
Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge

J. L. McCallum · R. S. Crosbie · G. R. Walker ·
W. R. Dawes

Abstract Groundwater recharge is a complex process reflecting many interactions between climate, vegetation and soils. Climate change will impact upon groundwater recharge but it is not clear which climate variables have the greatest influence over recharge. This study used a sensitivity analysis of climate variables using a modified version of WAVES, a soil-vegetation-atmosphere-transfer model (unsaturated zone), to determine the importance of each climate variable in the change in groundwater recharge for three points in Australia. This study found that change in recharge is most sensitive to change in rainfall. Increases in temperature and changes in rainfall intensity also led to significant changes in recharge. Although not as significant as other climate variables, some changes in recharge were observed due to changes in solar radiation and carbon dioxide concentration. When these variables were altered simultaneously, changes in recharge appeared to be closely related to changes in rainfall; however, in nearly all cases, recharge was greater than would have been predicted if only rainfall had been considered. These findings have implications for how recharge is projected to change due to climate change.

Keywords Climate change · Groundwater recharge/water budget · Water resources · WAVES · Australia

Received: 23 July 2009 / Accepted: 14 June 2010
Published online: 6 July 2010

© Springer-Verlag 2010

J. L. McCallum (✉)
School of Environment, Flinders University,
PO Box 2100, Adelaide, SA 5001, Australia
e-mail: james.mccallum@flinders.edu.au
Tel.: +61-8-83038712

R. S. Crosbie · G. R. Walker
CSIRO Water for a Healthy Country National Research Flagship,
CSIRO Land and Water,
PMB 2, Glen Osmond, SA 5064, Australia

W. R. Dawes
CSIRO Water for a Healthy Country National Research Flagship,
CSIRO Land and Water,
PMB 5, Wembley, WA 6913, Australia

Introduction

Diffuse groundwater recharge is an important process in the replenishment of groundwater resources. Changes to any of the variables that affect diffuse recharge (e.g. climate, soil type, vegetation cover) may have an impact on the amounts of water entering aquifers (Petheram et al. 2002). It is important to understand how climate change may affect diffuse recharge as it may have implications to the availability and management of groundwater resources. This paper investigates the sensitivity of recharge to carbon dioxide concentration, temperature, rainfall, vapour-pressure deficit, solar radiation and rainfall intensity to understand the potential impacts of climate change on recharge.

A wide range of methods have been implemented when projecting the change in diffuse recharge due to climate change. Some papers deal with recharge simply. Loaiciga et al. (2000) used seven general circulation models (GCMs) to determine impacts of climate change on the Edwards Aquifer in central Texas, USA. The GCMs were used to produce a climate that was representative of a doubling of CO₂ concentrations. Recharge was scaled based on changes to rainfall and streamflow determined by the GCMs and by using a water-balance technique to determine how this would impact on recharge. It was found that changes to rainfall and streamflow under such scenarios would result in reduced groundwater levels in the aquifer even if groundwater extraction was not increased. Kirshen (2002) used a relationship between rainfall and potential evapotranspiration (PET) to determine recharge under possible climate-change conditions in eastern Massachusetts, USA. It was found that groundwater levels across the aquifer could increase or decrease having implications on river flows, wetlands and water-use potential due to the expected changes in rainfall and potential evapotranspiration. Hsu et al. (2007) used the water-table fluctuation method to determine rainfall–recharge relationships, and extrapolated current rainfall trends to estimate future climate impacts on recharge on the Pingtung Plain in Taiwan. It was found that reduction in groundwater levels may induce additional seawater intrusion impacting groundwater quality. These methods use simple relationships between recharge and climate change. While this is advantageous in that less data is required, it does not account for all the processes that may change due to a changing climate.

Other studies on the impacts of climate change on groundwater use unsaturated zone models to assess potential changes in recharge. Such models account for climate variables and plant water use in addition to unsaturated flow. Bouraoui et al. (1999) used temperature and precipitation results from a downscaled GCM. Additionally, evapotranspiration was estimated by assuming a relationship with temperature, which did not account for plant-water-use changes associated with climate change. The projected climate from a doubling of CO₂ was applied to a catchment model of the Bievre-Valloire Watershed in France. It was found that although rainfall remained similar, an increase in evaporative demand would result in reduced recharge and a higher soil-water deficit. York et al. (2002) used a coupled groundwater and atmospheric model to investigate groundwater trends by extending a 1988 drought climate over 40 years in the Mill Creek Watershed (Kansas, USA). This model allowed for the groundwater system to provide feedbacks to the climate generation process; however, the unsaturated zone was simulated using a simple reservoir model. It was found that under this climate scenario, groundwater levels were projected to fall 15 m, mostly due to evapotranspiration from groundwater. Brouyère et al. (2004) used GCM scenarios to investigate the impacts of climate change in the Geer Basin, Belgium. Temperature and precipitation were altered on a monthly basis and used in conjunction with an unsaturated zone model. It was found that both played a role in determining changes to recharge. Allen et al. (2004) used a simple unsaturated model to estimate how changes in precipitation, temperature and evapotranspiration due to climate change would alter recharge for a numerical groundwater model of the Grand Forks aquifer, Canada. Recharge was modelled for four scenarios: low temperature and low precipitation, high temperature and high precipitation, high temperature low precipitation, and low temperature and high precipitation. (High temperature related to a 1–2°C increase, high temperature related to a 3.5–7.0°C increase, low precipitation represents a 0–20% decrease and high precipitation presented a 15–40% increase). It was found that these scenarios resulted in changes in recharge of –5.6, 10, –9.5 and 25.7% respectively. Woldeamlak et al. (2007) used an unsaturated zone model to determine changes in recharge due to changes in precipitation and evapotranspiration for the Grote-Nete Catchment in Belgium. Five scenarios were modelled. The dry extreme (dry scenario) showed a 10% reduction in precipitation and a 10% increase in evapotranspiration resulted in a 40% decrease in recharge. The wet extreme (high wet scenario) showed that a 14% increase in precipitation and a 13% increase in evapotranspiration resulted in a 14% increase in recharge. Additional studies have also accounted for CO₂ effects when dealing with assessments of how climate change will impact water resources. This assumes that an increase in the concentration of atmospheric CO₂ will have an impact on plant growth and on plant-water-use characteristics, altering water-balance characteristics. Rosenberg et al. (1999) and Eckhardt and Ulbrich (2003) used SWAT

(Arnold et al. 1998), a hydrological model, to account for vegetative feedbacks due to CO₂ fertilisation in studies on the impacts of climate change on water resources. Rosenberg et al. (1999) presented results of three GCM scenarios in the Missouri Basin and the Arkansas-White-Red Basin (USA). Each GCM was modelled for 12 scenarios. When CO₂ concentration was altered independent of temperature, results in the Missouri Basin indicated a decrease in recharge, whereas the Arkansas-White-Red Basin showed an increase in recharge with increasing CO₂ concentration. Both basins showed a decrease in recharge when temperature was increased independent of CO₂ concentration. Eckhardt and Ulbrich (2003) modelled changes in recharge due to changes in climate in the Dill Catchment in Germany. In a low scenario, CO₂ concentration was increased by 50% and temperature was increased 1.5°C resulting in a 3% decrease in recharge. In a high scenario, CO₂ concentration was doubled, temperature was increased by 4.5°C and rainfall was adjusted seasonally resulting in a 7.5% decrease in recharge. These models that account for unsaturated-zone processes provide a more detailed description of the recharge process making them potentially more advantageous. The disadvantage of these more complex methods is the requirement of additional data and computer processing time to determine recharge.

