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Potential climate change impacts on the water balance of regional unconfined aquifer systems in South-Western Australia

R. Ali[1], D. McFarlane[1], S. Varma[2], W. Dawes[1], I. Emelyanova[1], and G. Hodgson[1]

[1]CSIRO Floreat Laboratories, Private Bag 5, Wembley, Western Australia, 6913, Australia
[2]CSIRO Earth Science and Resource Engineering, 26 Dick Parry Avenue,
Kensington, WA6151, USA

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Correspondence to: R. Ali (riasat.ali@csiro.au)

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Abstract

This study assessed climate change impacts on water balance components of the regional unconfined aquifer systems in South-Western Australia, an area that has experienced a marked decline in rainfall since the mid 1970s and is expected to experience further decline due to global warming. Compared with the historical period of 1975 to 2007, reductions in the mean annual rainfall of between 15 and 18 % are expected under a dry variant of the 2030 climate which will reduce recharge rates by between 33 and 49 % relative to that under the historical period climate. Relative to the historical climate, reductions of up to 50 % in groundwater discharge to the ocean and drainage systems are also expected. Sea-water intrusion is likely in the Peel-Harvey area under the dry future climate and net leakage to confined systems is projected to decrease by up to 35 % which will cause reduction in pressures in confined systems under current abstraction. The percentage of net annual recharge consumed by groundwater storage, and ocean and drainage discharges is expected to decrease and percentage of net annual recharge consumed by pumping and net leakage to confined systems to increase under median and dry future climates.

1 Introduction

There was an increase of about 0.74 °C in the average surface temperature of the earth during the 20th century (IPPC, 2007; UNEP, 2007) and it is projected that the global temperature will increase by between 1.4 and 5.8 °C by 2100 due to greenhouse gas emissions (McCarthy et al., 2001). The temperature in China has increased by 1.2 °C since 1960 and is projected to further increase by 1 to 5 °C by 2100 (Piao et al., 2010). The temperature of the Central England has increased by 1 °C during the 20th century (Herrera-Pantoja and Hiscock, 2008). Temperature increases of 0.5 to 1 °C by 2030 and of 0.5 to 2 °C by 2070 are expected in Australia (PMSEIC Independent Working Group, 2007). Most believe that the global climate change is human induced due to an accelerated increase of greenhouse gas in the atmosphere caused by population growth, fossil fuel burning and high deforestation rates (FAO, 2007). Greenhouse gases in the atmosphere trap heat and warm the earth system (USEPA, 2004) causing changes in climate; namely temperature, potential evaporation, and rainfall amount, frequency and intensity. Climate change affects rainfall, temperature and relative humidity and has a flow-on effect throughout the hydrological cycle (Loáiciga et al., 1996). In European studies, Lasch et al. (2002) showed that a 10 to 20 % decrease in rainfall could lead to a 60 % decrease in recharge.

In the recent past, climate change has impacted rainfall amounts and intensity in many parts of the world (Ducci and Tranfaglia, 2008). In a number of regions climate change has caused significant reductions in rainfall impacting on the availability of both surface and groundwater resources. The summer and autumn precipitation in drier northeastern regions of China has decreased by about 12 % since 1960 (Piao et al., 2010). A consistent rainfall decline has been observed in the Southwest Western Australia and parts of the Southern and Eastern Australia during the second half of the 20th century (PMSEIC Independent Working Group, 2007).

Both the temperature rise and rainfall decline due to climate change affects various components of the groundwater balance by directly and indirectly affecting multiple factors (Zagonari, 2010). It affects the rate of groundwater recharge directly if it reduces rainfall. It affects potential evapotranspiration rates directly through increases in temperature and vapour pressure deficits. Reduced surface water supplies due to reduced rainfall and increased temperatures may require increased groundwater abstraction to meet water demands by the industry and population. Climate change may reduce groundwater discharge to oceans and drains due to lower groundwater levels. It can increase seawater intrusion risks in coastal aquifers. It can also affect inter-aquifer leakage rates and flow direction which may degrade the aquifer systems.

To assess the effects of future climate change on the water balance of groundwater systems, both historical and projected future climate data are required. Recent advances in modelling and improved understanding of the physical processes of climate systems have made projections of future climate more reliable (Christensen et al., 2007). Many Global Climate Models (GCM) are available for projecting future climates with varying degrees of uncertainty and application across the world. The data from GCMs can be used in models for assessing the impacts on future water balances of regional groundwater systems. There is a great deal of research on specific impacts of climate change however the information and research on climate change effects on groundwater and aquifer systems is scarce (Marshall and Randhir, 2007). Only a few studies have been published that have either fully or partly addressed the effects of recent past and projected climate change on the groundwater resources using various hydrological, regression, modelling and isotope techniques (Scibek and Allen, 2006; Isaar, 2008; Ducci and Tranfaglia, 2008; Polemio and Casarano, 2009; Sinha and Navada, 2008). Most studies focus on surface water and either oversimplify or neglect groundwater (Goderniaux et al., 2009). Often variable results are produced (Jiang et al., 2007) due to simplistic assumptions made in climate projections and representation of physical processes of the hydrological system.

Assessing climate change impacts on groundwater systems requires a good knowledge of climate data, land cover, soil hydraulic properties, groundwater data, abstraction rates, surface drainage locations and depths, hydrogeology and topography. Climate data, land cover, soil and watertable information can be used to estimate recharge and other data are used to develop and run numerical models of the groundwater system.

A reliable estimate of recharge is the first requirement in estimating the impact of climate change on groundwater systems because it represents the connection between atmospheric, surface and sub-surface processes. Various simple water balance techniques and models are available to estimate recharge (Aguilera and Murillo, 2009; Barr et al., 2003; Herrera-Pontoja and Hiscock, 2008). It can be used as input to numerical groundwater models which distribute this recharge into various components of the water balance.

Thomas et al. (2003) used a numerical groundwater flow model of the Saginaw and glacial aquifers in the Tri-County region surrounding Lansing, Michigan, to study the effects of climate change on recharge and groundwater. Woldeamlak et al. (2007) used a physically-based distributed water balance model, WetSpass (Batelaan and De Smedt, 2001), to estimate annual recharge and used this in a steady-state MODFLOW model to simulate the groundwater system condition in Grote-N, Belgium over the future years. Scibek and Allen (2006) simulated the direct recharge to aquifer from precipitation which consisted of spatially distributed and temporally varying recharge zones, using a GIS linked to the one-dimensional Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994). A MODFLOW-based three dimensional groundwater flow model was then used to simulate the impacts of climate change on recharge and groundwater levels in an unconfined aquifer near Grand Forks in South Central British Columbia, Canada.

Various recharge and groundwater models have been used in Australia to study the impacts of climate change on future groundwater resource availability in the Murray-Darling Basin, Northern Australia, Tasmania and South-West Western Australia (Crossbie et al., 2010; CSIRO, 2008, 2009; Post et al., 2011; Ali et al., 2010) using a consistent methodology. All these studies used historical data and scaling factors derived from 15 GCMs to project future rainfall. This paper assesses climate change impacts on various groundwater balance components in the regional unconfined aquifer systems of South-Western Australia.

2 Description of study area

The study area is located between Gingin to the north and Augusta to the south of Perth (Fig. 1). For this study the area was divided into three parts: the Central Perth Basin, the Peel-Harvey area and the Southern Perth Basin all of which are part of the Perth Basin (Fig. 1). The study area covers about 20 000 km^2 and is located in one of the highest rainfall parts of South-Western Australia. It includes all fresh, brackish and marginal groundwater resources near the coast. Inland groundwater supplies are either limited or too saline for most domestic, irrigation and industrial uses and were therefore excluded from this assessment. The study area has over 80 % of Western Australia's population and accounts for over half of the horticultural production of the state (Gool and Runge, 1999).

Groundwater is a major source of water in the study area. The Perth Basin comprises the flat sandy Swan and Scott coastal plains, and more elevated and clayey plateaux such as the Blackwood in the Southern Perth Basin and Dandaragan in the Central Perth Basin (Fig. 1).

