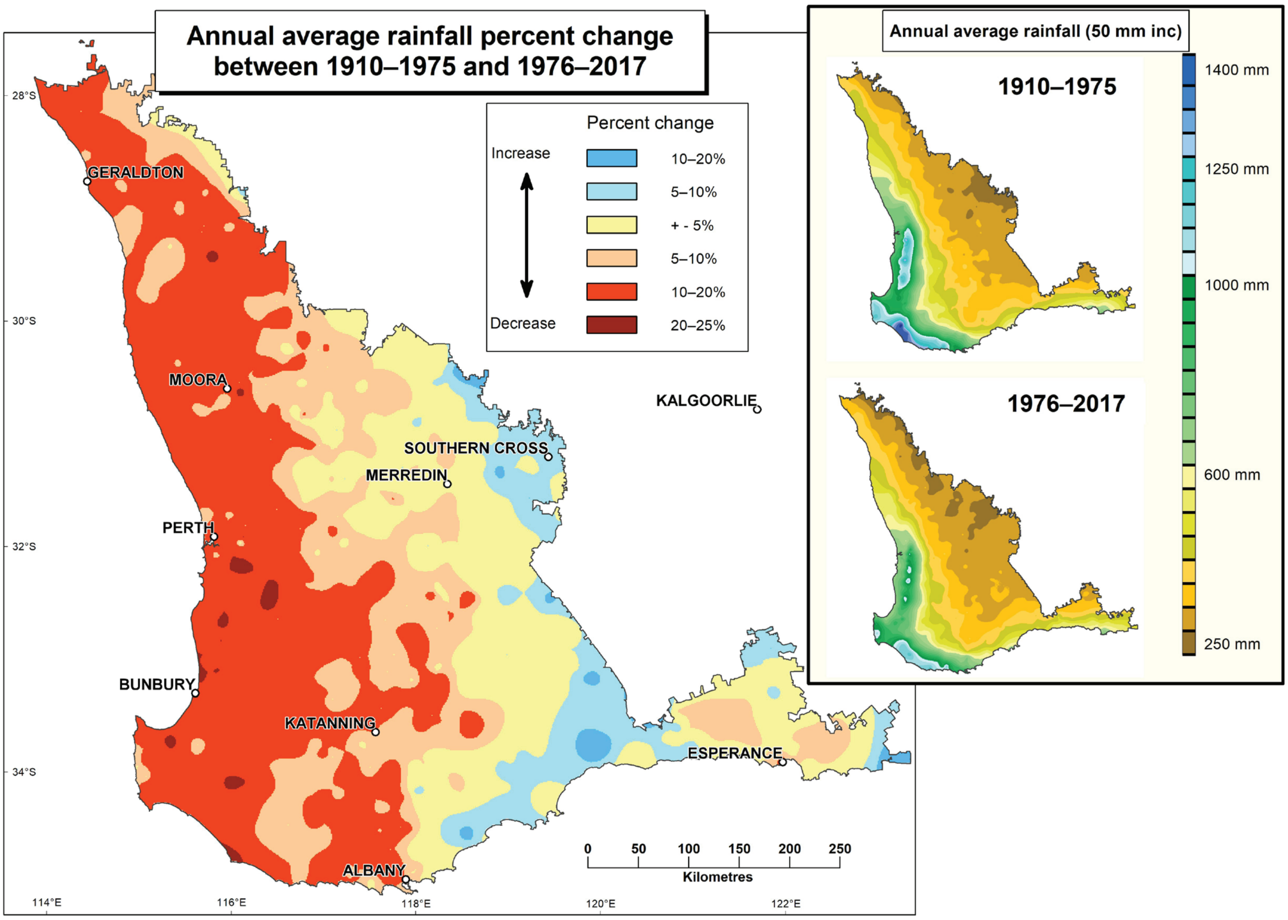

Figure 3. Average annual rainfall (upper right) and percentage change in annual average rainfall between 1910–1975 and 1976–2017 in southwestern Australia. Gridded data from Bureau of Meteorology and Department of Primary Industries and Regional Development weather stations.

have a sufficiently long record to estimate groundwater levels trends before and after 2000. The area with the highest proportion of salinity risk is near the South Coast (Fig. 7) because this region was cleared more recently and the decline in rainfall is less (Fig 3).

Two-thirds of all monitored bores had rising groundwater levels prior to 2000 but only 40% rose between 2000 and 2012 (Fig. 8). A quarter of all 700 bores were rising at a lower rate, indicating that the salt risk had decreased. Where watertables are deep it is possible that groundwater levels may never reach the surface especially if the climate continues to dry. Another satellite image monitoring survey is underway, which will assess whether the loss of 14 000 ha per annum to dryland salinity has continued or abated, along with continued monitoring of groundwater level trends to assess if the reduction in risk after 2000 is continuing.

Streamflows in the Wheatbelt and Zone of Rejuvenated Drainage have only been monitored since the 1970s. However, the annual exceedance probabilities (AEPs) of historic floods have been estimated from the extent of each flood within its floodplain or the height of flood waters on structures (Simon Rodgers, pers. comm. 2018). Using this record it is possible to plot AEPs against time for six major rivers in the South West (Fig. 9). Floods in the Swan, Murray and Greenough rivers were significantly higher in the past, indicated as lower AEP values ($P < 0.01$), than in recent decades. Floods in the Collie, Preston and Blackwood rivers have no significant trend ($P > 0.05$).

Maximum daily flows in the Swan River at Walyunga in 'winter' (April to September) and in 'summer' (October to March) show a decline in maximum flows in winter and a possible increase in the summer floods (Fig. 10a). These trends are also apparent in the Arthur River (a tributary of the Blackwood) at Mount Brown (Fig. 10b).

From the above observations, both historical flooding and maximum daily flows appear to be reducing in some rivers along with the decline in rainfalls shown in Figure 3. There is some indication that flood flows may be increasing in summer, which corresponds to the increased proportion of rain falling during this time of the year (Fig. 6). Increased wetting of the valleys because of rising groundwater levels therefore does not seem to be increasing flooding as has been predicted, with the lower rainfall (and possibly intensities), and higher temperatures and potential evaporation, being more important for runoff generation.

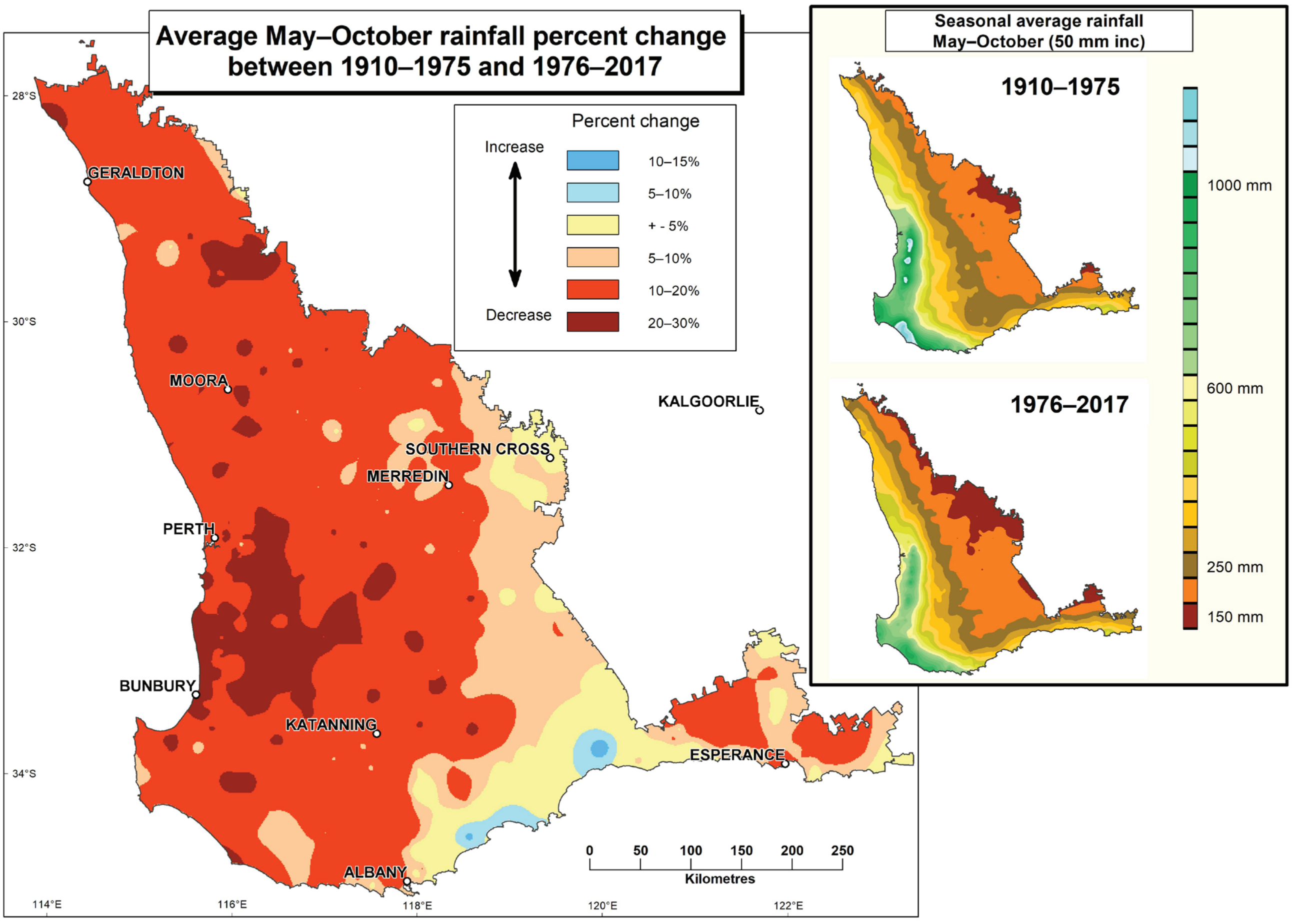

Figure 4. Average May to October rainfall (upper right) and percentage change in May to October rainfall between 1910–1975 and 1976–2017 in southwestern Australia. Gridded data from Bureau of Meteorology and Department of Primary Industries and Regional Development weather stations.