The most complex models are physically based models that apply Richards' equation to determine the effects of climate change on recharge. Green et al. (2007) used WAVES (Zhang and Dawes 1998), a soil-vegetation-atmosphere-transfer (SVAT) model to investigate the potential effects of climate change on groundwater recharge in two locations: Gngangara Mound, Australia and North Stradbroke Island, Australia. The authors used physical variables coupled with the output of a single GCM. They found that in a subtropical area (North Stradbroke Island), recharge was significantly increased, in some cases greater than the percentage increase in rainfall. It was found that for a Mediterranean climate (Gngangara Mound), changes in recharge were sensitive to soil texture, with some areas showing an increase in recharge and others showing a decrease. Crosbie et al. (2010) used WAVES to model projected changes in recharge due to climate change in the Murray Darling Basin, Australia. The authors used three scenarios, applied to 15 GCMs at 20 points. The authors accounted for changes in rainfall, temperature, solar radiation, vapour-pressure deficit and carbon dioxide concentration. When upscaling, the results from point to basin scale, the authors used a relationship between rainfall and recharge. They found that recharge could increase even if rainfall decreased.

Models with different levels of complexity include different processes in their conceptualisation. It has been shown in the previous that there is some variation in how the outputs of GCMs are used to determine changes in groundwater recharge. It has not been determined explicitly how individual climate variables are important in the impact of climate change upon groundwater recharge. In this paper, relationships between the changes in recharge due to changes in carbon dioxide concentration, temperature,

rainfall, vapour-pressure deficit, solar radiation and rainfall intensity associated with climate-change projections will be examined using a detailed sensitivity analysis. The sensitivity analysis will be carried out using a numerical unsaturated zone model to:

1. Determine the climate variables that are important to the process of recharge and how they may be altered by climate change
2. Give insight into what level of climate detail is required from GCM outputs to determine changes in recharge.

Methods

Site selection/characteristics

To investigate a wide range of climate environments, three sites were chosen to in three distinct parts of Australia: the Namoi Catchment, the Howard East Catchment and the Scottsdale Catchment (Fig. 1). The Namoi Catchment is a well-established groundwater-management area located in the northern part of the state of New South Wales. The study site selected was one of 20 points modelled as part of a broader coverage of the entire Murray-Darling Basin (MDB; Crosbie et al. 2010). Berhane (2001) found recharge to be 56 mm year⁻¹ at a location within this catchment. The Howard East Catchment is located in the

Northern Territory. Previous studies in this catchment have included Cook et al. (1998) and Hutley et al. (2000). A previous estimate of recharge was made by Cook et al. (1998) to be 200 mm year⁻¹. The Scottsdale Catchment is located in Tasmania. This site was chosen as it has a significantly different climate to other locations. Recharge estimates at this location were previously made by Harrington and Currie (2008) and ranged from 69 to 300 mm year⁻¹.

For each site, a baseline 112-year historical daily climate sequence of rainfall, temperature, solar radiation, and vapour-pressure deficit was obtained from gridded climate surfaces (Jeffrey et al. 2001). For the 112-year period, the average annual rainfall was 800, 1,600 and 1,250 mm year⁻¹ for Namoi, Howard East and Scottsdale, respectively. Potential evapotranspiration (Smith et al. 1992) at the three sites was 1,300, 1,740 and 850 mm year⁻¹ for Namoi, Howard East and Scottsdale, respectively. Additional information on soil and vegetation was also required for the modelling. The soil at the investigation point was based on information contained in the ASRIS 1 database (Johnston et al. 2003). The saturated hydraulic conductivity and plant available water capacity for all soil layers was available through this database.

WAVES code

The model selected for the investigation was WAVES; however, the code required modification to allow for

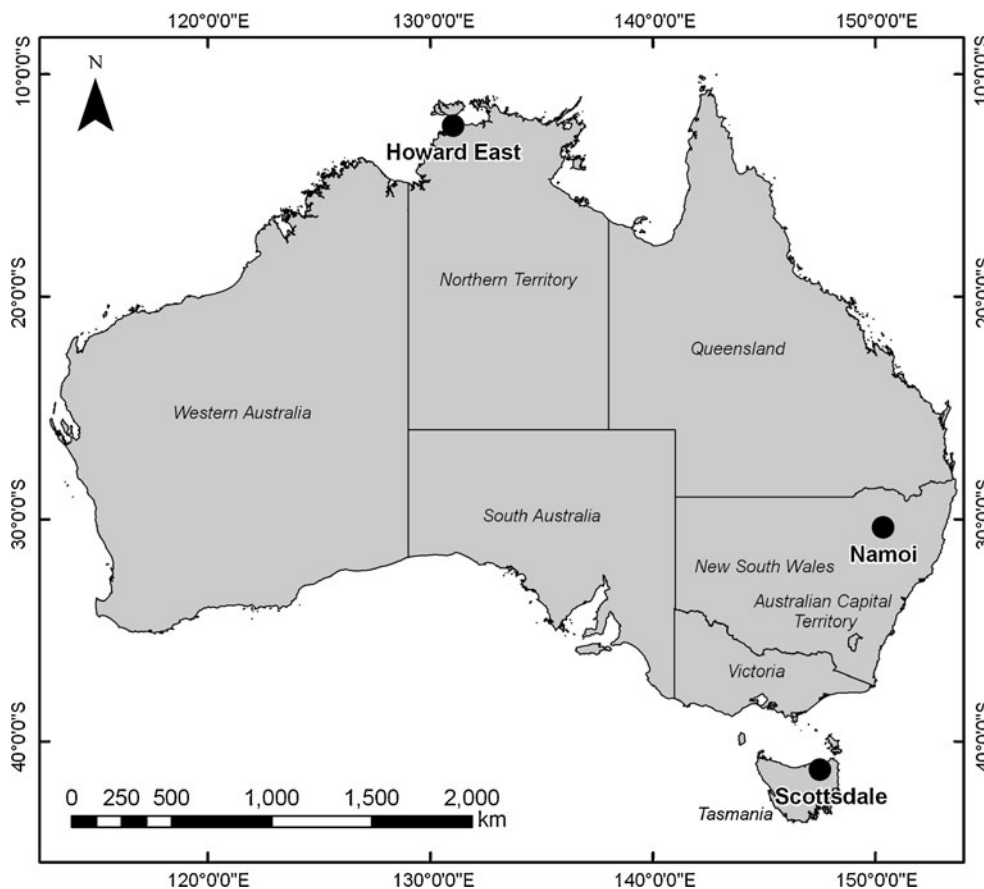


Fig. 1 Locations of the three sites modelled in Australia

carbon dioxide sensitivity to be undertaken. A detailed description of the algorithms used in the WAVES code can be found in Zhang and Dawes (1998). WAVES is a SVAT model. SVAT models have the advantage of simulating plant growth and routing water through the unsaturated zone. In WAVES, there is equal complexity placed on water, energy and carbon balances, and solute transport. Waves has been shown to be capable of reproducing water balances in the Murray-Darling Basin (Crosbie et al. 2008; Slavich et al. 1999; Zhang et al. 1999), the rest of Australia (Dawes et al. 2002; Salama et al. 1999; Xu et al. 2008) and elsewhere (Wang et al. 2001; Yang et al. 2003; Zhang et al. 1996).