2.1 Climate

The study area has a Mediterranean type climate, with mean annual rainfall of between 500 and 1195 mm, up to 80 % of which occurs between May and October. Temperatures are also at their lowest during this period, making the rainfall more effective in terms of producing runoff and recharge. There is a strong south-west to north-east gradient in rainfall (Fig. 2) with the highest rainfall in south-west coastal parts and along the Darling Range east of the Darling Scarp (Fig. 2). The mean annual areal potential evapotranspiration (APET; Morton, 1983) varies from 1555 mm in the north to 1260 mm in the south (Fig. 2). When mean annual rainfall deficit is calculated (by subtracting APET from rainfall), almost all of the study area has a negative moisture balance (Fig. 2).

2.2 Land cover

Major land covers within the study area include dryland agriculture, native vegetation, pine plantation and urban (Fig. 3). Over 88 % of the 20 000 km^2 study area is covered by either native vegetation (45 %) or dryland agriculture (43 %). Pine plantations cover 2 % of the area. Horticulture, valuing at $166 million, covers less than 1 % of the study area and makes up 33 % of total agricultural production (Gool and Runge, 1999). Intensive urban and commercial buildings cover about 6 % of the study area and occur in the Perth region and, to a lesser extent, around Bunbury and Busselton.

The main areas under native vegetation occur east of the Darling Fault in the Darling Ranges, along the south coast and north of Perth. Pine plantations occur in the Gnangara area north of Perth, near Myalup east of Lake Clifton and on the Blackwood Plateau. Cleared areas used for dryland agriculture (cropping and grazing) mainly occur on the Swan Coastal Plain. Irrigated areas occur in the Harvey and Preston areas (Fig. 3). Self-supplied (i.e. using water extracted from farmer-owned wells or dams) horticultural areas occur around Gingin, in peri-urban parts of Perth, and in south-western coastal areas at Myalup, Jindong and Margaret River.

2.3 Hydrogeology

The Central Perth Basin extends 150 km north and 70 km south of Perth and comprises the Swan Coastal Plain and Southern Dandaragan Plateau. The three main aquifers are the Superficial, Leederville and Yarragadee. The Superficial Aquifer is mainly clayey (Guildford Formation) in the east near Gingin Scarp and becomes sandy towards the west. Its average thickness is about 30 m. The aquifer is underlain by a number of permeable aquifers or impermeable clays. The horizontal hydraulic conductivities range from 10^{-6} m per day for clayey deposits to 40 m per day for sandy deposits. Recharge by rainfall infiltration often decreases from the coast to the east because of decreasing rainfall and sediments becoming clayey in the east. Recharge can also occur from upward leakage from underlying formations where there are upward hydraulic gradients and confining beds are absent. Recharge rates vary depending on rainfall, lithology, depth to watertable and topographic gradient and land cover. Discharge is to the ocean, to natural and engineered drainages and to coastal lakes. Large losses occur through evaporation from wetlands and in areas with shallow watertables. Groundwater flow is usually westwards towards the coast. The Gnangara Mound north of Perth and the Jandakot Mound south of Perth are the main flow systems. Two major confined aquifers are the Leederville and Yarragadee Aquifers. Further details about hydrogeology and confined aquifer systems of the Central Perth Basin can be found in CSIRO (2009) and Davidson (1995).

The Peel-Harvey area extends between the coastal cities of Mandurah and Bunbury and the Darling Scarp. The major aquifers are the Superficial, Leederville and Cockleshell Gully. The Superficial Aquifer extends over the entire region and consists of superficial formations including the Bassendean Sand and the Ascot, Guildford and Yoganup formations. Its thickness ranges from 20 to 30 m. The hydraulic conductivity of the sandy aquifers ranges between 3 and 16 m per day. The watertable is generally shallow in the area. Recharge mainly occurs through rainfall infiltration but some is rejected due to shallow watertables. Groundwater flow is towards the Indian Ocean in the west and discharges into the natural and engineered drainages, wetlands and ocean. The Superficial Aquifer is underlain by a number of confined aquifer systems including the Leederville, Cockleshell Gully and Yarragadee. Further details on the hydrogeology and confined aquifer systems of the Peel-Harvey area are given in CSIRO (2009), URS (2009a) and ANRA (2009).

The Southern Perth Basin lies between the Darling and Dunsborough Faults and includes the easterly Bunbury Trough and westerly Vasse Shelf which are separated by the Busselton Fault (Fig. 1). Major aquifers include the Superficial, Leederville and Yarragadee (Baddock, 2005). The Superficial Aquifer extends over the Swan Coastal and Scott Coastal Plains. The Superficial Aquifer under the Swan Coastal Plain consists of clay, sand and limestone. The aquifer material is more uniform and sandy under the Scott Coastal Plain. However the aquifer material on this plain can be locally confined by a ferruginous cemented layer in the lower parts of the formation (Strategen, 2005). Its thickness is often less than 10 m but is up to 200 m under the coastal sands. On both plains the Superficial Aquifer is mainly recharged by rainfall infiltration with some upward leakage from the underlying Leederville or Yarragadee aquifers near Bunbury within the Swan Coastal Plain and in the centre of the Scott Coastal Plain. The groundwater discharge is to the natural drainages, wetlands, ocean or to the underlying Leederville and Yarragadee aquifers. The main groundwater flow direction is to the north towards the Indian Ocean with some southerly flow towards the Southern Ocean. The Leederville and the Yarragadee outcrop over extensive areas and receive direct recharge from rainfall infiltration. Further details about hydrogeology of the confined aquifer systems of the Southern Perth Basin are given in CSIRO (2009) and Strategen (2005).

2.4 Historical groundwater use and future demand

Western Australia is faced with a scientifically complex challenge as the state relies heavily on groundwater systems which are difficult to quantify due to their complex geology and hydrogeology so that resource availability often requires sophisticated measurements (DoW, 2008). Groundwater use has been sharply increasing over time across all sectors in Western Australia. The annual abstraction from aquifers in the Central Perth Basin (Fig. 4a) trebled from 200 Gl in 1985 to nearly 600 Gl in 2007. Abstraction from the Superficial Aquifer in the Peel-Harvey area (Fig. 4b) has increased from about 0.3 Gl in 1994 but to 20 Gl by 2007. The total annual abstraction from the Southern Perth Basin (Fig. 4c) increased from 0.5 Gll in 1985 to about 75 Gl in 2007.

In the study area the estimated total groundwater use in 2007 was about 695 Gl. Groundwater demand is projected to increase further with population and industrial growth, and depleting surface water supplies (CSIRO, 2009). The future population growth within the study area is likely to be centred on the Greater Perth area, the Bunbury area, the coastal area between Bunbury and Busselton and the Shire of Augusta-Margaret River and will therefore have increased demand for water (DoW, 2007).

3 Methods

3.1 Recharge estimation

Recharge was estimated using a Vertical Flux Model (VFM) (Barr et al., 2003) linked with three groundwater models: the Perth Regional Aquifer Modelling System (PRAMS) for the Central Perth Basin; the South West Aquifer Modelling System (SWAMS) for the Southern Perth Basin; and the Peel-Harvey Regional Aquifer Modelling System (PHRAMS) for the Peel-Harvey area. For PRAMS and SWAMS, the VFM was coupled with the MODFLOW model making it able to estimate the watertable depth at each simulation period which is required to estimate the recharge and discharge amounts. For PHRAMS the rainfall-recharge modelling was done using a linked but not dynamically coupled VFM.