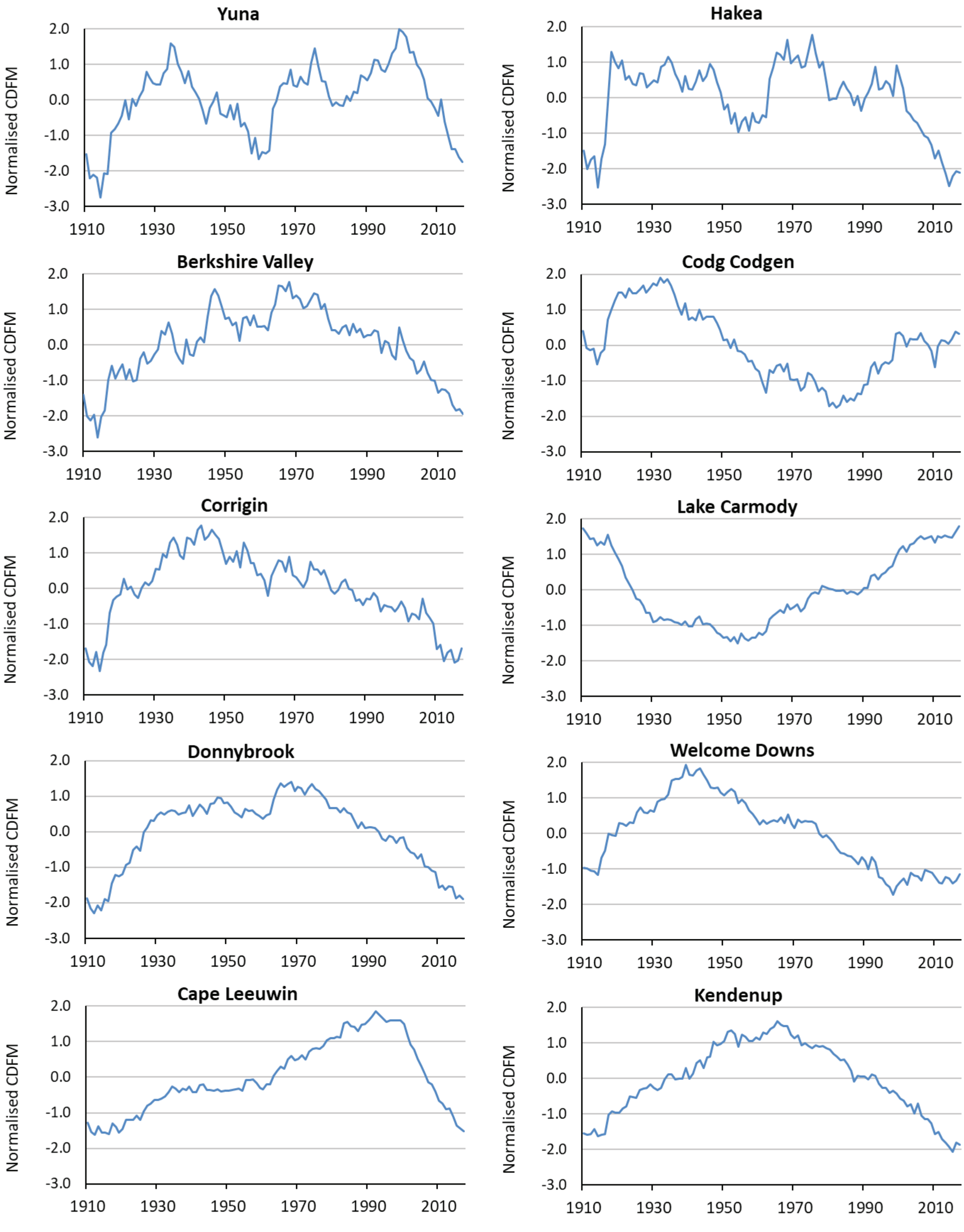

Figure 5. Changes in rainfall over the last ca. 100 years through normalised CDFM for 10 representative stations (Station locations shown in inset map along with the location of four catchments referred to later).

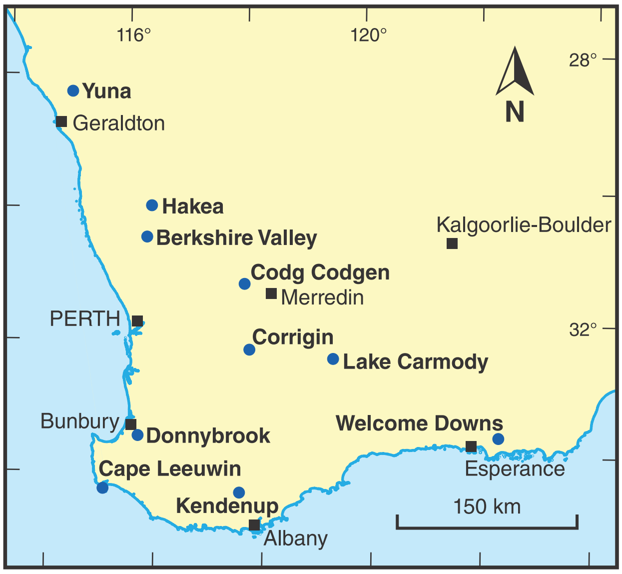

Figure 5. (Cont.)

In 1987 and 1988 about 60% of soils in an Upper Great Southern catchment had perched water in the root zone of crops and over 90% of the floodplain was waterlogged (McFarlane *et al*. 1992). Waterlogging and inundation (ponded surface water) were major constraints to cereal production before drier winters became more common. With the declining rainfall the Wheatbelt has therefore shifted to the southwest into what was termed the woolbelt (McFarlane & George 1994).

DARLING RANGE

Groundwater is a critical element for both streamflow generation and stream salinity in the Darling Range. The presence of a groundwater discharge area adds baseflow and provides a saturated zone for runoff generation (Ruprecht & Schofield 1991). Groundwater levels within forested research catchments in the Darling Range show a nearly continuous decline since 1975 (Kinal & Stoneman 2012; Croton *et al.* 2014). Trends for four catchments are shown in Figure 11. If the current trend in rainfall continues Croton *et al*. (2014) forecast that the regional groundwater in the Gordon research catchment could disappear by 2025.

Whereas groundwater levels are important because they respond to runs of dry years, shallow lateral throughflow in the upper gravelly sand horizon is the main source of streamflow in the jarrah forest in the Darling Range (Fig. 12). Williamson *et al*. (1987) calculated that in an above average rainfall year (1983), 90% of streamflow in a research catchment near Collie originated from throughflow. A perched watertable forms during winter in the sandy gravel or loamy surface soil above a relatively impermeable clay horizon (Stokes 1985; Ruprecht & Schofield 1991). Overland flow and groundwater discharge make minor contributions to annual flow volumes.

Stream salinity

Stream salinity is governed by the relative volumes and salinities of overland flow, shallow throughflow and runoff from valleys that have concentrated salts through evaporation over summer, and groundwater flow. Permanent groundwater, although a low contributor to total flow volume, is the major source of salts, but other flows tend to dilute this source.

Annual mean stream salinities of forested catchments range from 80 to 400 mg/L Total Dissolved Salts (TDS; Mayer *et al.* 2005). The lowest stream salinities (~ 100 mg/L TDS) are in low rainfall areas (mean annual rainfall less than 900 mm) where groundwater does not discharge into streams (Schofield & Ruprecht 1989). In high-rainfall areas (mean annual rainfall >1100 mm), where discharging groundwater salinities are low, stream salinities are again low (~150 mg/L TDS). Streams in the Intermediate Rainfall Zone (mean annual rainfall 900–1100 mm) have the highest salinities in all forest areas. Annual average values are commonly 250 mg/L TDS but can approach 400 mg/L TDS. These high salinities result from a limited discharge of groundwater of moderate salinity, combined with throughflow of low salinity (Loh *et al.* 1984).

Lower rainfall since the mid-1970s has not only reduced streamflows but also stream salinity for many forested streams (Fig. 13). This is probably due to lower groundwater levels along valleys preventing the discharge of higher salinity groundwater.