As stated previously, the standard WAVES code does not allow for the atmospheric concentration of CO₂ to be altered. When dealing with carbon assimilation, WAVES uses an integrated rate methodology (IRM; Wu et al. 1994). Here, a potential growth rate is determined, and a multiplier between zero and one is applied based on the availability of nutrients, light and water. This factor combines a number of biochemical and biophysical processes in an empirical relationship, allowing for a number of processes on which plant growth is dependant upon to be dealt with simultaneously. The relative assimilation factor has been modified from the standard WAVES code to include CO₂. The new equation for

relative carbon assimilation is the same as that used by Hatton et al. (1992):

$$r_i = \frac{1 + W_W + W_N + W_{CO_2}}{\frac{1}{m_T X_P} + \frac{W_W}{X_W} + \frac{W_N}{X_N} + \frac{W_{CO_2}}{m_V X_{CO_2}}} \quad (1)$$

where r_i is the relative carbon assimilation, W_w is the weighting factor of water relative to light, W_N is the weighting factor of nutrients relative to light, W_{CO_2} is the weighting factor of CO₂ relative to light, m_T is the temperature modifier, m_V is the vapour-pressure modifier, X_P is the normalised photosynthetically available radiation (PAR) availability, X_W is the normalised water availability, X_N is the normalised nitrogen availability and X_{CO_2} is the normalised carbon dioxide availability (values of weighting factors are presented in Table 1). To determine the actual carbon assimilation rate, the potential assimilation rate is multiplied by the relative carbon assimilation. Once assimilated, carbon is partitioned to the leaves, stems or roots. Carbon added to leaves increases leaf area index (LAI) having implications for interception of rainfall as well as transpiration.

In addition to carbon assimilation, the stomatal conductance and consequently the canopy resistance, which in turn affects transpiration, is also affected by changes in CO₂ concentration. The stomatal conductance

Table 1 Parameters used to represent vegetation in WAVES (Dawes et al. 1998)

Location Parameter	Units	Namoi	Howard East		Scottsdale
			Overstorey	Understorey	
Vegetation type	–	C ₃ Perennial pasture	Eucalypt	C ₄ Perennial pasture	C ₃ Annual pasture
1 minus albedo of the canopy ^a	–	0.85	0.8	0.9	0.85
1 minus albedo of the soil ^b	–	0.85	0.85	0.9	0.85
Rainfall interception coefficient	m d ⁻¹ LAI ⁻¹	0.001	0.001	0.001	0.0005
Light extinction coefficient	–	–0.65	–0.45	–0.9	–0.65
Maximum carbon assimilation rate	kg C ⁻² d ⁻¹	0.02	0.03	0.04	0.025
Slope parameter for the conductance model (<i>k</i>)	–	1	0.9	1.1	0.9
Maximum plant available water potential	m	–150	–150	–150	–150
IRM weighting of water (W_w)	–	2.0	2.1	2.5	2
IRM weighting of nutrients (W_N)	–	0.5	0.3	1	0.5
IRM weighting of CO ₂ (W_{CO_2})	–	1.42	1.42	1.42	1.42
Ratio of stomatal to mesophyll conductance	–	0.2	0.2	0.8	0.2
Temperature when growth is 1/2 of optimum	°C	7	15	20	7
Temperature when growth is optimum	°C	12	25	25	12
Julian day of germination	d	NA	NA	NA	120
Degree-daylight hours of growing season	°C hr	NA	NA	NA	16,000
Saturation light intensity	μmoles ⁻² d ⁻¹	1,000	1,000	2,000	1,000
Maximum rooting depth	m	1.5	3.9	1.5	1
Specific leaf area	LAI kg C ⁻¹	24	10	20	24
Leaf respiration coefficient	kg C kg C ⁻¹	0.001	0.001	0.0002	0.001
Stem respiration coefficient	kg C kg C ⁻¹	NA	0.0006	NA	NA
Root respiration coefficient	kg C kg C ⁻¹	0.001	0.0001	0.0002	0.0002
Leaf mortality rate	fraction of C d ⁻¹	0.005	0.0001	0.01	0.004
Above-ground partitioning factor	–	0.3	0.4	0.3	0.4
Aerodynamic resistance	s d ⁻¹	30.00	10	30	30
Crop harvest index	–	NA	NA	NA	NA
Crop harvest factor	–	NA	NA	NA	NA

^a Refers to the fraction of radiation not reflected by the canopy

^b Refers to the fraction of radiation not reflected by the soil

LAI leaf area index; IRM weighting weighting in the integrated rate methodology (Eq. 1); NA A parameter that is not defined for the specific vegetation type

Table 2 Parameters used to represent soils in the Broadbridge-White equation

Location Parameter	Units	Namoi		Howard East		Scottsdale				
		Topsoil	Subsoil	Topsoil	Subsoil	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Saturated hydraulic conductivity	m d ⁻¹	2.3	0.12	2.4	0.72	1.86	0.19	0.026	0.003	0.006
Inverse capillary length scale	m	0.04	0.2	0.075	0.375	0.05	0.1	0.5	1	1
Empirical moisture content	–	1.01	1.5	1.04	1.3	1.02	1.1	1.5	1.7	1.7
Saturated moisture content	m ³ /m ³	0.21	0.33	0.4	0.37	0.3	0.3	0.32	0.34	0.34
Residual moisture content	m ³ /m ³	0.07	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

model in WAVES is defined using the empirical model of Ball et al. (1987) as modified by Leuning (1995) to give:

$$g_s = \frac{g_0 + g_1 A}{\left[(c_s - \Gamma) \left(1 + \frac{D_c}{D_{c0}} \right) \right]} \quad (2)$$

where g_s is the leaf stomatal conductance, g_0 is the residual stomatal conductance, g_1 is an empirical coefficient, A is the carbon assimilation rate, c_s is the CO₂ mole fraction of the air at the canopy surface, Γ is the CO₂ compensation point, D_c is the vapour-pressure deficit at the canopy surface, and D_{c0} is an empirical coefficient. To determine the canopy resistance term used in the Penman-Montieth equation for transpiration, the inverse of leaf stomatal conductance is scaled from the leaf to canopy level to obtain (Sellers et al. 1992):

$$r_c = \left\{ \left(g_s LAI - \frac{g_1 ALAI - g_1 A}{[(c_s - \Gamma)(1 + D_c/D_{c0})]} \right) \frac{(1 - e^{-kLAI})}{k} \right\}^{-1} \quad (3)$$

where r_c is canopy resistance, LAI is leaf area index and k is a constant. It is shown that an increase in stomatal conductance results in a decrease in canopy resistance, allowing for greater transpiration which could lead to a decrease in recharge. As a change in atmospheric CO₂ concentrations could have an impact on processes important to the water balance, it is important to allow the model to reflect this. To allow for changes in CO₂ concentrations to be modelled, the WAVES code was altered so that the variables of CO₂ concentration and W_{CO_2} became parameters that were fixed for the duration of the model run.

The CO₂ concentration used for the 112-year historical sequence was 378 parts per million (ppm), as measured in 2006 (IPCC 2007). The IRM weighting factor for CO₂ (W_{CO_2}) used was 1.42 based on the work of Wong and Dunin (1987) and previous modelling of Hatton et al. (1992). Though this number was based on forest trees, it was assumed to be valid for use with all vegetation types.