The VFM calculates recharge to, and discharge from, an aquifer system. "VFM Manager" incorporates a number of different recharge models such as WAVES (Water, Atmosphere, Vegetation, Energy Simulation; Zhang and Dawes, 1998) and other simple empirical models (Barr et al., 2003). Crosbie et al. (2010) used WAVES to assess the climate change impacts on groundwater recharge in the Murray-Darling Basin, Australia. WAVES is a 1-dimensional biophysical model and simulates vertical water flow through soil and water uptake by vegetation such as pasture, pine plantations and Banksia woodlands. Simple empirical models are used for urban areas, market gardens, wetlands and areas where watertables are close to the soil surface. Two of these simple models include a "linear vertical flux model" and a "piece-wise linear vertical flux model". For the linear vertical flux model a constant multiplier for the rainfall and potential evaporation is used to calculate the recharge as (Barr et al., 2003):

$$R = (C_{\text{rainfall}} \cdot P) - (C_{\text{evap}} \cdot E) \qquad (1)$$

where R is the rate of recharge per unit surface area in a cell; C_{rainfall} is the multiplier for the rainfall in that cell; P is the rainfall per unit surface area per unit time; C_{evap} is the multiplier for the evaporation; and E is the potential evaporation per unit surface area per unit time.

The "piece-wise linear flux model" is based on a piece-wise linear relationship about critical watertable depths for both rainfall and evaporation. The critical watertable depths may be different for the rainfall and evaporation and a multiplier (C_{rainfall} and C_{evap}) is supplied for each critical watertable depth. This is expressed in Eq. (2) (Barr et al., 2003):

$$
\begin{aligned}
\text{WT} \leq \text{Depth}_{\text{lowest}} &: \quad \text{MLT} = \text{Multiplier}_{\text{lowest}} \\
\text{WT} \geq \text{Depth}_{\text{highest}} &: \quad \text{MLT} = \text{Multiplier}_{\text{highest}} \qquad (2) \\
\text{WT} \geq \text{Depth}_{\text{highest}} &: \quad \text{MLT} = \text{Multiplier}_{\text{highest}} \\
\text{Depth}_{i-1} < \text{WT} < \text{Depth}_i &: \quad \text{MLT} = \frac{\left(\text{Multiplier}_i - \text{Multiplier}_{i-1}\right)}{\left(\text{Depth}_i - \text{Depth}_{i-1}\right)} \cdot \left(\text{WT} - \text{Depth}_{i-1}\right) + \\
&\quad \text{Multiplier}_{i-1}
\end{aligned}
$$

where MLT is the multiplier for the climate quantity (it may be C_{rainfall} or C_{evap}) at the specified watertable depth; WT is the given watertable depth; Depth_i is the ith specified depth; and Multiplier_i is the multiplier associated with that depth.

The VFM estimates aquifer recharge or deep drainage based on climate; land cover; soil type; and watertable depth. Before running the VFM, the grid cells of similar attributes were grouped together into recharge response units (RRUs) based on climate zone, soil type, and land cover. For grouping into RRUs the study areas was divided into 12 climate zones based on rainfall and evaporation gradients. The future climate data, for each climate zone, was derived following the procedure described in Sect. 3.3. The study area was also divided into 14 land cover classes. The current land cover (2007) and LAI (leaf area index) remained constant for all future scenarios, except the development scenario, although McCallum et al. (2010) noted possible changes in LAI under projected future climate scenarios. The soil units were grouped into 11 soil types of similar hydrological properties and texture based on Australian Soils Resource Information

System (ASRIS) level 4 data. For each RRU the VFM estimated the recharge and discharge rates at each stress period by obtaining the watertable depth from the groundwater model.

3.2 Groundwater models – description and calibration

Three groundwater models (PRAMS, SWAMS and PHRAMS) were used for assessing the impacts on components of the water balance under five climates and one development scenario. The PRAMS model, used for the Central Perth Basin, covers an area of about 10 000 km^2 between Mandurah in the south and Dandaragan in the north (Fig. 1). It is a finite difference MODFLOW-based model (McDonald and Harbaugh, 1996) with a grid size of 500 by 500 m (25 ha cells). The version 3.2 of the model has 13 layers representing various aquifers and confining beds. The quasi steady-state model was calibrated by adjusting vertical and horizontal hydraulic conductivities, storage coefficients and specific yields. The calibration and validation periods of the transient model were from 1985 to 2003 and from 2004 to 2008, respectively (Cymod, 2009). The model calibration error (Root Mean Squared Error, RMSE) was 2.1 m for the Superficial Aquifer.

The SWAMS version 2.1 model, used in the Southern Perth Basin, covers an onshore area of approximately 6000 km^2. The model boundaries extend from the Brunswick River north of Bunbury to the Warren River south of Pemberton, and from the Dunsborough Fault in the west to the Darling Scarp to the east (Fig. 1). It is a variable finite difference grid, with 363 rows and 193 columns, rotated 4.5 degrees anti-clockwise from north. The cell size varies from 250 by 250 m to 1000 by 1000 m. Eight layers of the model represent the major aquifers and aquitards in the region. It was calibrated from 1990 to 2000 using 54 bores in the Superficial Aquifer, 98 calibration bores in the Leederville Aquifer, and 88 calibration bores in the Yarragadee Aquifer. The Superficial Aquifer calibration error was 3.3 m (RMSE) (CSIRO, 2009). It was validated from 2000 to 2008.

For the Peel-Harvey area a newly developed PHRAMS covers an area of 4095 km^2 between the Peel Inlet and Bunbury (Fig. 1). Its boundary extends from the Darling Fault to the east to the Indian ocean to the west and the Murray River and Peel Inlet to the north to the Collie River to the south. Visual MODFLOW Version 2009.1 Pro with MODFLOW-SURFACT Version 3.0 was used for the construction of the PHRAMS for the Superficial Aquifer. The model consists of 6 layers and has a uniform grid of 500 by 500 m. It was calibrated from 1980 to 2002 using 198 calibration bores and has a calibration error of 1.83 m (RMSE). Its validation period was from 2003 to 2007. The maximum potential recharge rates were provided as input and the net recharge rate was estimated internally using the EVT package of MODFLOW. Further details about model are given in URS (2009b).

For modelling the groundwater abstraction, an important input into the groundwater models, was kept constant at 2007 levels in all scenarios except the development scenario where it was increased to full allocation levels.

3.3 Modelling scenarios

Following procedure was used for deriving the future climate data for the six modelling scenarios.

(i) The historical climate scenario was based on the climate of the 1975 to 2007 period. It was assumed that the subsequent 33 yr would have the same climate. The historical climate between 1975 and 2007 inclusive was used to make 11 sequences of 23 yr duration. The climate data from each of the 11 sequences were used to estimate recharge rates using the WAVES model. The estimated recharge rates were ranked from lowest to highest for 11 sequences and the 50th percentile sequence selected. In the selected 50th percentile sequence the remaining 10 yr of the climate data were added to make 33 yr and this constituted the historical climate. This historical climate scenario was used as the baseline against which other scenarios were compared.

(ii) The recent climate scenario was used to assess the impacts on water balance should the climate between 2008 and 2030 prove to be similar to that of the recent past. Climate data for 11 yr (1997 to 2007 inclusive) were repeated three times to extend it to 2040. The simulated groundwater levels in 2030 were reported.

(iii–v) The daily downscaling approach outlined by Chiew et al. (2009) was used to derive finer resolution climate data from coarser resolution GCM projections. This approach is based on pattern scaling (Mitchell, 2003) with additional scaling to account for the projected changes in daily rainfall intensity (Mpelasoka and Chiew, 2009). The scenarios were developed on a "per degree of global warming" basis. Firstly, monthly rainfall and other climate variables (as used in PET calculation) for 1870–2100 were obtained for 15 GCMs (selected based on availability of daily rainfall data) as used in the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC, 2007). For each GCM, season, and GCM grid point these output were linearly regressed against simulated global average surface air temperature to give percent change in each variable per degree of global warming. Secondly, daily scaling factors for rainfall intensity were obtained based on GCM simulated changes to daily rainfall percentiles (also by GCM, season and GCM grid point) and also expressed as percent change per degree of global warming (Chiew et al., 2009). These seasonal and daily scaling factors were multiplied by the low, medium and high global warming scenarios, 0.7 °C, 1.0 °C and 1.3 °C, to account for the full range of the IPCC AR4 projections for 2030 (relative to a 1990 climatological baseline). The historical time-series for all 0.05° grid cells within the study area were multiplied by the 45 sets of seasonal and daily scaling factors (15 GCMs × 3 global warming scenarios) to produce an ensemble of daily rainfall and PET scenarios encompassing the projected range of climate change for the region. Results and discussion of this approach can be found in detail in Charles et al. (2010).