For any given salinity to streamflow relationship, a lower streamflow is likely to yield a higher salinity because the more saline groundwater contribution would remain relatively constant, but the fresher surface and shallow sub-surface runoff would be less. When valleys dry there is also less concentration of salts because of evapotranspiration.

Schofield & Ruprecht (1989) reported declining stream salinity in the Mt Saddleback catchments, whereas Kinal & Stoneman (2012) showed a reducing stream salinity over 1976–2011 for a forested research catchment. In both studies the reduction in salt load was greater than the reduction in streamflow, therefore the salinity concentration was lower for the period with lower streamflow.

It is therefore likely that stream salinity will continue to reduce in the fully forested catchments under the predicted climate change scenarios, albeit also with greatly reduced streamflows. The impacts of this reduction in salinity on stream ecology has not been considered in the literature. Some consequences could be the re-establishment of fresh-water species, although this is complicated with the significant reductions in streamflow volumes and in many cases dry streambeds for extended periods of time given the reductions in rainfall.

Runoff trends, rainfall–runoff relationships and non-stationary system

Ruprecht & Schofield (1989) identified the importance of groundwater discharge on streamflow generation after forest clearing. Bari *et al.* (1996) found a similar

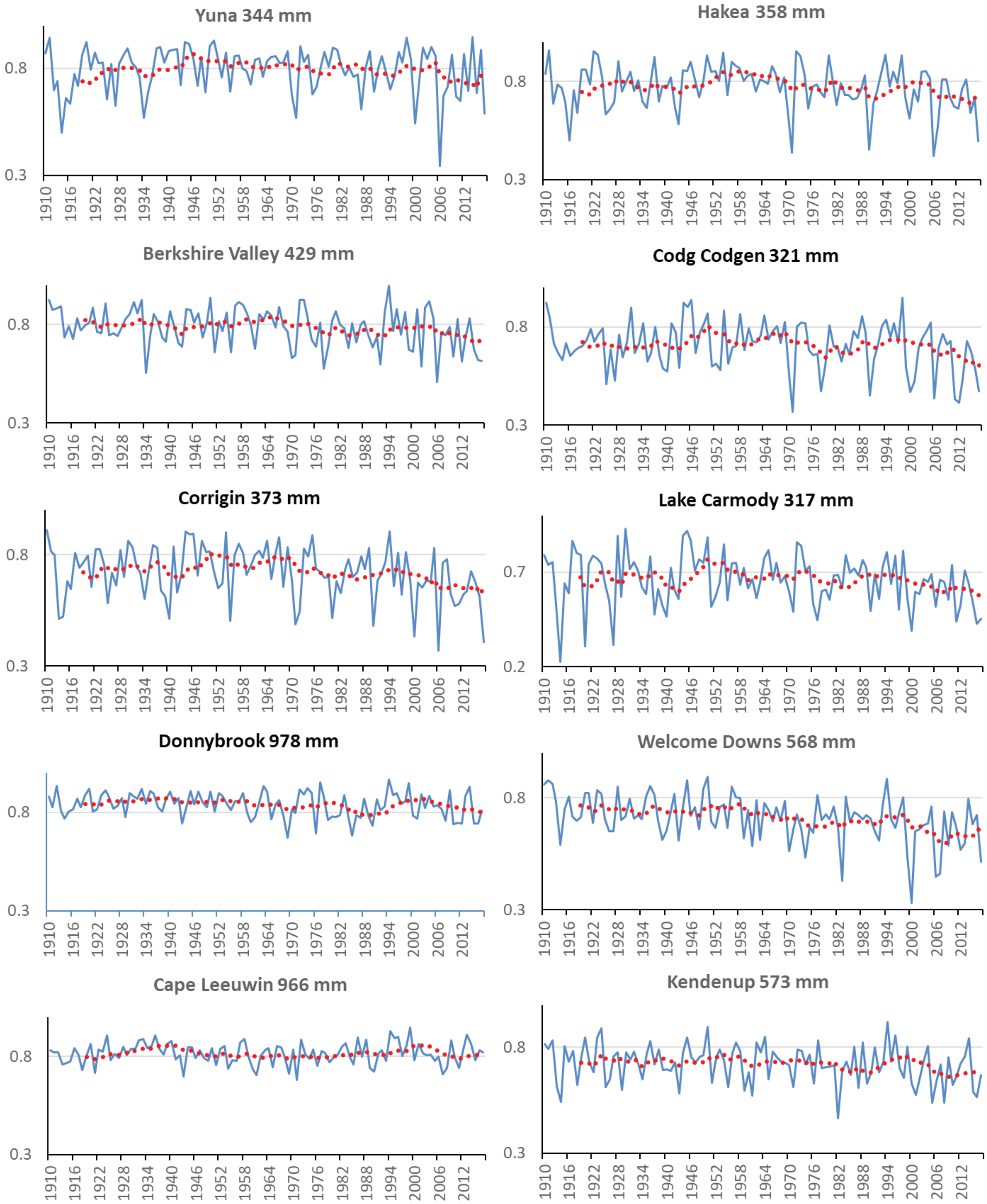

Figure 6. Proportion of annual rain that falls in the wettest six months (April–September for Codg Codgen, Hakea, Yuna, Corrigin and Lake Carmody; May–October for Berkshire Valley, Kendenup, Welcome Downs, Cape Leeuwin and Donnybrook) over time for ten South West rainfall stations. Moving average shown in red. Average annual rainfalls are in mm.

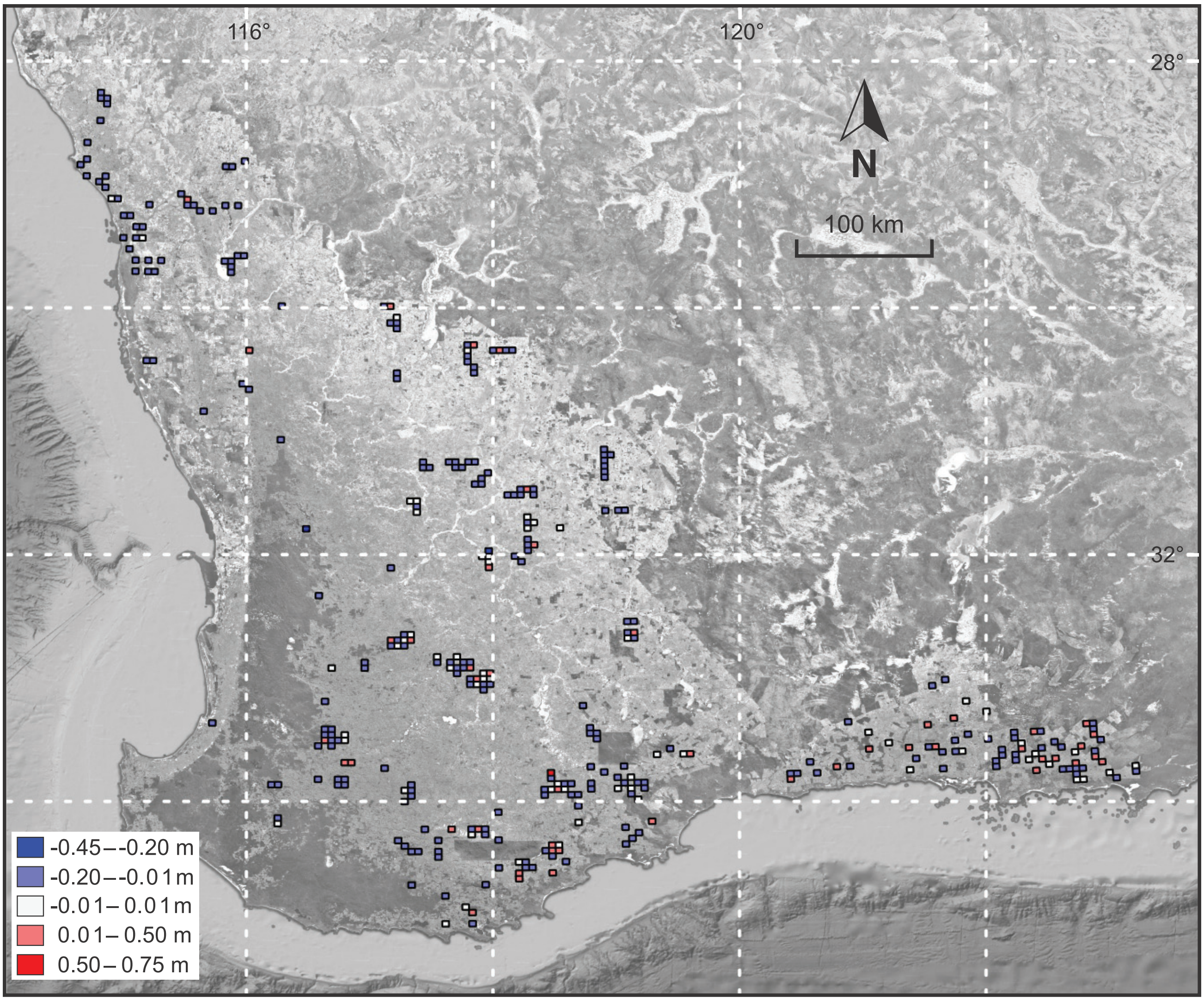

Figure 7. Change in groundwater trends (m/y) since 2000, each square is 5 x 5 km, the colour of the square is determined by the mean change in groundwater trend of the bores within the square since 2000. A blue square means the mean change in trend is positive (the groundwater is rising slower or dropping faster). A red square means the mean change in trend since 2000 is negative (the groundwater is rising faster or decreasing slower). Background image from Google Earth.

relationship with increasing water yield following timber harvesting in southern forests of the South West. Subsequent studies (Kinal & Stoneman 2012; Petrone *et al.* 2010) identified the influence of groundwater discharge areas on declining streamflows after rainfalls. Kinal & Stoneman (2012) found that for the Yarragil catchment in the intermediate rainfall zone of the Darling Range there was not only a change in the streamflow to rainfall relationship, but also greater variability. This change was also noted from drinking water supply catchments.