Model inputs

The WAVES model requires three data sets as inputs: vegetation parameters, soil parameters, and climate variables on a daily time step. The vegetation was modelled to be perennial pasture in Namoi, a savannah in Howard

East, and an annual crop in Scottsdale. The values used for vegetation modelling are presented in Table 1 and are based on parameters taken from the ranges specified in the WAVES user manual for each specific vegetation type (Dawes et al. 1998). The soil data required were obtained using ASRIS 1 database (Johnston et al. 2003) and the analytical model of Broadbridge and White (1988). The parameters used in this model are presented in Table 2. All parameters for vegetation and soil were kept constant at each site for all model runs.

For the Namoi and Howard East sites, the soil profile was modelled with a 0.2-m topsoil layer, and a subsoil layer continuing to 4.0 m below ground level. At the Scottsdale site, five soil layers were utilised. Layer 1 extended from the surface to 0.2 m, layer 2 was 0.2–0.35 m, layer 3 was 0.35–0.7 m, layer 4 was 0.7–1.0 m and layer 5 was 1.0–4.0 m. The lower boundary condition of the model was set to be free draining. Recharge was assumed to be equal to all water that drained below the 4.0 m depth. This assumed that the water table was not important to diffuse recharge (i.e. water table deeper than 4 m). This boundary condition would not be valid if the water table was shallow, as recharge would have a shorter distance to travel through the unsaturated zone and would likely be increased.

The baseline recharge scenario was determined by running the model with the historical climate dataset. To test the impacts of climate change on recharge, the climate variables of the 112-year sequence were systematically changed. The altered variables were: CO₂ concentration, temperature, rainfall, vapour-pressure deficit, solar radiation, and rainfall intensity. This process allowed for a sensitivity analysis of the individual climate variables and to determine their relative effects on recharge.

The variables were changed over different ranges. CO₂ concentration was varied between 300 and 1,100 ppm

Table 3 Climate variables used to model multiple-variable sensitivity

Scenario	[CO ₂] (ppm)	Temperature (°C)	Solar radiation (%)	Rainfall (%)
Low	455	+1	–1	–10
				0
				+10
Med	760	+3	+0.5	–10
				0
				+10
High	1,062	+5	+2	–10
				0
				+10

Table 4 Results of baseline model scenarios

Location	Recharge (mm year ⁻¹)	Evaporation (mm year ⁻¹)	Transpiration (mm year ⁻¹)	Leaf area index (m ² m ⁻²)
Namoi	14	562	217	3.98
Howard East	281	706	598	1.36 (overstorey) 3.16 (understorey)
Scottsdale	233	307	652	2.79

compared to a baseline 2006 concentration of 378 ppm. This covered a range of pre-industrial levels through to a high emission prediction of the A1FI (a scenario that assumes population growth with a continued dependence on fossil fuels) scenario for 2100 of 1,062 ppm (IPCC 2007). Temperatures were increased from historical records by up to 5°C to cover a range between historical and the A1FI projection for 2100 (IPCC 2007). Rainfall was varied between -25 and +25%. Projections for Australia using the A1FI scenario suggest a change in rainfall of between -30 and +20% by 2070 (CSIRO and BOM 2007). Solar radiation in Australia is projected to vary between -1 and +2% by 2030, with larger magnitudes by 2050 and 2070 (CSIRO and BOM 2007). A

range between -5 and +5% was modelled. Whilst values for vapour-pressure deficit are not published, values for relative humidity are available. Vapour-pressure deficit is the saturated vapour pressure minus the actual vapour pressure, whilst relative humidity is the actual vapour pressure divided by the saturated vapour pressure. It is estimated that by 2030, changes in relative humidity will range from -2 to +0.5% (CSIRO and BOM 2007). A range in vapour-pressure deficit of -10 to +10% was modelled. Rainfall intensity was altered by applying various scaling factors to the rainfall depending on the magnitude. The scaling factor varied linearly according to the rank of the daily rainfall amount in the 112-year time series. Mean rainfall over the 112-year period was always

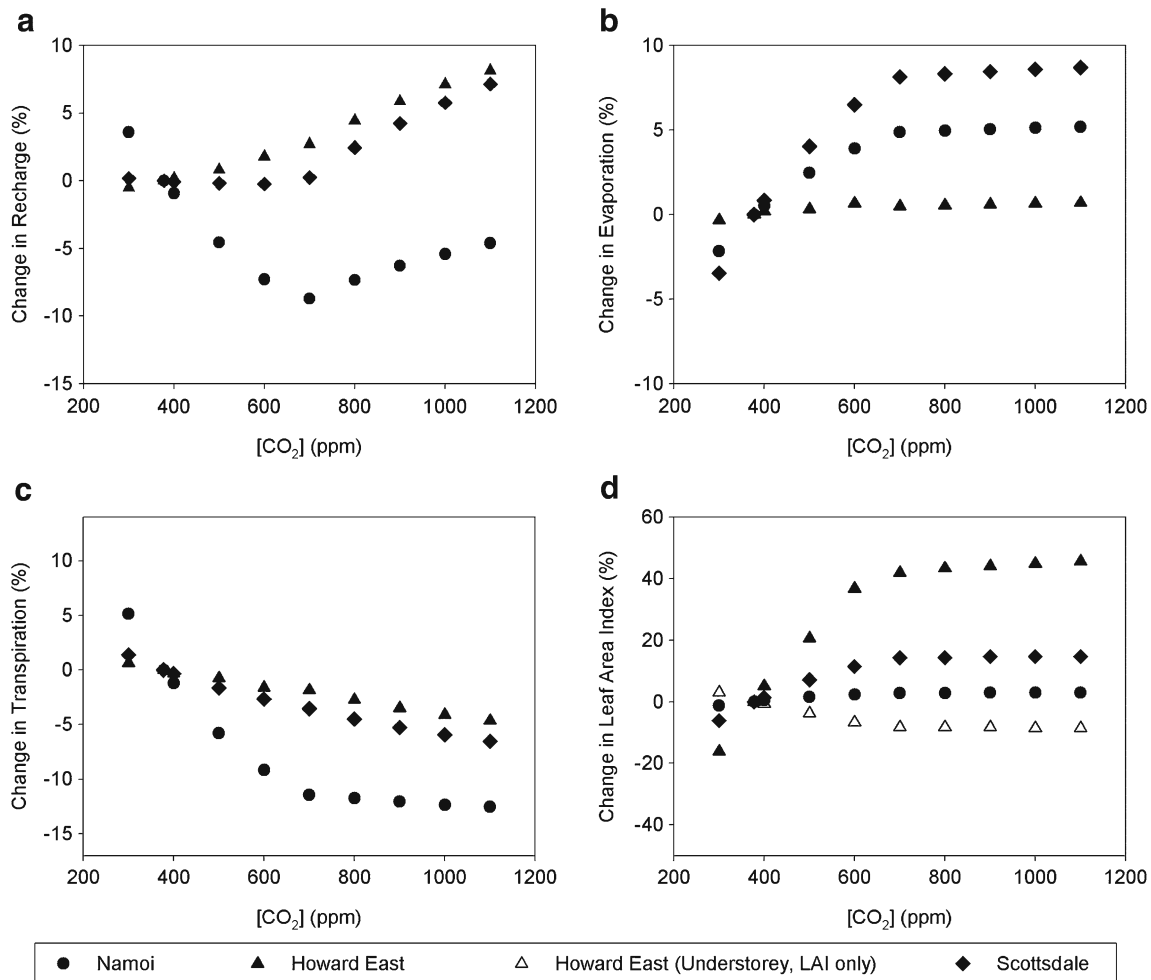


Fig. 2 Responses of modelled **a** recharge, **b** evaporation, **c** transpiration and **d** leaf area index to changes in CO₂ concentration with all other variables unchanged. Changes presented (for Figs. 3–7 also) are based on daily averages of the 112-year time series

preserved. For changes in first percentile rainfall greater than 1, values greater than the median rainfall were increased and values less than the median were decreased. The opposite was true for decreases in the first percentile of rainfall. The depths obtained from this were then scaled to ensure that the total depth of rainfall remained the same as for the baseline scenario, so the comparison was only for daily rainfall intensity.