For each of the low, medium and high global warming scenarios and each of the 15 climate series, the mean annual recharge over the study area was estimated using the WAVES model in de-coupled mode. The estimated recharge rates from each of the 15 climates were ranked separately for the low, medium and high global warming. GCMs considered unreliable in terms of reproducing Southern Hemisphere weather phenomena and historical rainfall patterns over Southwest Western Australia were discarded and the dry, median and wet selected from those remaining. The selected GCMs were GFDL + 1.3 °C for the dry future climate, MIROC + 1 °C for the median future climate, and INMCM + 1.3 °C for the wet future climate.

To select the historical climate sequence, from which future climates were to be derived by applying scaling factors of the above selected GCMs, the average annual recharge from 23-yr sequences were ranked. The climate sequence from 1984 to 2006 was selected as the representative period for simulation of the 2008 to 2030. This climate sequence was modified by the scaling factors of the above GCMs to derive (iii) the dry future climate, (iv) the median future climate, and (v) the wet future climate.

(vi) The development scenario was based on the median future climate and future land development. The future land development however included increased groundwater abstractions only since no significant new plantations and irrigation developments, or plantation removals, except in the Gnangara Mound area, were identified. The groundwater abstraction was increased to full allocation levels from the start of 2008 where this was below 2009 allocation limits. In the Gnangara Mound area of the Central Perth Basin the scheduled legislated removal of the pine plantations and expansion of the urban area was allowed to take place between 2008 and 2030.

3.4 Water balance components

The groundwater models estimate various components of aquifer water balance. These water balance components can be expressed as:

$$R = S_{\mathrm{sc}} + D_{\mathrm{disch}} + O_{\mathrm{disch}} + A_{\mathrm{abs}} + F_{\mathrm{conf}} + E \tag{3}$$

where R is net recharge (it is the amount of water that is added to the aquifer less losses caused by evapotranspiration); S_{sc} is storage change in an aquifer; D_{disch} is the groundwater discharge to natural and engineered drainage systems; O_{disch} represents discharge to the ocean; A_{abs} is total groundwater abstraction by pumping; F_{conf} is net leakage to confined aquifer systems; and E represents error in water balance. All terms have units of mm per unit time which is volume per unit aquifer area.

4 Results

4.1 Climate change impacts on rainfall

Since 1975 the mean annual rainfall in South-Western Australia has decreased by about 15 % from the long-term average. The projected mean annual rainfall between 2008 and 2030 under the climate scenarios and percent change relative to a continuation of the historical climate of 1975–2007 to 2030 are listed in Table 1 for three regions in South-Western Australia. The projected rainfall is highest in the Peel-Harvey area and lowest in the Central Perth Basin under all scenarios. Under the historical climate the projected mean annual rainfall is 660 mm in the Central Perth Basin, 924 mm in the Peel-Harvey area and 893 mm in the Southern Perth Basin. Relative to the historical climate the mean annual rainfall under all future climate scenarios is projected to reduce in all three regions except under the wet future climate across the Central Perth Basin. Relative to the historical climate the largest reduction of between 15 and 18 % is expected under the dry future climate (Table 1).

4.2 Overall water balance

The overall Superficial Aquifer water balance between 2008 and 2030 under various scenarios shows the distribution of net recharge into storage change and various discharges in the three regions (Table 2). Positive numbers in this table indicate additions to storage and negative numbers indicate losses. Pumped abstraction is constant under all except the development scenario. Net leakage to the confined aquifers occurs in the Central and Southern Perth basins where the unconfined and confined aquifers are inter-connected. The 23-yr mean annual value of each water balance component in Gl (giga litres) is divided by total surface area of the Superficial Aquifer in each region to convert into mm per year for a meaningful comparison between the regions. The overall water balance error was small with its significance less than the decimal points listed in Table 2. The changes in rainfall, recharge and other components of the water balance are reported relative to a continuation of the historical climate of 1975–2007 to 2030.

4.3 Climate change impacts on groundwater recharge

The net recharge values, listed in Table 2, are annual means (mm) over the 23-yr forecast period (2008 to 2030). The highest recharge is expected in the Central Perth Basin and lowest in the Peel-Harvey area despite the rainfall being higher in the latter. It is highest in the Central Perth Basin due to several factors: a deeper watertable (less evaporative losses), urban areas where stormwater is directed into the aquifer, and the presence of cleared sandy soils used for dryland agriculture. It is lowest in the Peel-Harvey area due to widespread occurrence of the swampy areas that result in large evapotranspiration losses due to potential evaporation rates being two to three times greater than rainfall and shallow watertables in many areas which reject some of recharge that would occur if watertables were deeper. The recharge rates are lower in the Southern Perth Basin than in the Central Perth Basin despite its higher rainfall. This is due to native vegetation on most of the Blackwood Plateau together with clayey soils both of which reduce net recharge.

The highest recharge is projected to occur under the historical and wet future climates and lowest under the dry future climate across all three regions (Table 2). The projected reductions in net recharge under the median future climate are 15, 18 and 27 % in the Peel-Harvey area, Central Perth Basin and Southern Perth Basin, respectively. Whereas under the dry future climate the projected reductions are 33, 35 and 49 % in the Peel-Harvey area, Central Perth Basin and Southern Perth Basin, respectively. Thus, the recharge under the median future climate may reduce by 1.5 to 4 times the rainfall reduction on a percentage basis in three regions. Under the dry future climate recharge may reduce by two to three times the rainfall reduction on a percentage basis in these regions.

4.4 Impacts on superficial aquifer storage change

The groundwater storage change is projected to be positive, i.e. gaining, and highest in the Central Perth Basin corresponding with larger net recharge rates, and lowest and mostly negative, i.e. losing, in the Peel-Harvey area due to low net recharge rates (Table 2). The storage change of 39 $\mathrm{mm\,yr^{-1}}$ (increase) under the historical climate is projected to reduce by 88 percent under the dry future climate in the Central Perth Basin. Based on regional averages no groundwater storage loss is expected under any scenario in the Central Perth Basin due to high recharge rates, especially in the north east of this region. Some areas will however continue to experience significant declines in storage, especially under the dry future climate.

The storage is likely to remain stable if the historical climate continues into the future in the Peel-Harvey area. Under the dry future climate an average loss in groundwater storage of 4 $\mathrm{mm\,yr^{-1}}$ is expected in this area. The groundwater storage loss is highest under the development scenario due to increased pumping. However increased groundwater pumping also creates extra storage space to accommodate more recharge (Table 2).

The storage, when averaged at basin scale level, is projected to increase under all scenarios except the dry future climate in the Southern Perth Basin. There are areas within the basin, such as the Blackwood Plateau, where a groundwater storage loss is occurring. In these areas the groundwater levels have been declining in the past and are projected to decline further under the median and dry future climates. A net loss in groundwater storage is likely to occur under the dry future climate.

The dry future climate causes the largest reduction in groundwater storage across all three regions. It means if climate similar to the dry future eventuates in South-Western Australia, the groundwater resource is likely to reduce over time in the Peel-Harvey area and Southern Perth Basin and remain stable in the Central Perth Basin provided the current groundwater abstraction and land development conditions are maintained. This stability however masks substantial decreases in storage in important drinking water supply areas while areas under dryland agriculture may continue to have rising groundwater levels.