The importance of groundwater discharge areas on streamflow generation in the high-rainfall zone means that the drying climate has reduced streamflow more than expected for many catchments. The streamflow to rainfall relationship is, however, not consistent across the jarrah forest. The Salmon catchment (a fully forested research catchment in the Collie River catchment) does not show a change in relationship between rainfall and runoff. This is attributed to the lack of a significant groundwater discharge area contributing to streamflow generation, in this case estimated at only 1% of the catchment. Therefore, streamflow generation in the Salmon catchment is related to the ‘wetting up’ of the lower slope soil profile rather than being generated from a saturated groundwater discharge area.

The data from the water supply catchments supports the likelihood of a changing relationship between rainfall and streamflow (Fig. 14). The significance of the changing relationship is that for specific annual rainfalls the predicted annual streamflow has decreased substantially since 2001. This relationship may continue to change or it may represent a new equilibrium relationship.

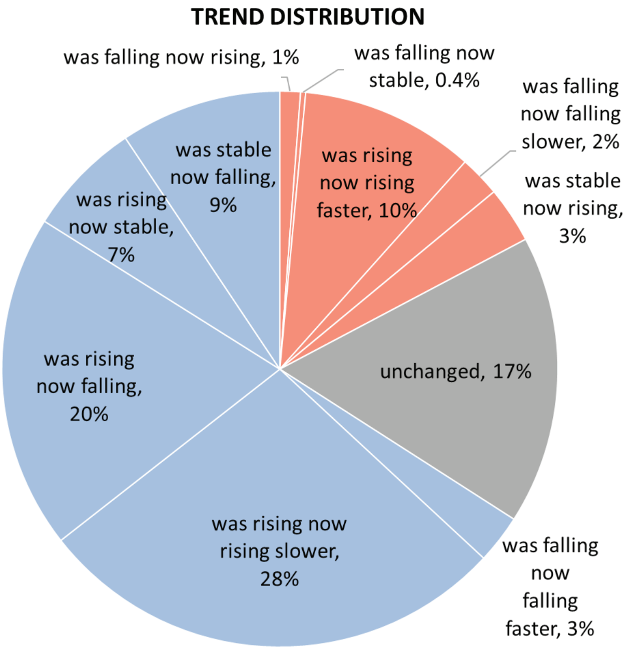

Figure 8. Trends in groundwater levels in 700 bores in southwestern Australia comparing before 2000 and 2000–2012.

The reduction (based on total volume) in mean annual streamflow from 1975–2000 compared to 2000–2012 was 51% while mean annual rainfall only declined by 9%. From the linear regression 30% of the contribution to the reduction in streamflow is attributable to the change in mean annual rainfall, and 70% is from the change in the rainfall to runoff relationship.

Silberstein *et al.* (2012a) indicated that the median future climate rainfall may decline by another 10%. Based on the existing rainfall to runoff relationship this equates to a further runoff decline of 30%. Petrone *et al.* (2010) considered "rainfall variability superimposed on falling watertables as an important cause of streamflow decline in SWWA [the South West] observed as a threshold response in a changing climate". In addition the changes in flow duration and monthly flow distribution for forest streams can be related to falling groundwater levels and loss of groundwater-surface water connectivity, contributing to lower annual runoff (Petrone *et al.* 2010). The observed current declines in catchment runoff and Perth water reservoir inflows brings into question the reliability of surface water catchments for future water supplies as well as the ecology of jarrah forest streams (Petrone *et al.* 2010).

While rainfall in higher rainfall areas has continued to decline by 6–7% since 2000, streamflow at the water supply catchment scale has declined by 45–55%. One explanation for the decline is that a lag in the groundwater response to the lower rainfall since 1975 has delayed changes to the rainfall to streamflow relationship. Alternatively, the changing approach to jarrah forest management (Conservation Commission of Western Australia 2013) over the last 30–40 years may be a contributing factor to the declining water yields (Burrows *et al.* 2011).

Water availability within the forest is considered a key driver of vegetation patterns and the types and abundance of fauna. Watertables in the northern jarrah forest have fallen by approximately 0.2 m/y over the last 35 years (Croton *et al.* 2012; Kinal & Stoneman 2012) and streamflow has reduced by more than 50% over the same period. This has resulted in many streams becoming ephemeral, more variable and less frequent flows, and projections that more streams will become ephemeral. The impact of the changes to the forest river hydrology on the aquatic ecology is not well understood but is likely to be significant.

Water yield into Perth reservoirs

The decline in water inflows into southwestern reservoirs is 28–58% for urban water supplies and 18–42% for irrigation water supplies (Fig. 15). Over all sources the total mean annual flow has reduced from 435 to 265 GL/y, or by 39%. In addition to the reduction in mean annual flow, streamflows have become more variable with the average coefficients of variation increasing from 0.42 to 0.55.

The drying climate in the South West has not only reduced streamflows but has impacted on the forest environment. Although ecosystems such as the jarrah forest are understood to be resilient to drought and other disturbances, Matusick *et al.* (2013) observed a sudden and unparalleled forest collapse in small parts of the jarrah forest corresponding with record dry and heat conditions in 2010–2011.

In the section on Climate we showed how rainfall is projected to decrease whereas temperatures and potential evaporation are expected to increase. Previous modelling studies at the large water supply catchment scale found that for a unit change in rainfall there was a threefold change in runoff (Berti *et al.* 2004; Kitsios *et al.* 2009; Silberstein *et al.* 2012a; Smith *et al.* 2009). However, the data from the water supply catchments (Fig. 16) indicates that this change may be greater than that.

Silberstein *et al.* (2012a) estimated the impact of climate change on the main water supply catchments in 2030 under scenarios in which rainfall declined by 2% (wet), 8% (median) and 14% (dry) compared to the average between 1975 and 2007 using 15 Global Circulation Models (GCMs). This analysis projected a change in mean annual inflow from -7% for the wet scenario to -43% for the dry scenario. However, over 2001–2013 the inflow into these reservoirs has averaged 94.5 GL, which represents a reduction of 36%, i.e. close to the dry scenario. This may mean that the climate impacts on inflow to major water supply reservoirs for Perth have been under predicted.

PERTH BASIN

The decline in annual and seasonal rainfall since 1975 has been most marked in the west across the Perth Basin (Figs. 3, 4). Nevertheless, recharge has been enhanced across this region due to clearing of native vegetation and highly permeable sandy soils.

The watertable is less than 10 m deep over about half of the Perth Basin south of Moora (185 km north of Perth) and less than 3 m across most of the Swan Coastal Plain