Multiple-variable sensitivity

As it is unrealistic to assume that climate change will only alter individual variables, modelling was also undertaken to determine the effects of changing multiple climate variables simultaneously. These theoretical scenarios were chosen based on the ranges discussed previously (see section *Model inputs*). These ranges are presented in Table 3. Although these scenarios were not based on a specific GCM, they were selected based on the extremes of individual parameter sensitivity to try and capture the range of potential impacts of climate change on recharge. In addition to the changes listed, vapour-pressure deficit was also altered by recalculating the saturated vapour

pressure at higher temperatures and subtracting the observed vapour pressure from the new value.

Results and discussion

Results are presented as a percentage change from the 112-year baseline average water balance from the historical climate series. The results for the baseline scenarios are presented in Table 4. All results are presented as annual averages for the 112-year period. Recharge estimates in Namoi are lower than those predicted in a previous study by Berhane (2001; 14 mm year⁻¹ modelled compared to 56 mm year⁻¹); however, these estimates are not from the exact location. It also notable that the estimate made was for a single point in time and may not be comparable to long-term averages. Estimates of recharge in Howard East (281 mm year⁻¹ modelled compared to 200 mm year⁻¹) were comparable to those of Cook et al. (1998); however, this latter estimate was for a single point in time also. Estimates of recharge at Scottsdale were within the ranges specified by Harrington and Currie (2008; 233 mm year⁻¹ modelled compared to

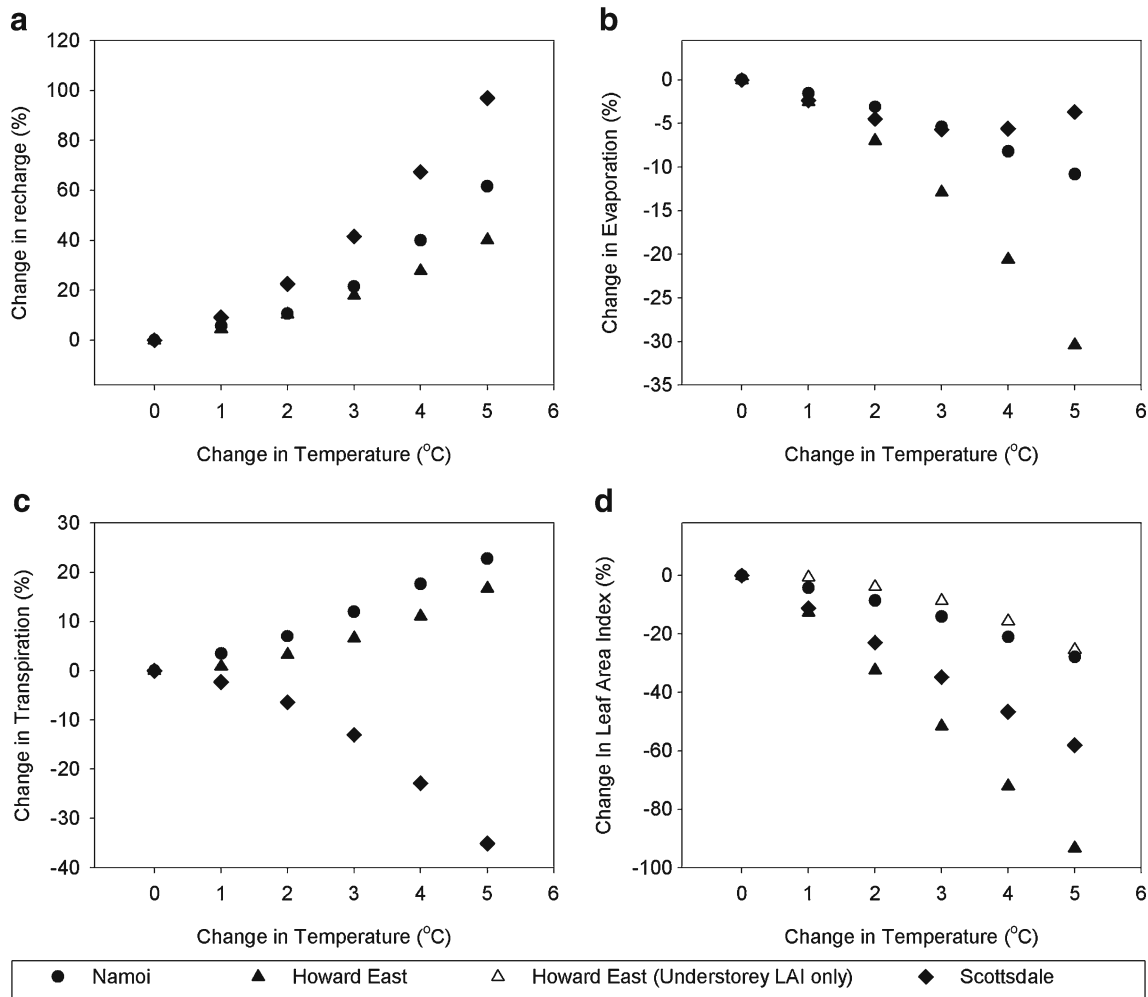


Fig. 3 Responses of modelled a recharge, b evaporation, c transpiration and d leaf area index to increases in temperature with other variables unchanged

an estimated range between 69 and 300 mm year⁻¹). Specifically, recharge numbers were similar to estimates made using a steady-state chloride mass balance of 150–300 mm year⁻¹. This method does predict time-averaged recharge.

Carbon dioxide

When investigating the effects of an increased carbon dioxide concentration on groundwater recharge, two key processes occur. Firstly, an increased carbon dioxide concentration increases leaf area, which may result in an increase in transpiration. Secondly, a decrease in stomatal conductance occurs resulting in a reduction in transpiration. Figure 2 indicates that for all locations transpiration, decreases as carbon dioxide increases. This is due to a reduction in stomatal conductance. Additionally, at all sites, excluding the understorey in Howard East, leaf area increases at a high rate for CO₂ concentrations less than approximately 700 ppm before stabilising. The difference with the understorey at Howard East is likely related to the overstorey, in that as leaf area increases in the overstorey, a significant amount of light is intercepted affecting the

understorey. The increase in leaf area also affects evaporation in that an increased amount of water is intercepted and subsequently evaporated by the vegetation. This also stabilises at CO₂ concentrations greater than 700 ppm consistent with LAI. All these factors are reflected in recharge. For the Namoi, the increases in leaf area index outweigh the effects of a reduction in stomatal conductance for CO₂ concentrations less than 700 ppm. After this point, as LAI and evaporation effects stabilise recharge increases. In Howard East, a similar trend is observed at CO₂ concentrations greater than 700 ppm; however, at lower CO₂ concentrations, recharge is also increased. For Scottsdale, recharge appears to be insensitive to CO₂ concentrations less than 700 ppm; however, increases are observed at higher concentrations. Overall, it is shown that changes in CO₂ concentrations independent of other climate variables could impact groundwater recharge. The increase in LAI and decrease in transpiration due to increased CO₂ concentration has been well studied (Ghannoum et al. 2001; Long et al. 2006; Pritchard et al. 1999; Ramirez and Finnerty 1996; Wand et al. 1999; Wand et al. 2001). These studies have shown that an increase in CO₂ concentration may lead to a