4.5 Impacts on ocean groundwater discharge

Climate change impacts groundwater levels which affect hydraulic gradients and groundwater discharge to the ocean. The mean annual groundwater discharge to the ocean is similar in the Central and Southern Perth basins and lower in the Peel-Harvey area (Table 2). As expected, larger ocean discharges are expected under the wetter climate (historical and wet) and smaller under the drier climates (median and dry) in all three regions. Groundwater discharge to the ocean under the dry future climate is expected to reduce by 27 % in the Central Perth Basin and by 38 % in the Southern Perth Basin. Instead of groundwater discharge, seawater intrusion is likely in the Peel-Harvey area under the dry future climate due to lower groundwater levels in coastal areas. Under the median future climate the ocean discharge is expected to reduce by 15 % in the Central Perth Basin, by 24 % in the Southern Perth Basin and by 50 % in the Peel-Harvey area. Relatively large reductions in ocean discharge expected under the median and dry future climates in the Central and Southern Perth basins are due to lower groundwater levels, which increase the risk of seawater intrusion especially in conjunction with sea level rise projected due to climate change.

4.6 Impacts on groundwater discharge to drains and rivers

The mean annual groundwater discharge to drains and rivers is highest (23 to 36 $\text{mm}\,\text{yr}^{-1}$) in the heavily drained Peel-Harvey area and lowest (2.5 to 4.1 $\text{mm}\,\text{yr}^{-1}$) in the relatively undeveloped Southern Perth Basin (Table 2). About 50 % of mean annual recharge is discharged to the drainage systems annually due to shallow watertables and an extensive network of natural and engineered drainage systems in the

Peel-Harvey area. Winter rainfall causes watertables to rise above the invert level of drainage systems in most of this area causing substantial groundwater discharges. Due to fewer river systems, lower groundwater levels and extensive native vegetation, groundwater discharge to river and drainage systems is relatively small in the Southern Perth Basin.

Groundwater discharge to drains under the dry future climate is expected to reduce by 32, 40 and 48 % in the Peel-Harvey area, Southern Perth Basin and Central Perth Basin, respectively. Substantial reductions in groundwater discharge to drains are also expected under the median future climate and the development scenario in all three regions. The reductions expected under the median and dry future climates are due to projected decline in watertables. Groundwater discharge to drains under the historical and wet future climates are mostly similar.

4.7 Impacts on net leakage to confined aquifers

The mean annual net leakage from superficial to confined aquifer systems is highest (37 to 44 $\mathrm{mm\,yr^{-1}}$) in the Central Perth Basin, lowest (18 to 31 $\mathrm{mm\,yr^{-1}}$) in the Southern Perth Basin, and zero in the Peel-Harvey area due to the relative paucity of interconnections with lower aquifers in this area. The net leakage to the confined systems under the dry future climate is expected to reduce by 16 % in the Central Perth Basin and by 34 % in the Southern Perth Basin. Reduction in leakage (replenishment) to confined systems will result in larger drawdowns if groundwater abstraction from the confined systems continues at current levels.

4.8 Climate impacts on the distribution of net recharge

The distribution of net annual recharge into various water balance components is different under various scenarios in three regions (Fig. 5). In the Central Perth Basin over 23 % of the mean annual recharge, projected to be added to groundwater storage under the wetter climates (historical and wet), is expected to reduce to only 4 % of net annual recharge under the dry future climate. In the Southern Perth Basin and Peel-Harvey area the addition in groundwater storage of about 13 % and 0 %, respectively of net annual recharge is likely under the historical climate. This is expected to change to loss in groundwater storage equivalent to about 10 to 12 % of the net annual recharge under the dry future climate.

The annual groundwater discharge to the ocean is 19 to 22 % of the net annual recharge in the Central Perth Basin and varies little among scenarios. It is 41 to 58 % of net annual recharge in the Southern Perth Basin under various scenarios (Fig. 5). Highest percent (58) of net annual recharge is expected to discharge to the ocean under the dry future climate, however the net annual recharge is lowest under this scenario. It is only a small percentage (0 to 5) of net annual recharge in the Peel-Harvey area.

Groundwater discharge to drains is a major portion of net annual recharge in the Peel-Harvey area (above 60 %) because of shallow watertables and is less likely to change under drier scenarios except under the development scenario where it is expected to reduce to about 37 % of net annual recharge due to lower watertables caused by additional groundwater pumping. The groundwater discharge to drains is a small portion of the net recharge in the Central Perth Basin (8 %) and Southern Perth Basin (5 %) and is expected to reduce under the drier future climates. This is due to shallow watertables in smaller areas compared with the Peel-Harvey area where most recharge is drained.

Pumping accounts for 21 to 34 % of net annual recharge in the Central Perth Basin, 32 to 73 % in the Peel-Harvey area and 1 to 8 % in the Southern Perth Basin. When recharge reduces under the drier climates a greater portion of recharge is consumed by pumping which remains constant between 2008 and 2030. Net leakage to confined aquifers is a major component of the water balance in both Central (26 to 34 %) and Southern Perth basins (33 to 45 %). Under the drier future climate the percentage of net annual recharge that becomes leakage to confined systems increases due to higher hydraulic gradients as a result of the drawdowns from pumping in the unconfined and confined systems. This does not mean that net leakage volumetrically increases but a greater portion of the reduced recharge leaks to the confined systems.

4.9 Sensitivity of water balance components to climate change

The percent change in each water balance component was plotted against percent change in rainfall for three regions of the study area (Fig. 6) to assess the sensitivity of water balance components to climate change. The percent changes are relative to their values under the historical climate. Linear trend lines were fitted to show the rate of percent change in each water balance component as a function of percent change in rainfall. An overall average value for percent change in rainfall and water balance components was estimated which was an average of the rates of percent change under four climate scenarios. The rate of percent change indicated by the trend lines may be different to the average of all four scenarios because the trends are indicators and should not be used to estimate the percent change of water balance components.

Figure 6 shows varying sensitivities of water balance components to climate change. Storage is most sensitive to climate and net leakage to confined systems is least sensitive. For every one percent reduction in rainfall the storage reduces by 5 and 8 % in the Southern and Central Perth basins, respectively. In the Peel-Harvey area the storage change under the historical climate was zero and percent change under various scenarios relative to that under the historical climate was not estimated but its sensitivity to climate change is similar to the other two regions. The net leakage to confined aquifers is expected to reduce by 1.5 times the percent reduction in rainfall in the Central Perth Basin and 2.5 times the percent decrease in rainfall in the Southern Perth Basin. Low sensitivity of net leakage to confined aquifers is likely due to the hydraulic gradients remaining similar and leakage being controlled by hydraulic conductivities rather than overlying storage.

Recharge is highly sensitive to climate change in the Central and Southern Perth basins. It is expected to reduce by 3.6 times the percent reduction in rainfall in these regions. Percent reductions in recharge are similar between two regions although the rainfall is higher in the Southern Perth Basin and a small proportion of rainfall becomes recharge due to perennial vegetation and clayey soils. Recharge is generally higher in the Central Perth Basin because of its greater proportion of sandy soils cleared for dryland agriculture. Recharge is less sensitive to climate change in the Peel-Harvey area and is expected to reduce by only 1.2 times the percent reduction in rainfall due to shallow watertables in most areas which reject some of the total winter recharge.

Groundwater discharge to the ocean is relatively less sensitive to climate change in the Central and Southern Perth Basins but very sensitive in the Peel-Harvey area (Fig. 6). For every one percent reduction in rainfall the ocean discharge reduces by about 3 % in the Central and Southern Perth basins but by over 6 % in the Peel-Harvey area. A change from ocean discharge under the wetter climates (historical and wet) to seawater intrusion under the dry future climate is due to lower watertables. Groundwater discharge to drains is also very sensitive to climate change in the Central Perth Basin but less sensitive in the Peel-Harvey area. For every one percent reduction in rainfall the groundwater discharge to drains reduces by 5.4 % in the Central Perth Basin, by 3.2 % in the Southern Perth Basin and by 1.3 % in the Peel-Harvey area. There are extensive natural and engineered drainage systems in both the Central Perth Basin and Peel Harvey area. Those in the Peel-Harvey area are less affected due to shallow watertables over large areas. When shallow watertables decline they accept recharge that would otherwise be rejected and as a result are less sensitive to climate change. In the Central Perth Basin the watertables are relatively deeper and as a result any reduction in recharge results in the watertable falling below drain invert levels making them sensitive to climate change. Drainage systems are relatively small in the Southern Perth Basin but are sensitive to climate change due to projected large declines in watertables.