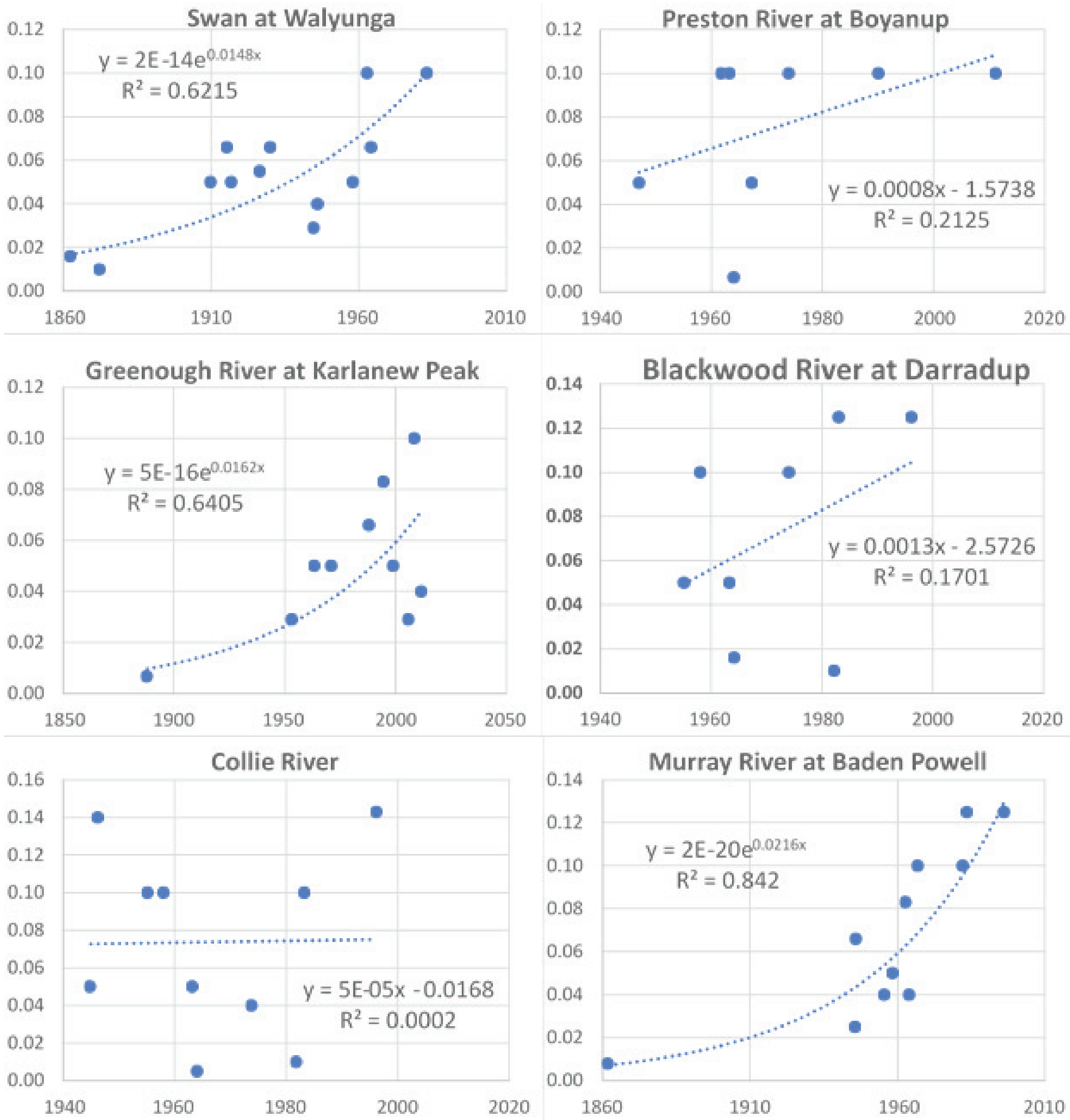

Figure 9. Annual exceedance probabilities of floods for six South West rivers. Data from Department of Water and Environmental Regulation.

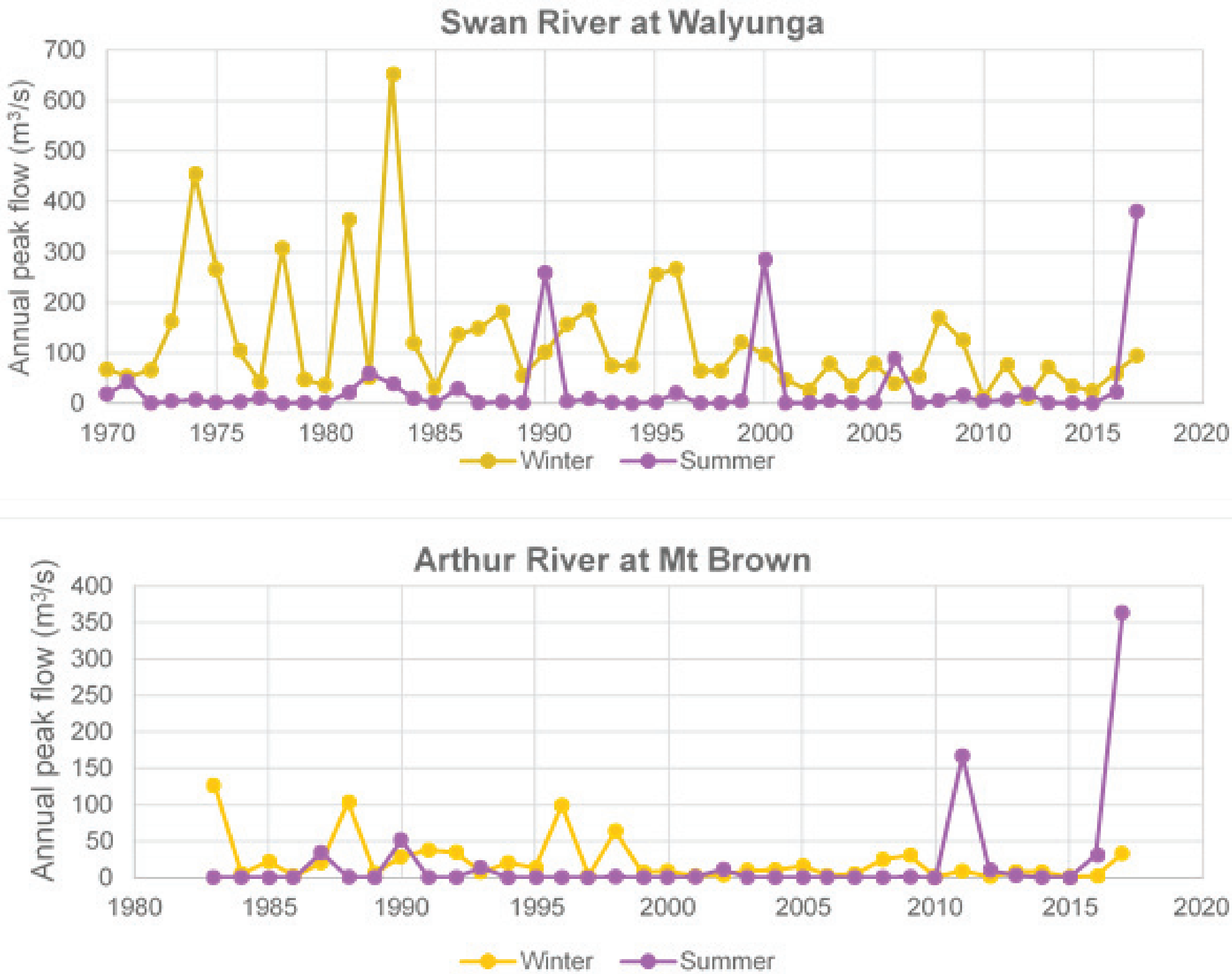

Figure 10. Maximum winter and summer flows in a) the Swan River at Walyunga; and b) the Arthur River at Mt Brown. Data from Department of Water and Environmental Regulation.

(Barron *et al*. 2012). Where watertables are close to the surface, there are losses because of direct evaporation from wetlands, uptake by vegetation that can access the watertable, and by drains used to remove water to enable agriculture and urbanisation. Researchers have shown that native and introduced vegetation (e.g. pines) can access the watertable when it is within 15–18 m of the surface (McFarlane 1984; Silberstein 2012b).

Maps of watertable changes for 2000–2015 show significant falls in unconfined groundwater levels in the south, while a few have risen (Fig. 17). The distribution of monitored bores reflects the intensity of use of the aquifer with it being heavily used on the Swan Coastal Plain around Perth and Peel, and less used where the watertable is much deeper in the north and under the mainly forested Blackwood Plateau in the south. The greatest recorded falls are north of Perth in the Gnangara Mound area and south of Perth near the eastern edge of the coastal plain. Gnangara has one of the most extensive covers of Banksia woodland left on the Swan Coastal Plain, pine plantations and pumping for both public and private use, all of which have impacted on groundwater levels (McFarlane *et al*. 2012).

Where the watertable is close to the surface, buffering (as described above) can reduce falls to 1 m or less, despite the decline in rainfall over 35 years. It is only when winter recharge fails to replace the losses over summer that the watertable starts to accumulate losses and falls of over 5 m are recorded. Groundwater-throughflow wetlands on the Swan Coastal Plain are usually less than 2 m deep so many have dried because of the fall in groundwater levels (Barron *et al.* 2012). Falls have been greatest under perennial vegetation as would be expected given interception by both the canopy and root systems.

The impact of climate on groundwater levels is evident in Figure 18. Landuse (except pine removal) and pumping were kept constant for four climate scenarios applied to three regional groundwater models for the Perth Basin south of Moora (Ali *et al*. 2012). For all the