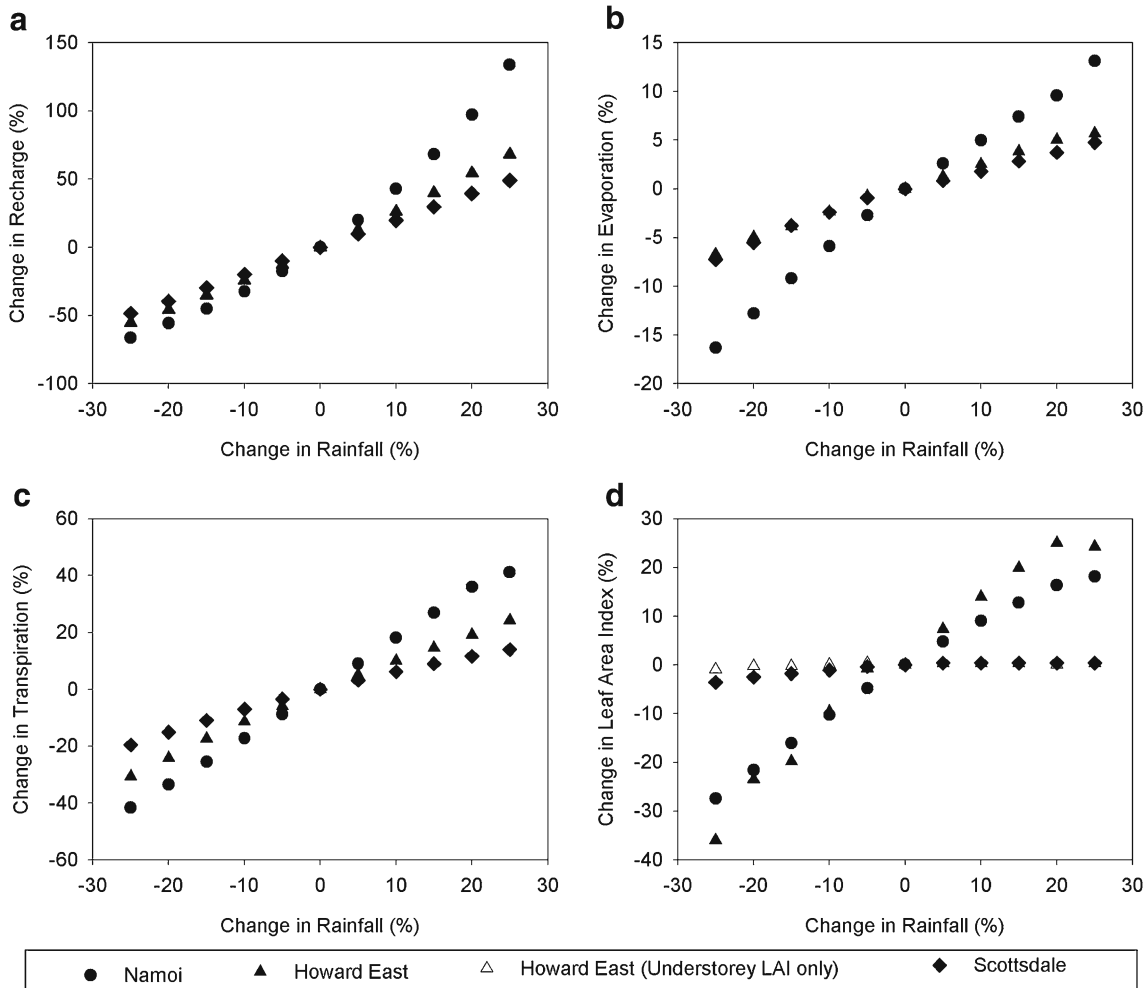


Fig. 4 Responses of modelled a recharge, b evaporation, c transpiration and d leaf area index to changes in rainfall with all other variables unchanged

decrease in transpiration due to a reduction in stomatal conductance; however, carbon assimilation is also increased leading to an increase in LAI.

Temperature

Changes in temperature have a significant impact on most aspects of the water balance (Fig. 3). All sites show an increase in recharge with increasing temperature. This is consistent with changes hypothesised by Cartwright and Simmonds (2008). This is apparently due to decreases in evaporation; however, this should be observed with caution. Leaf area index of both the Howard East overstorey and the pastures at Scottsdale show significant reductions. While LAI did not reach $0 \text{ m}^2 \text{ m}^{-2}$ during the model runs, it was severely reduced by implementing a constant increase in temperature. Additionally, Scottsdale results reflect both a decrease in leaf area index and the number of growing days. For example, in the baseline scenario, the average number of growth days per year is 172 as opposed to 117 for a 5°C increase. It is likely that under such situations, some form of vegetation change

would occur. In Howard East, this may be due to natural ecological succession. In Scottsdale, this would likely be due to cropping changes driven by economics. It is not within the scope of this study to investigate such possibilities; however, this should be considered when interpreting these results. Although these results suggest that an increase in temperature would result in an increase in recharge, it is sensible to think that vegetation may change making this scenario unlikely at the extreme end.

Rainfall

Increases in rainfall result in increases in recharge at all sites despite increases in evaporation and transpiration (Fig. 4). Decreases in rainfall also result in decreases in recharge, evaporation and transpiration. Leaf area index follows the same trend but at different magnitudes in the various locations. In Namoi and for the overstorey in Howard East, changes are fairly significant, whereas for Scottsdale and the Howard East understorey, changes are quite mild.