5 Discussion

Mean annual rainfall in South-Western Australia and a number of other regions of the world has substantially reduced during second half of the 20th century (Ducci and Tranfaglia, 2008; Pio et al., 2010; PMSEIC Independent Working Group, 2007). Almost all GCMs consistently project a further decrease in rainfall in South-Western Australia by 2030. This is similar to the Geer Basin in Belgium where all RCMs (Regional Climate Models) which had been derived from GCMs, project a decrease in annual precipitation (Goderniaux et al., 2009). Reduction in mean annual rainfall reduces groundwater recharge and affects other components of the water balance (Zagonari, 2010).

Projected reductions in recharge are 2 to 3 times the reduction in rainfall (15 to 18 %) in the study area which shows high sensitivity of groundwater recharge to climate change. Candela et al. (2009) projects between 4 and 20 % reduction in recharge by 2025 in the Inca-Sa Pobla Plain, Spain, in response to about 2 % reduction in rainfall. Sandstorm (1995) notes a 40 to 50 % reduction in recharge in response to 15 % reduction in precipitation in semi-arid Tanzania. The sensitivity of groundwater recharge to climate change also depends, in addition to rainfall, on land cover, soil, watertable depth as is also reported by Crosbie et al. (2010) and McCallum et al. (2010) for Australia and by Jyrkama and Sykes (2007), Liu (2011) and Green et al. (2011) for other regions. For this reason it is different across three regions of the study areas. It is high in the Central and Southern Perth basins, where recharge is projected to reduce by 3.6 % for every one percent reduction in rainfall. In the Central Perth Basin the rainfall is lower than the Southern Perth Basin but a greater proportion of rainfall becomes recharge due to extensive built-up areas the rainfall from which is directed to the underlying aquifers via recharge pits, predominantly sandy soils and land being used for dryland agriculture. In the Southern Perth Basin a lower portion of relatively higher annual rainfall becomes recharge due to perennial vegetation and clayey soils both of which discourage recharge. Therefore reductions in recharge may be similar but due to different processes in response to a reduction in rainfall. Recharge has less sensitivity to climate change in the Peel-Harvey area due to shallow watertables over extensive areas. Water levels decline under projected drier climates but this is buffered by increases in recharge which would otherwise have been rejected.

According to Döll (2009) the climate change effect on groundwater recharge is likely to impact many regions around the globe; he notes that about 18 % of global population would be affected by a reduction in recharge of at least 10 %. The reduction in recharge, in turn, impacts all components of the water balance, including discharge. Reduced groundwater recharge means decline in watertables which reduce groundwater discharge to the ocean in the Central and Southern Perth basins and an increased risk of seawater intrusion in the Peel-Harvey area. Giambastiani et al. (2007) similarly reports an increased risk of seawater intrusion, due to climate change, in the unconfined coastal aquifer of Ravenna, Italy. A reduction in recharge is also likely to affect groundwater discharge to natural and engineered drainages and net leakage to confined aquifers. Substantial reductions (32 to 48 %) in the mean annual discharge to drains and rivers are expected under the dry future climate. However its sensitivity to climate change is not uniform across the three regions of the study area, i.e. it is highly sensitive in the Central Perth Basin but less sensitive the Peel-Harvey area. The latter area has shallow watertables in most of the area and an extensive network of drainages. When watertables decline they accept more recharge which would otherwise have been rejected. This is not the case in the Central and Southern Perth basins where watertables are deeper. When these decline below the invert levels in large areas under climate change they cause substantial reductions in groundwater discharge to drains.

The effect of climate change on groundwater resources or storage is a global issue; it is likely to impact the groundwater storage in many regions even if the current pumping continues into the future (Green et al., 2011; Loaiciga et al., 2000; Yusoff et al., 2002). The groundwater storage in the study area is also very sensitive to climate change and is expected to reduce due to less groundwater recharge occurring under drier future climates. For example, in the Central Perth Basin over 23 % of the mean annual recharge expected to be added to groundwater storage under the wetter (historical and wet future climate) climates is projected to reduce to 4 % of net annual recharge under the dry future climate. Whereas in the Southern Perth Basin and Peel-Harvey area 13 and 0 % of mean annual recharge expected to be added to groundwater storage, respectively under a continuation of the historical climate is projected to change to a loss in groundwater storage equivalent to about 10 to 12 % of net annual recharge under the dry future climate.

All climate change studies have some uncertainty in projections (Scibek and Allen, 2006; Weare and Du, 2008; Crosbie et al., 2011) due to uncertainty in GCM predictions, downscaling methods, input parameters and aquifer heterogeneity. Modelling of groundwater systems involves many steps and each introduces some uncertainty. For this study, 15 GCMs were used to derive future climates for South-Western Australia and 14 of 15 project a drier future climate for this region. Therefore there is less uncertainty in GCMs projections in South-Western Australia compared to those regions where GCMs project either a wetter or drier future climate. Daily downscaling techniques used to derive the scaling factors for modification of the historical climate, introduced some uncertainty in the derived future climates. A relatively sophisticated Vertical Flux Model (VFM) was used to estimate recharge instead of its direct input in the groundwater models. The uncertainty in input parameters (land cover, soil and climate) to the VFM was reduced by validation of VFM based recharge estimates with those determined through field studies. However this could not be done for all land cover types, soils and climate zones in all regions of the study area due to availability of limited field data, so there could still be some uncertainty in these estimates. Two of the three groundwater models used for this assessment have gone through an extensive refinement and recalibration process over time. As a result their reliability, as predictive tools, has improved and uncertainty has reduced. However the Peel Harvey model used in this study is new and still has to go through the review process. Thus, uncertainty of projections from this model is greater than from the other two models.

6 Conclusions

Groundwater modelling, using future climate data, was undertaken to assess the impacts of climate change on the water balance in unconfined aquifers with a variety of land uses, soil types and depths of the watertable. The VFM linked groundwater models are used to project future groundwater recharge and various discharges (other components of the water balance) under a range of future climates.

The mean annual rainfall in South-Western Australia is projected to further reduce by 7 to 11 % under the median future climate and by 15 to 18 % under the dry future climate. This will lead to reductions in groundwater recharge of 33 to 49 % under the dry future climate relative to a continuation of the historical climate of 1975–2007 to 2030. The reduction in groundwater recharge is expected to impact all other components of the water balance. The groundwater discharge to the ocean and natural drainages is expected to reduce substantially under the dry future climate. In the Peel-Harvey area in particular there may be an increased risk of seawater intrusion under the dry future climate. The leakage to underlying confined aquifer systems is likely to reduce by 16 to 34 % in the Central and Southern Perth basins under the dry future climate. The proportion of mean annual recharge being added to groundwater storage is expected to reduce from 23 % under the wetter (historical and wet future climate) climates to only 4 % under the dry future climate in the Central Perth Basin. In the Southern Perth Basin and Peel-Harvey area the addition in groundwater storage under a continuation of the historical climate is projected to change to a loss in groundwater storage under the dry future climate.

Storage changes are most sensitive and net leakage to confined systems is least sensitive to climate change. Recharge is highly sensitive to climate change in the Central and Southern Perth basins and less sensitive in the Peel-Harvey area. Groundwater discharge to the ocean is very sensitive to climate change in the Peel-Harvey area but less sensitive in the Central and Southern Perth basins. Groundwater discharge to drains is highly sensitive to climate change in the Central Perth Basin and less sensitive in the Peel-Harvey area.

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Table 1. Mean annual rainfall in the Central Perth Basin, Peel-Harvey area and Southern Perth Basin under various scenarios. Percent changes under various scenarios relative to the historical climate scenario are also shown.