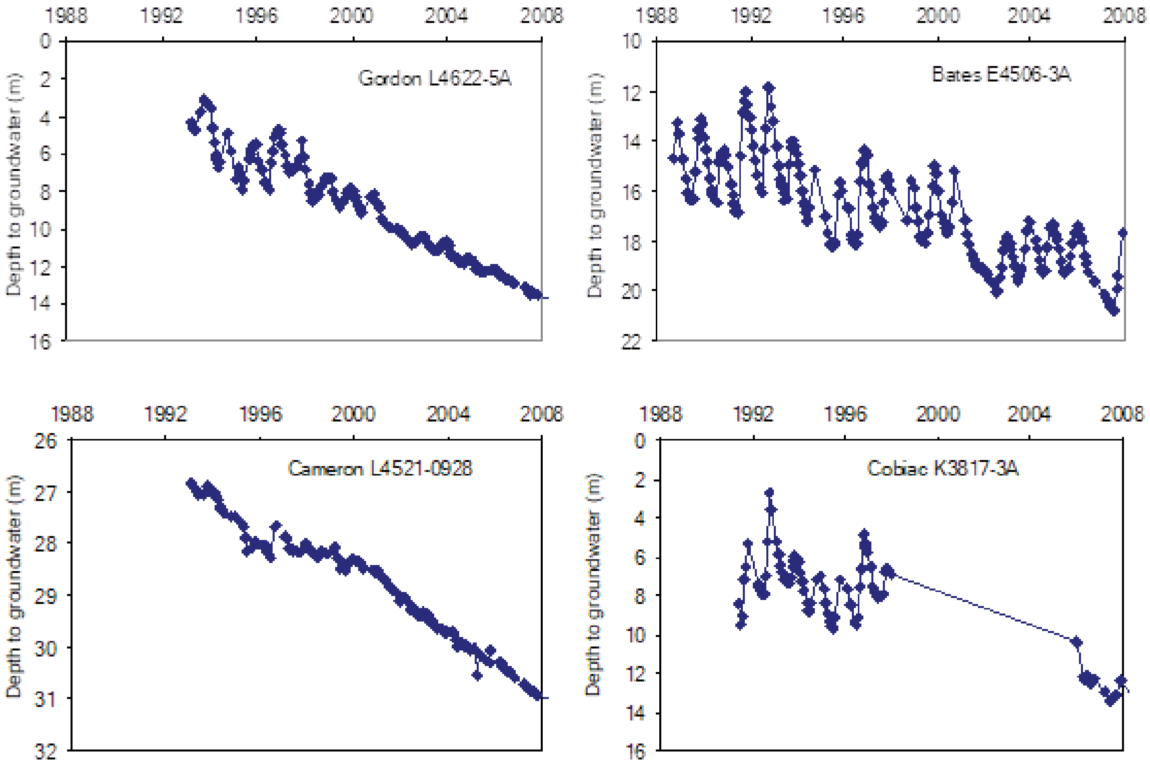

Figure 11. Groundwater levels declines in four Darling Range catchments (CSIRO 2009a). Bates, Gordon and Cameron are in the Murray basin, and Cobiac is a sub-catchment of the Wungong Brook.

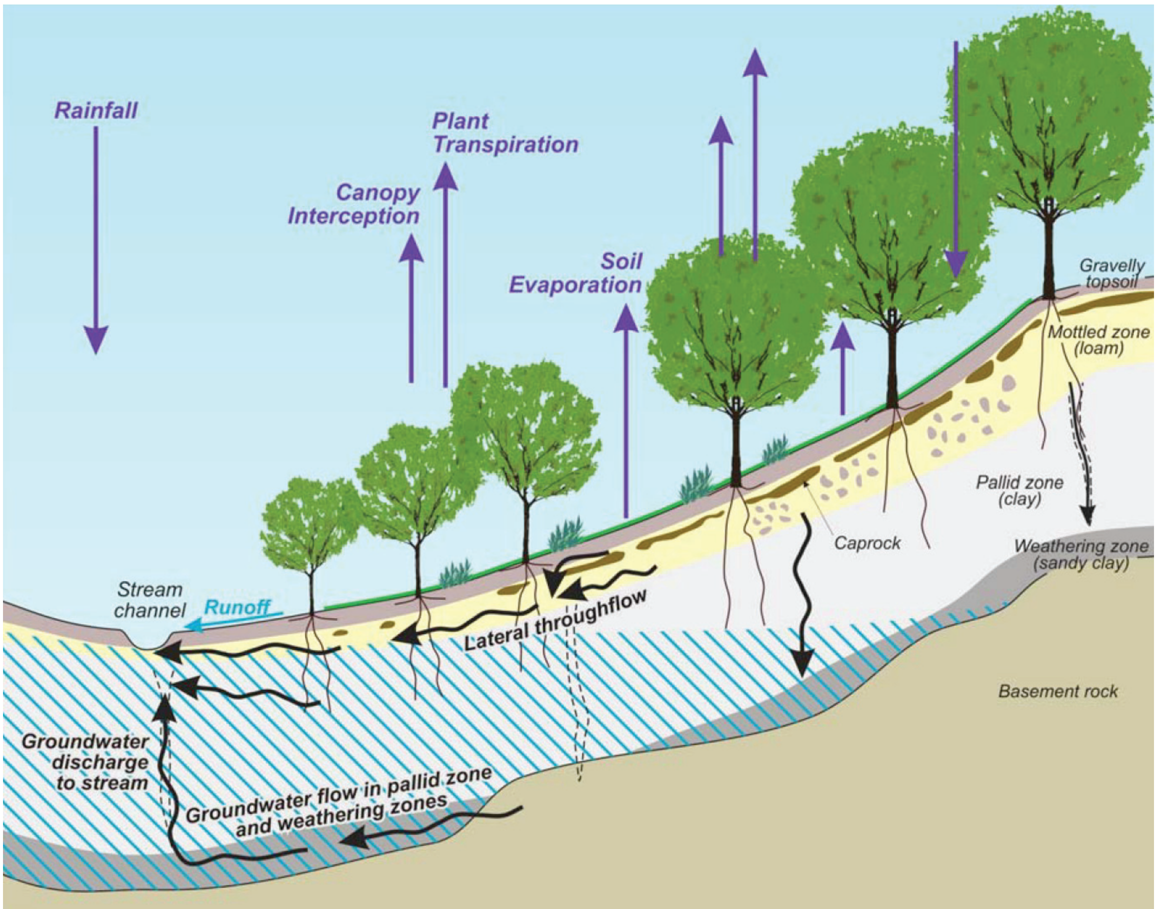

Figure 12. Cross-section showing typical Darling Range valley and runoff processes (CSIRO 2009a, fig. 3-3).

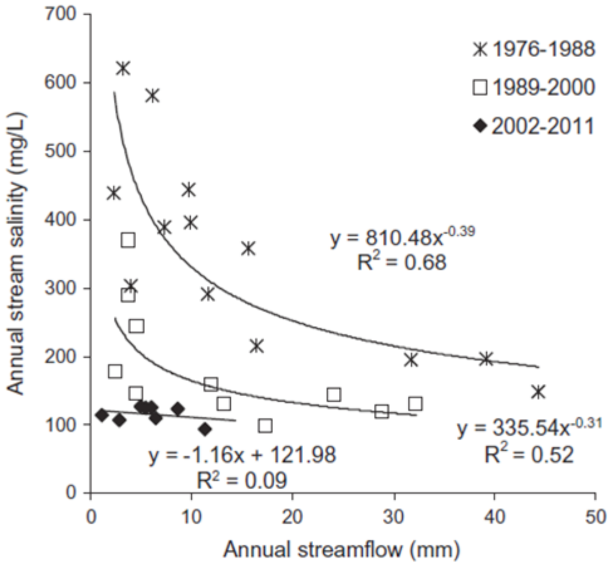

Figure 13. Flow-weighted annual stream salinity to annual streamflow relationship for 1976–1988, 1989–2000 and 2002–2011 (Kinal & Stoneman 2012).

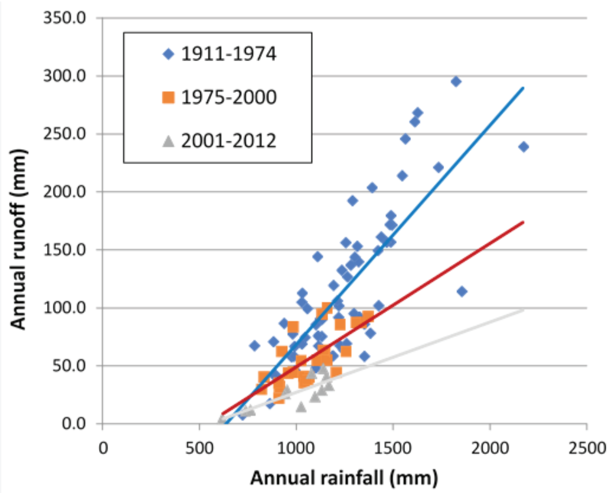

Figure 14. Changes in rainfall–runoff relationship over time in a typical catchment (Serpentine River).

resultant climate scenarios groundwater levels across the Blackwood Plateau and the Gnangara Mound fell because of vegetation. Climate scenarios in Figure 18 become drier from left to right. Perennial vegetation is anticipated to use an increasing proportion of the lower rainfall, thereby reducing recharge. Modelling of recharge showed that there was a one- to three-fold change in recharge for a unit change in rainfall for all combinations of soil, cover and climate examined (Dawes *et al*. 2012). This sensitivity to rainfall is also evident in runoff in the Darling Range (Silberstein *et al*. 2012a).