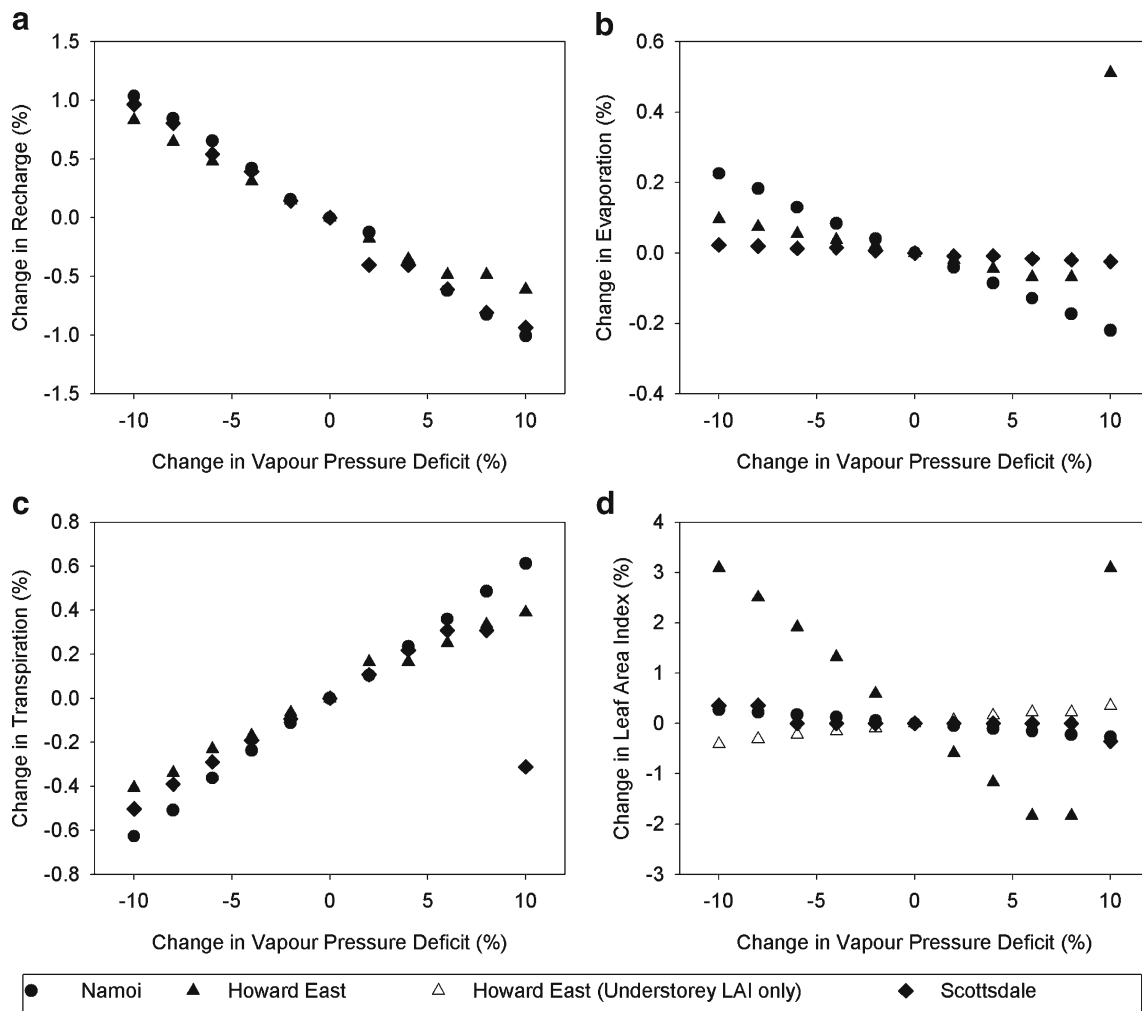


Fig. 5 Responses of modelled a recharge, b evaporation, c transpiration and d leaf area index to changes in vapour-pressure deficit with all other variables unchanged

Vapour-pressure deficit

Changes in recharge due to changes in vapour-pressure deficit are minimal when compared to other climate factors (Fig. 5). A decrease in recharge occurs at all locations for an increase in vapour-pressure deficit which appears to be driven by an increase in transpiration. Evaporation and leaf area index decrease with increasing vapour-pressure deficit (this excludes the understorey in Howard East, which is likely related to feedbacks from an increase in overstorey LAI, as discussed in the previous). It is likely that the two are related in that a reduced LAI reduces the amount of water intercepted and subsequently evaporated.

Solar radiation

Increases in solar radiation produce a decrease in recharge at all locations (Fig. 6). Whilst changes in leaf area index and transpiration are inconsistent between the sites, an increase in evaporation is observed at all locations. This is the likely cause of decreasing recharge. Of most interest is Namoi, where transpiration shows an opposite trend to

other locations. Here, LAI is unchanged by the change in solar radiation. It is shown that changes in solar radiation could have an effect on recharge.

Changes in rainfall intensity

Changes in recharge due to changes in first percentile rainfall show varied responses (Fig. 7). In all locations, both evaporation and transpiration decrease, which would indicate excess water for recharge. Recharge increases at both the Namoi and Howard East sites. At Scottsdale, recharge decreases by a small amount. It is believed that this is due to runoff. WAVES simulates Hortonian runoff (when available water exceeds infiltration capacity), which can lead to runoff in duplex soils even with the free draining lower boundary condition. Table 2 shows that there are significant changes in hydraulic conductivity with depth which supports this. The changes in recharge are quite significant in the other two cases. This suggests that changes in the daily distribution of rainfall can cause significant changes in recharge even if the overall volume of rainfall is unchanged.

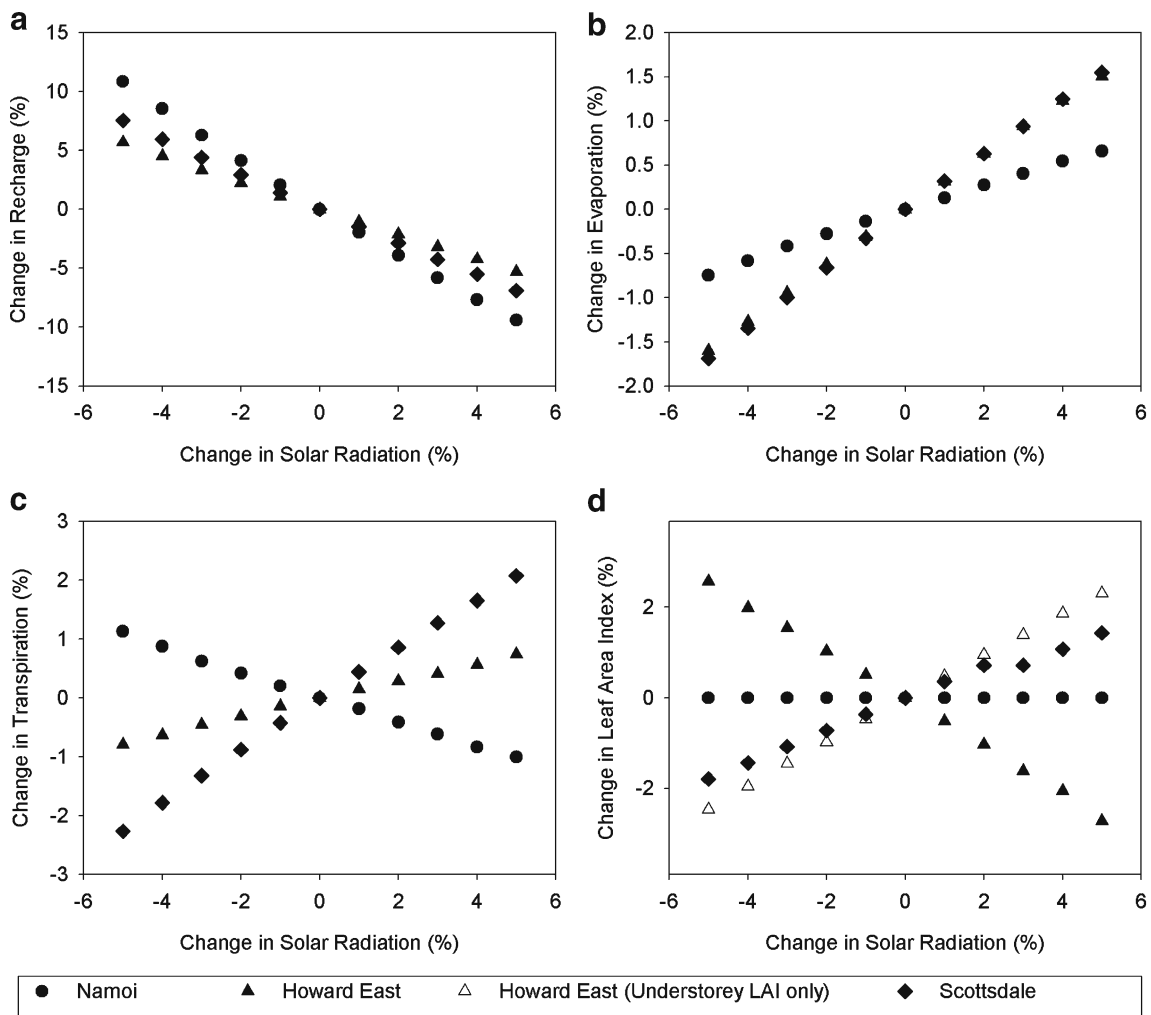


Fig. 6 Responses of modelled a recharge, b evaporation, c transpiration and d leaf area index due to changes in solar radiation with all other variables unchanged

Multiple-variable sensitivity

The results of changing multiple climate variables are presented in Fig. 8. For scenarios that do not include changes to rainfall, recharge appears to be higher than it would be if only CO₂ concentrations were altered.