Mean annual rainfall and percent change from the historical climate	Historical	Recent	Wet	Median	Dry
Central Perth Basin (mm yr^{-1})	660.0	625.0	688.0	632.0	564.0
Percent of historical		94.6	104.2	95.7	85.5
Peel-Harvey area (mm yr^{-1})	924.0	820.0	901.0	829.0	754.0
Percent of historical		88.7	97.6	89.7	81.6
Southern Perth Basin (mm yr^{-1})	893.0	869.0	889.0	814.0	745.0
Percent of historical		97.3	99.6	91.1	83.4

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Table 2. Water balance components in the Superficial Aquifer in the Central Perth Basin, Peel-Harvey area and Southern Perth Basin over 2008 to 2030 period under various scenarios. The numbers show 23-yr annual means (mm) under various scenarios.

Scenario	Storage change	Recharge	Discharge to ocean	Discharge to drains	Pumping	Net flow to confined aquifers	Balance error
				$\mathrm{mm\,yr^{-1}}$			
			Central Perth Basin				
Historical	39.3	166.7	−32.8	−15.5	−35.1	−44.0	0.00
Recent	23.0	137.2	−27.8	−11.1	−35.1	−40.1	0.00
Wet	38.4	163.0	−31.6	−14.8	−35.1	−43.2	0.00
Median	22.9	137.2	−27.8	−11.3	−35.1	−40.0	0.00
Dry	4.5	108.5	−24.0	−8.1	−35.1	−36.8	0.00
Development	17.9	142.6	−26.7	−10.2	−49.2	−38.6	0.00
			Peel-Harvey area				
Historical	0.0	54.1	−2.5	−34.4	−17.8	0.0	0.0
Recent	0.6	50.4	−1.2	−30.7	−17.8	0.0	0.0
Wet	−0.6	56.0	−3.1	−35.7	−17.8	0.0	0.0
Median	−2.5	46.1	−1.2	−29.5	−17.8	0.0	0.0
Dry	−4.3	36.3	0.6	−23.4	−17.8	0.0	0.0
Development	−6.8	67.6	0.0	−25.2	−49.8	0.0	0.0
			Southern Perth Basin				
Historical	10.4	82.8	−39.5	−4.1	−1.2	−27.5	0.0
Recent	2.5	63.3	−32.6	−3.5	−1.2	−23.5	0.0
Wet	13.3	80.9	−36.2	−3.8	−1.2	−26.4	0.1
Median	4.4	60.4	−29.9	−3.0	−1.2	−21.9	0.0
Dry	−4.2	42.2	−24.4	−2.5	−1.2	−18.3	0.0
Development	1.4	69.9	−28.4	−2.8	−5.9	−31.4	0.1

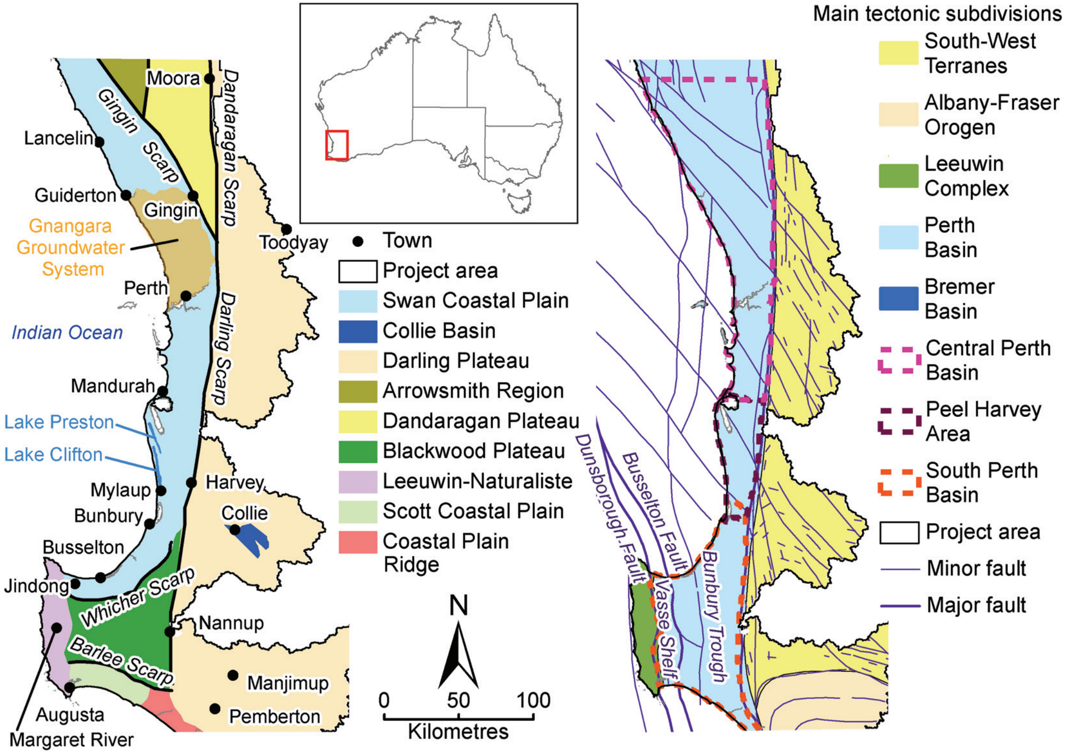

Fig. 1. Map of the study area and main tectonic subdivisions.

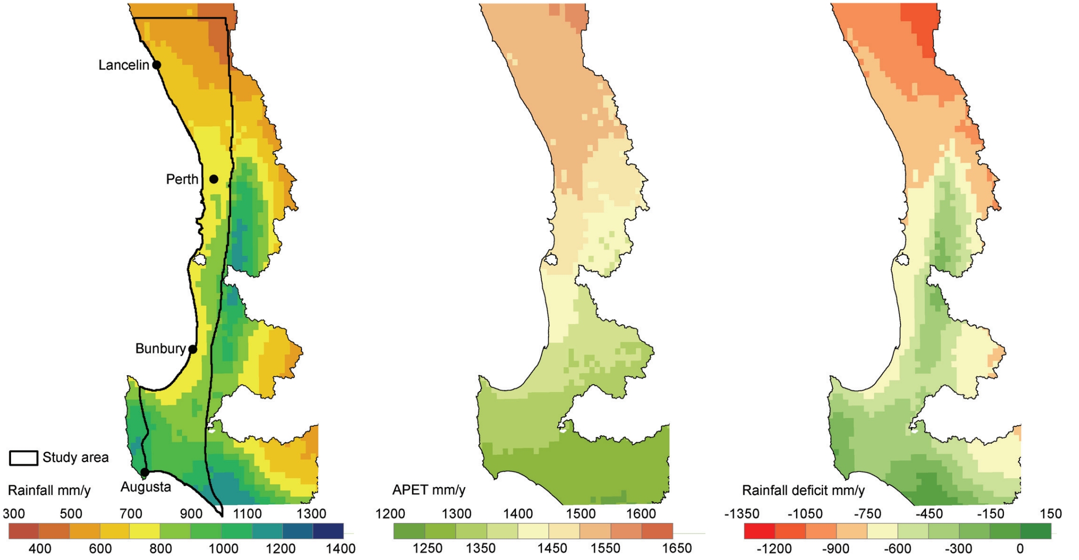

Fig. 2. Spatial distribution of mean annual historical (1975 to 2007) rainfall, areal evapotranspiration (APET) and rainfall deficit (rainfall less areal potential evapotranspiration) across the study area.