In an area west of the Gnangara Mound groundwater levels were projected to rise after pines were removed. The largely cleared Swan Coastal Plain is less affected by

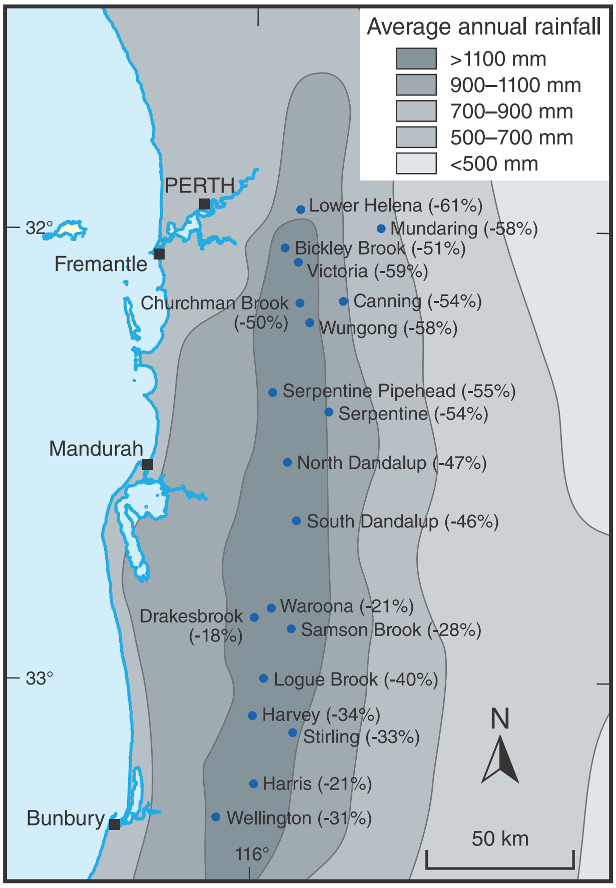

Figure 15. Percentage decrease in runoff in Darling Range catchments for 2001–2012 compared with 1975–2000. Data from Water Corporation.

the drying climate because, as mentioned above, reduced rainfall initially causes less surface water drainage and evapotranspiration losses rather than lower groundwater levels. This is a form of 'rejected recharge'. Once storages in the aquifer at the end of summer are not replenished by winter recharge, levels start to fall as shown in the Dry Scenario.

Across the Dandaragan Plateau water levels are projected to rise because it is largely cleared, the soils are permeable, rainfall is moderate (500–600mm per annum) and there is limited extraction. This is comparable to inland wheatbelt areas that experience dryland salinity. However, in this case the groundwater is mainly fresh, and wetlands form in low-lying areas.

Given the highly permeable soils across the Perth Basin, the few streams that originate within it are the result of groundwater discharge. Falls in streamflow therefore reflect reductions in groundwater level. Rivers that cross the Perth Basin usually gain fresh baseflow from the unconfined superficial aquifer. However, as groundwater levels fall, these rivers may become losing streams and those that are saline may contaminate the aquifer (CSIRO 2009b). Therefore, the relative impacts of a drying climate on runoff and groundwater levels needs to be understood to predict whether past hydrological processes will continue or reverse.

The modelling results in Figure 18 were developed using three regional groundwater models calibrated using rainfall and groundwater level data from the wetter 1975–2007 years. Observed groundwater level changes between 2000 and 2015 in Figure 17 show that the model projections were optimistic. Levels have been following the Future Dry scenario that only has a 10% probability of being exceeded.

DISCUSSION AND RECOMMENDATIONS FOR FURTHER WORK

Changes induced by the poleward movement of the climate system that bring most of the winter rain to Australia's South West are similar in Mediterranean climate zones around the world. The South West is unusual in having a higher rainfall than other west coasts in the southern hemisphere because of the warm Leeuwin Current. The long-term topographic stability of the region (unaffected by glaciation, volcanism or substantial uplift for several hundred million years), has produced poor drainage and a deep regolith in which rainfall and dryfall salts have accumulated. The progressive clearing of perennial vegetation in the past 180 years has altered the water balance and mobilised some of the salt stored in the Wheatbelt and Zone of Rejuvenated Drainage.

The drying and warming climate that has been most evident since 1975, and especially after 2000, must be understood in this broad context. Runoff was the first hydrological change to be observed after dams used for metropolitan drinking water supplies failed to meet demands. The reduction in flooding of inland areas and the gradual drying of throughflow lakes on the Swan Coastal Plain have been less well reported. All these reductions in surface hydrology were preceded by falls in groundwater levels, which was detected because there has generally been good monitoring of aquifers across the region. In Darling Range catchments, aquifers have been monitored since the 1980s because of concerns that the clearing of native forests for bauxite mining could cause stream salinisation. Similarly, groundwater levels over large areas in the Wheatbelt were monitored to assess salinisation risks, and levels in the superficial aquifer around production borefields across the Perth Basin were monitored after the *Environmental Protection Act 1986* required that lakes with high conservation values be protected.

Both runoff and recharge reduce about three-times for a unit reduction in rainfall. This relationship is affected by landuse and how close the watertable is to the surface. When watertables are high there can be rejected recharge because there is insufficient room for the incoming water. This is the case over large parts of the Swan Coastal Plain where the reducing rainfalls have not (yet) affected groundwater and lake levels for many years. The relationship is also affected when watertables fall below the invert of streams in the Darling Range, reducing both saturation-excess runoff and baseflow. This resulted in stepped reductions in runoff as rainfall–runoff processes changed, which points to the development of a non-stationary hydrological system.

The effect of landuse on reductions in runoff and recharge as the climate changed is more complex. Perennial vegetation is expected to transition to more

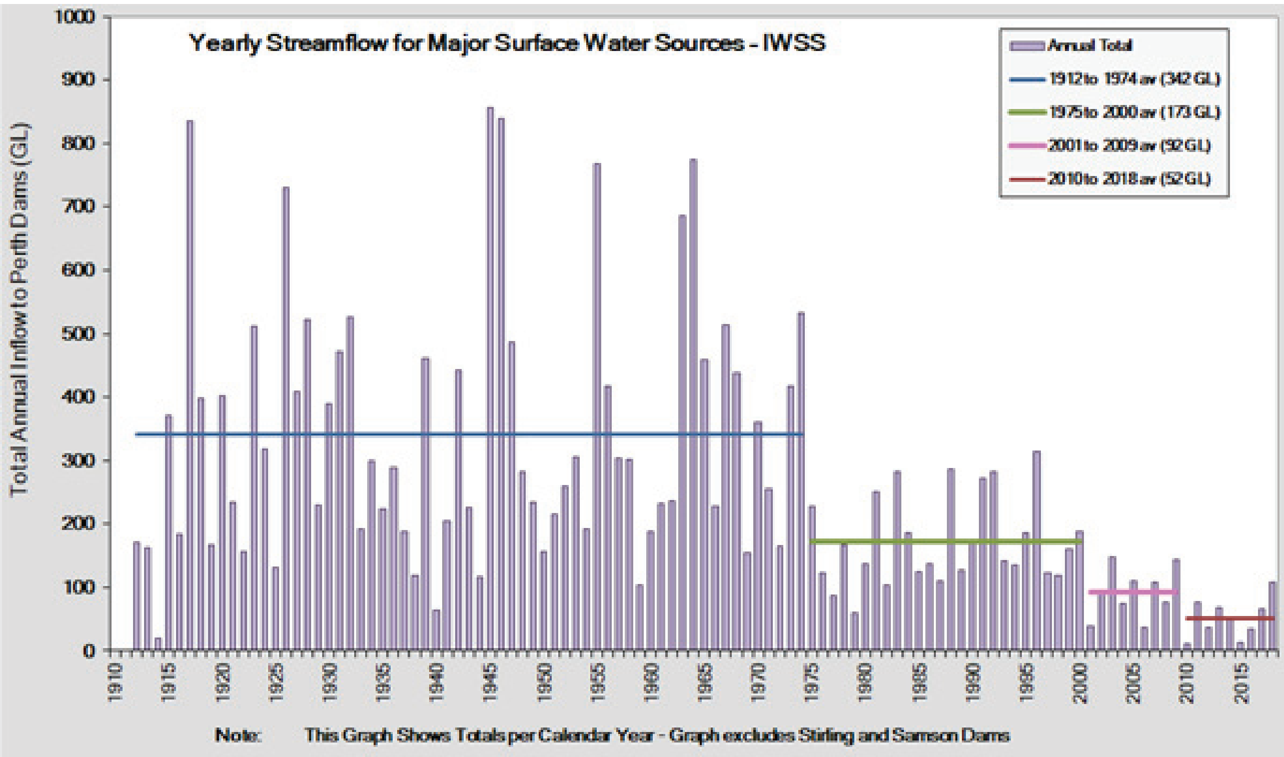

Figure 16. Trends in runoff into Perth metropolitan reservoirs supplying drinking water to the Integrated Water Supply Scheme or IWSS. Data from Water Corporation.