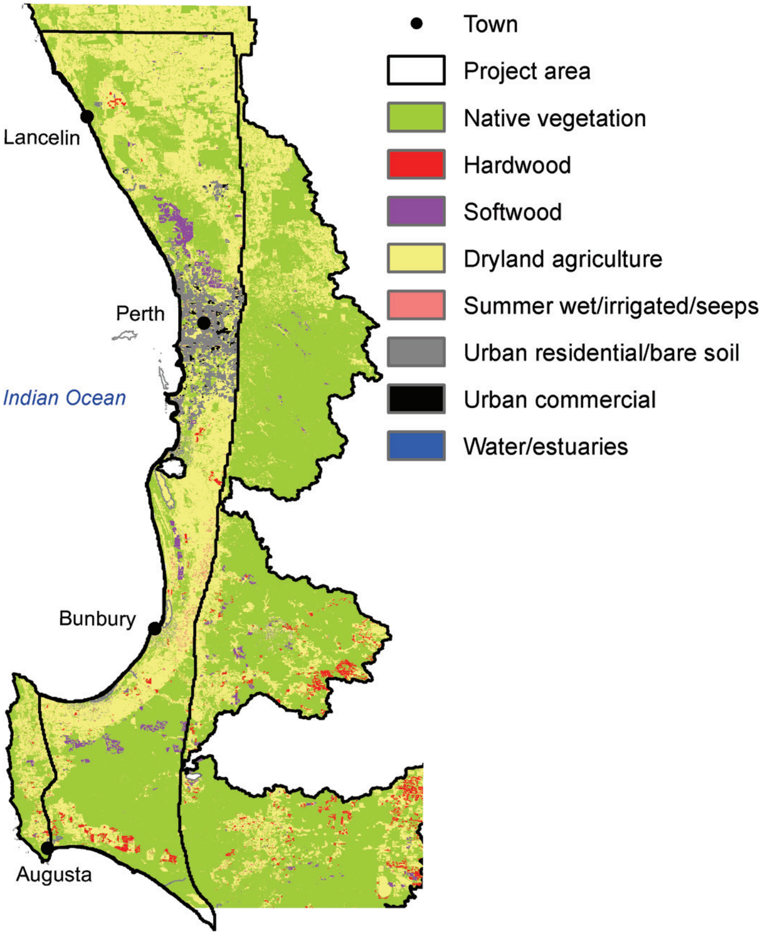

Fig. 3. Major land cover types in the study area (using satellite imagery from 2005).

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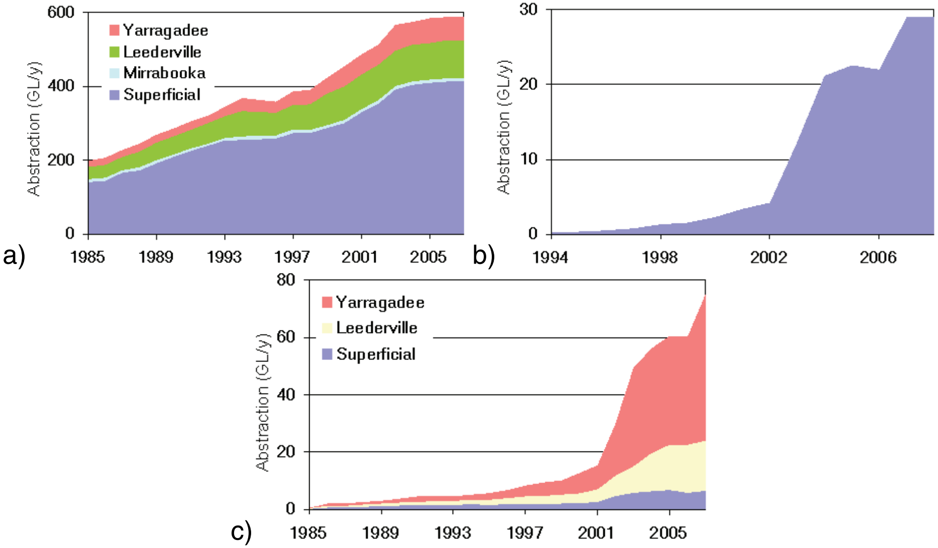

Fig. 4. (a) Abstraction from four aquifers between 1985 and 2007 in the Central Perth Basin, **(b)** licensed allocation from the Superficial Aquifer between 1994 and 2007 in the Peel-Harvey area, and **(c)** abstraction from three aquifers between 1985 to 2007 in the Southern Perth Basin.

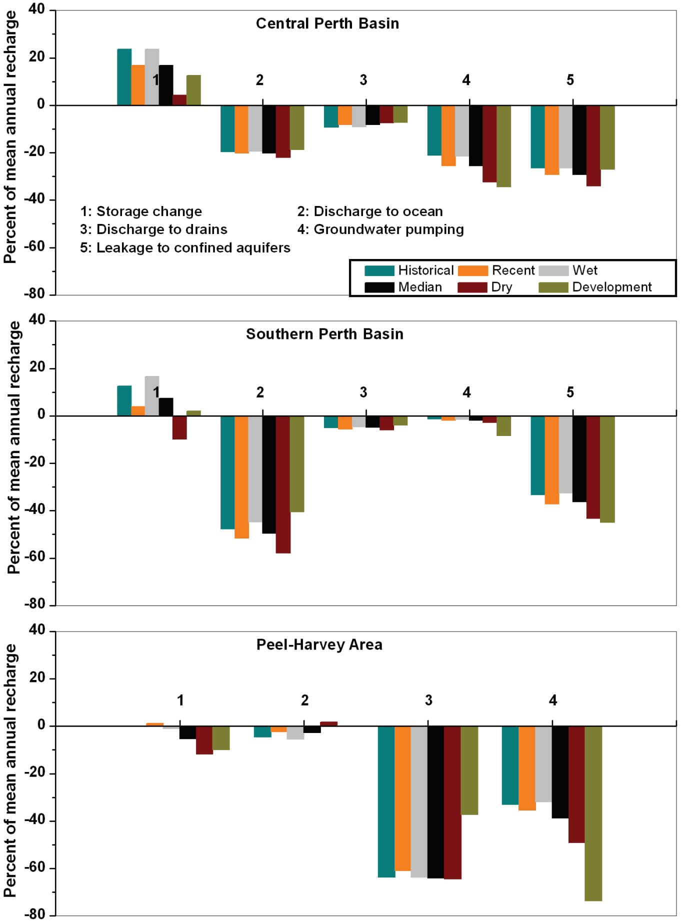

Fig. 5. Water balance components under various scenarios shown as percent of net annual recharge in the Central Perth Basin, Peel-Harvey area and Southern Perth Basin.

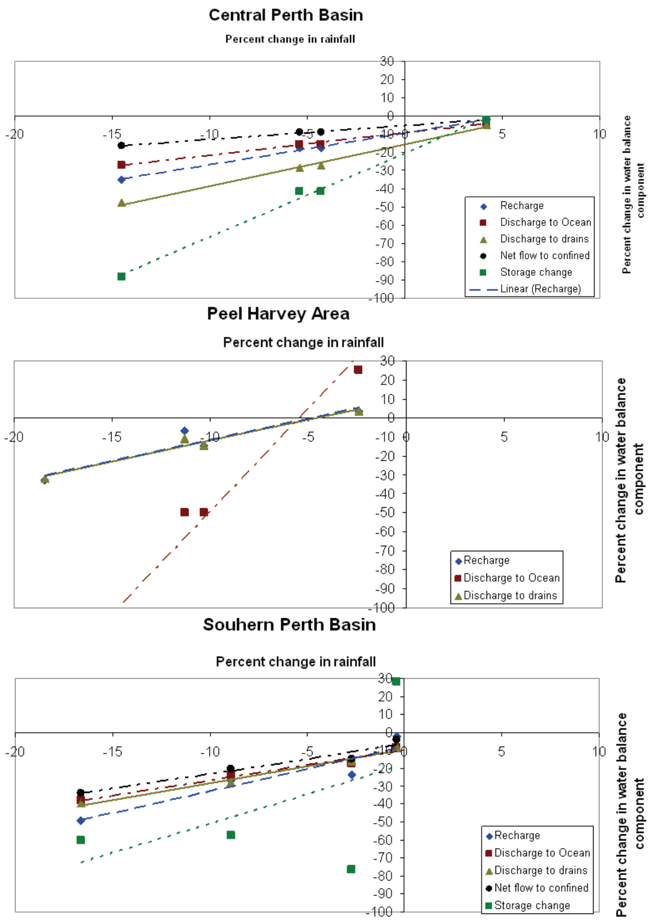

Fig. 6. Relationship between percent change in rainfall and percent change in water balance components relative to the historical climate in the Central Perth Basin, Peel-Harvey area and Southern Perth Basin.

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