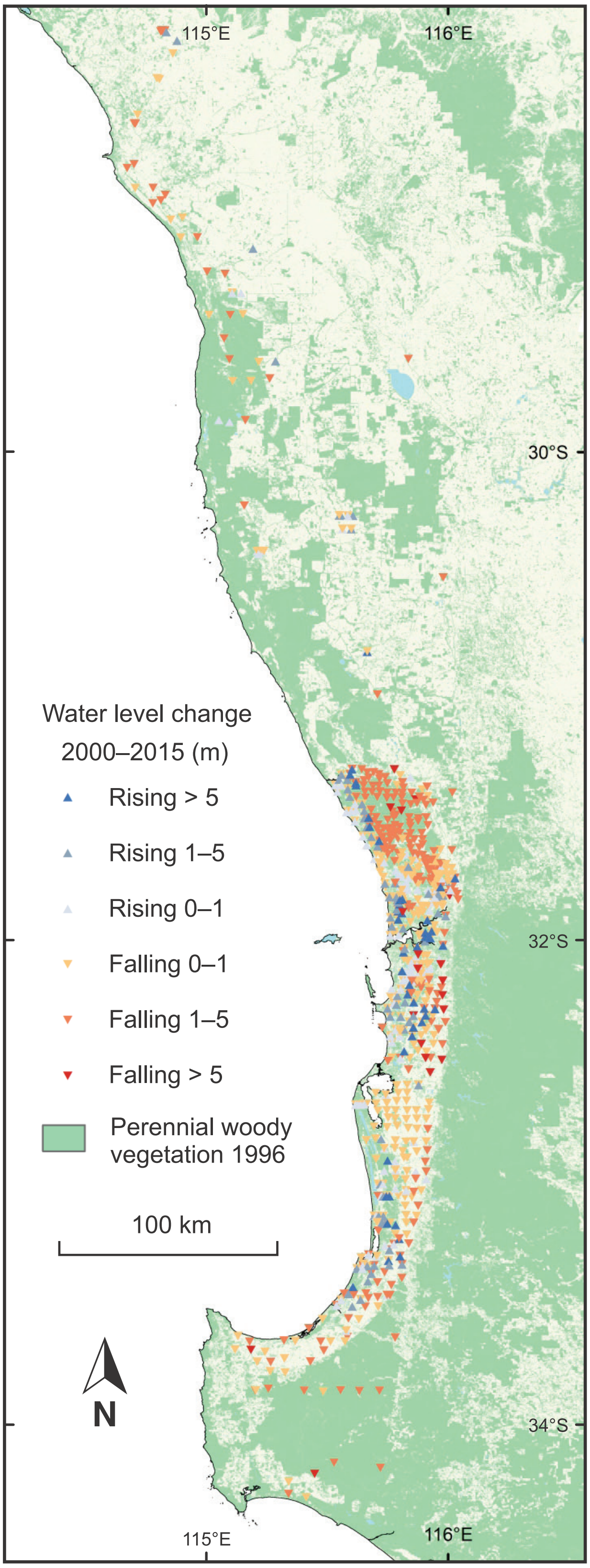

Figure 17. Changes in groundwater levels on the Perth Basin between 2000 and 2015 in relation to perennial vegetation. Data from Department of Water and Environmental Regulation & Department of Primary Industries and Regional Development.

xeric communities under a hotter and drier climate. However, perennial vegetation has already started to thicken and expand as a result of CO_2 fertilisation (Donohue *et al*. 2013). In the South West these factors have probably encouraged vegetation to use a higher proportion of incoming rainfall. There are inadequate data to identify these processes, and there may be thresholds beyond which the vegetation cannot adapt quickly enough, i.e. such adaptation may be non-linear. For example, the widespread death of native trees in the Darling Range (especially on shallow soils) were reported after a very dry year in 2010 and a following hot-dry summer (Matusik *et al*. 2013). The authors concluded that Mediterranean-type forests, once thought to be resilient to climate change, may be susceptible to sudden and severe forest collapse when key thresholds have been reached. Urban areas are increasingly covering parts of the Swan Coastal Plain as native vegetation is cleared. Increasing urban density can at least partially offset the effects of lower rainfall and higher temperatures on the water balance because runoff from man-made surfaces are mostly directed into the superficial aquifer (McFarlane 1984).

The hydrology of the Wheatbelt is responding to climate change in complex ways depending on the time since clearing, the depth of the regolith and the degree of climate change, all of which are geographically determined. Groundwater systems are variably equilibrating with the recent climate where clearing was early, annual rainfalls are higher, and/or where the regolith is shallow. Overall it appears that the hotter, drier climate is reducing the risk of flooding, salinisation and waterlogging. However, dryland salinity is still increasing in some areas and long lags in groundwater response suggest it will remain a problem for decades. It is probable that the rate of salinity spread of 14 000 ha/y for 1989–1997 has now reduced because of the drying phase since 2000; however, this cannot be confirmed without repeated acquisition of data. Episodic events, such as occurred in 2017, may increase salinity and flooding for a period despite the overall decreasing trend in such risks. Whether summer rainfall will become a more significant driver of flooding and salinisation remains to be seen.

Comparisons between the South West of Australia and other Mediterranean regions to climate change would allow the anticipation of changes and sharing of response of adaptation practices. Understanding the causes for the reduction of runoff into Perth metropolitan dams has shown that they are unreliable future water sources. This has resulted in more confident investments in new borefields, seawater desalination and reuse, including indirect potable reuse of treated wastewater.

A reassessment of salt-affected areas is underway for the South West to see if rates have decreased as foreshadowed by the groundwater trends. Maintaining these monitoring systems to track responses, and to define risks and opportunities, is critical for the next decades. Understanding how native and introduced vegetation is adapting to an altered hydrology due to land use and climate change will enable better management of both conservation and forestry estates.

Climate change impacts on hydrology have caused some benefits (reduced flooding, waterlogging and

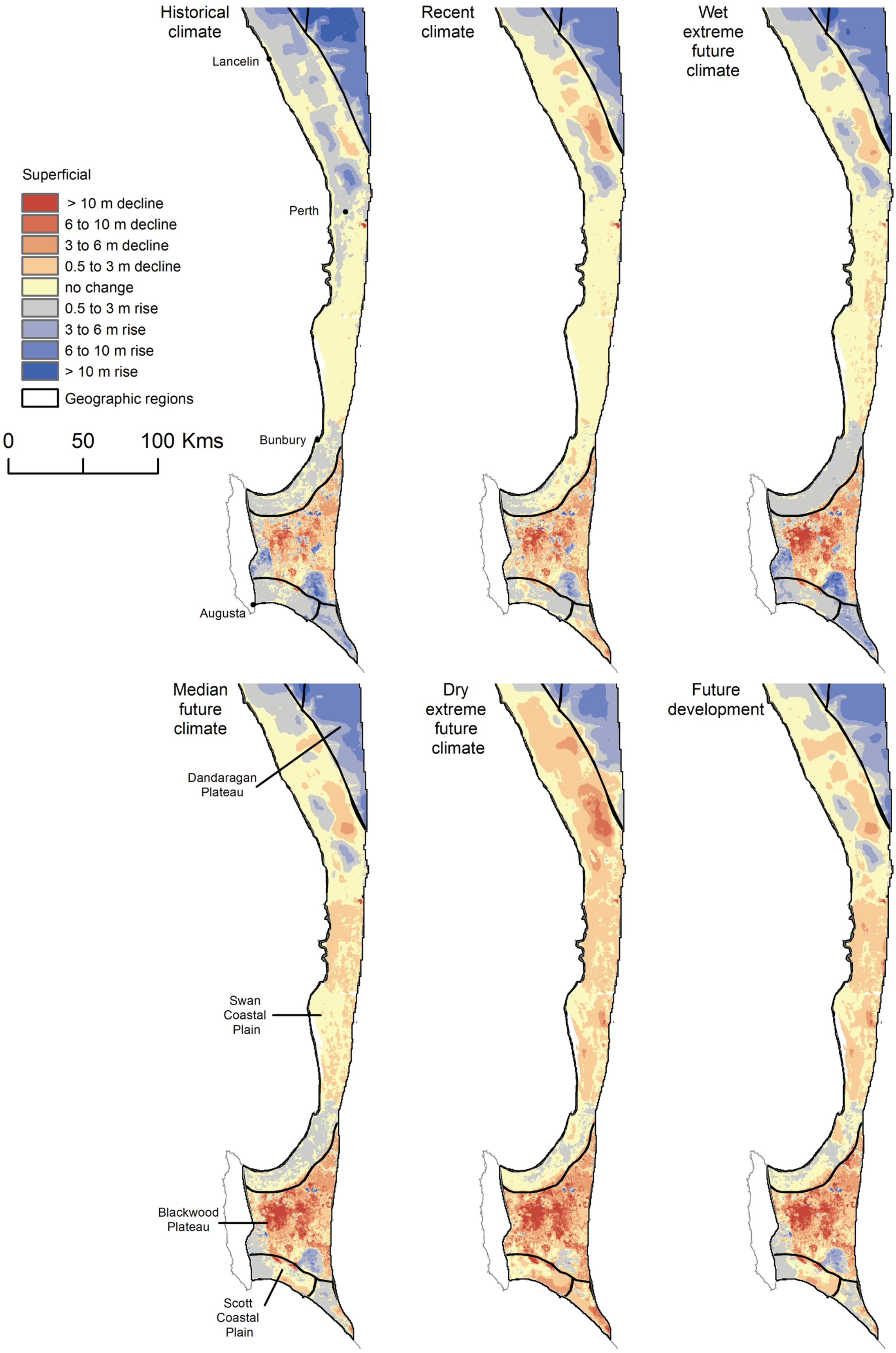

Figure 18. Projected changes in groundwater levels under four future climate regimes showing a) a continuation of the 1975–2007 climate, b) a continuation of the drier 1998–2007 climate, c) an even drier median future climate from Global Climate Models and d) a dry future climate from Global Climate Models (from Ali *et al*. 2012).

salinisation risk) but exacerbated problems (reduced water resources and impacts on native vegetation, riverine ecology and wetland systems). The assessment and conclusion in this paper are heavily dependent on effective monitoring without which an understanding of trends and changes in hydrological processes will not be apparent. This understanding is critical to enable effective resource management decisions now and in the future.

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