Temperature increases appear to lead to increases in recharge when rainfall is not altered. In Scottsdale and Namoi, these changes appear to be less than what would be expected if only temperatures were altered. At the Howard East site, changes appear to be quite similar to changes that would be observed if no other parameter were varied. This may indicate that, in this location, temperature is the control (this is likely due to changes in vegetation at this site).

Recharge appears to increase with solar radiation, which is inconsistent with results when solar radiation is altered independently of other variables. It appears though that the slight drop in recharge for Namoi between the low and medium scenario could be due to changes in solar radiation. Outside of this, the overall changes appear uncorrelated to the changes that would be expected if only solar radiation was changed.

A good correlation to altering only rainfall was observed when altering multiple climate variables. Despite a good correlation, it appears that recharge is nearly always greater than would be expected just accounting for rainfall. The exception to this is for low and medium scenarios in Namoi. Of the three sites modelled, this location has the highest discrepancy between annual rainfall and potential evapotranspiration. This site may be less sensitive to the other changes than to rainfall due to water being a limiting factor in this environment. Also of interest is that for the high and medium scenarios in Scottsdale, and the high scenario at Howard East, recharge appears to increase even when rainfall decreases. This is consistent with the findings of Crosbie et al. (2010), who observed that modelled recharge could increase even when rainfall projected from a GCM decreased.

Relative importance of climate variables

With respect to the altering of single variables, rainfall, temperature and rainfall intensity (with the exception of

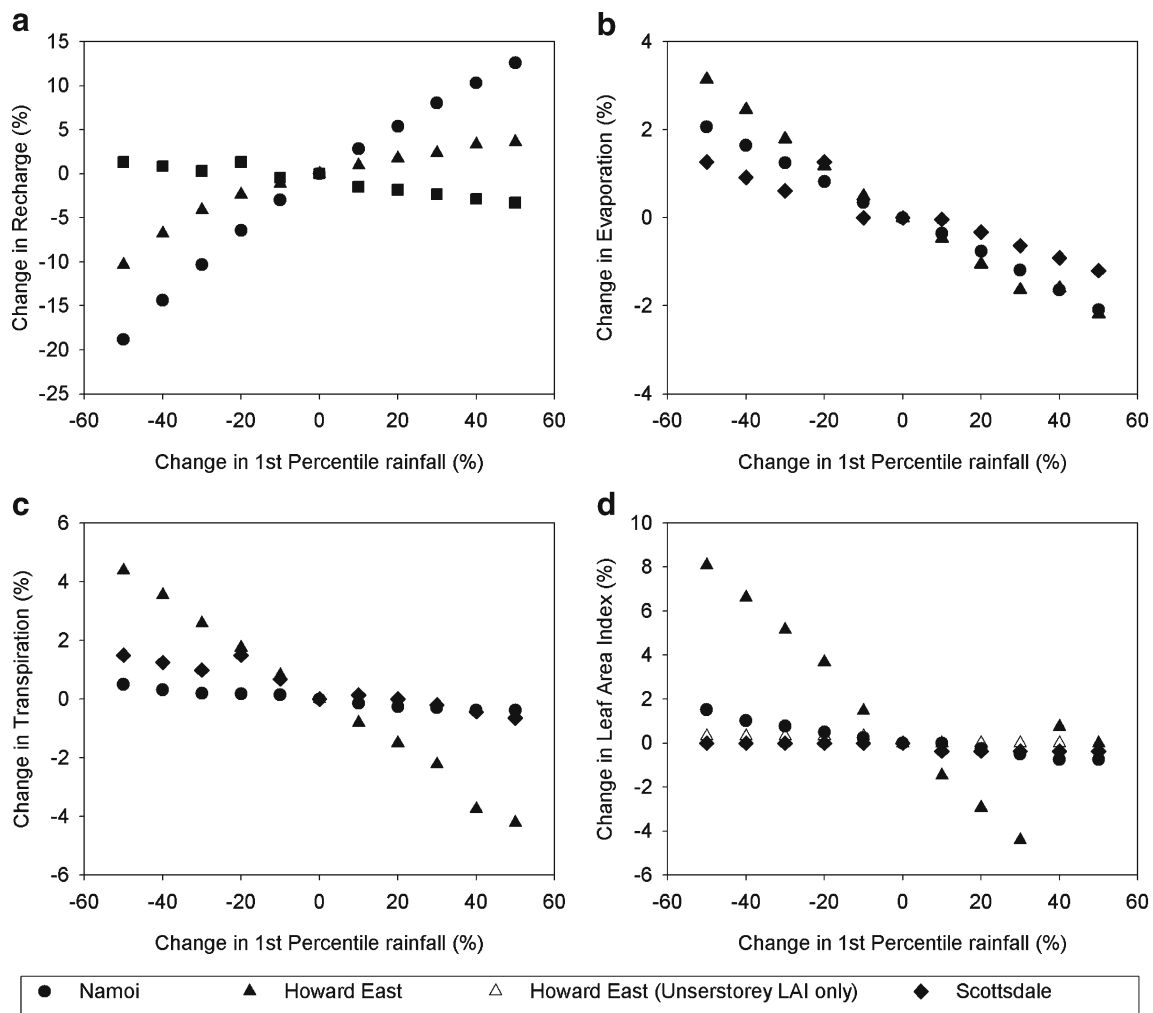


Fig. 7 Responses of modelled **a** recharge, **b** evaporation, **c** transpiration and **d** leaf area index due to changes in 1st percentile rainfall with all other variables unchanged

Scottsdale) seem to have the largest impact on recharge. Rainfall is consistently important but in Howard East and Scottsdale, significant changes to vegetation due to temperature have quite a large impact on recharge; however, as stated previously, these scenarios would be unlikely. Carbon dioxide concentration and solar radiation also have some effect; however, the changes do not appear as large. Changes in vapour-pressure deficit are quite minor. When variables are altered simultaneously, different sites show different trends.

For a climate where CO₂ concentration, temperature and solar radiation are altered and rainfall is left the same, trends do not seem to follow those of any one variable with the exception of temperature relationships in Howard East. This would suggest that all variables contribute to the observed changes. In general, recharge increases from the low to high scenario. The exception to this is the medium scenario for Namoi which suggests a slightly lower recharge than for the low scenario. This could be

due to reductions in recharge due to increasing CO₂ concentrations or solar radiation at this site, consistent with single parameter results.

Of note is the importance of rainfall when altered with other variables. The changes in recharge when all variables are altered are well correlated to changes when only rainfall is altered. This is consistent with the findings of individual parameter testing that indicated that rainfall caused the most significant change. The recharge expected due to rainfall, however, is nearly always exceeded, which suggests that other variables contribute to changes in recharge.

Implications for recharge estimates

It has been demonstrated that the process of diffuse groundwater recharge is quite complex and affected by multiple climate factors. Whilst it would be practical to scale recharge with data available readily from GCMs, it would appear that this may not be appropriate. For

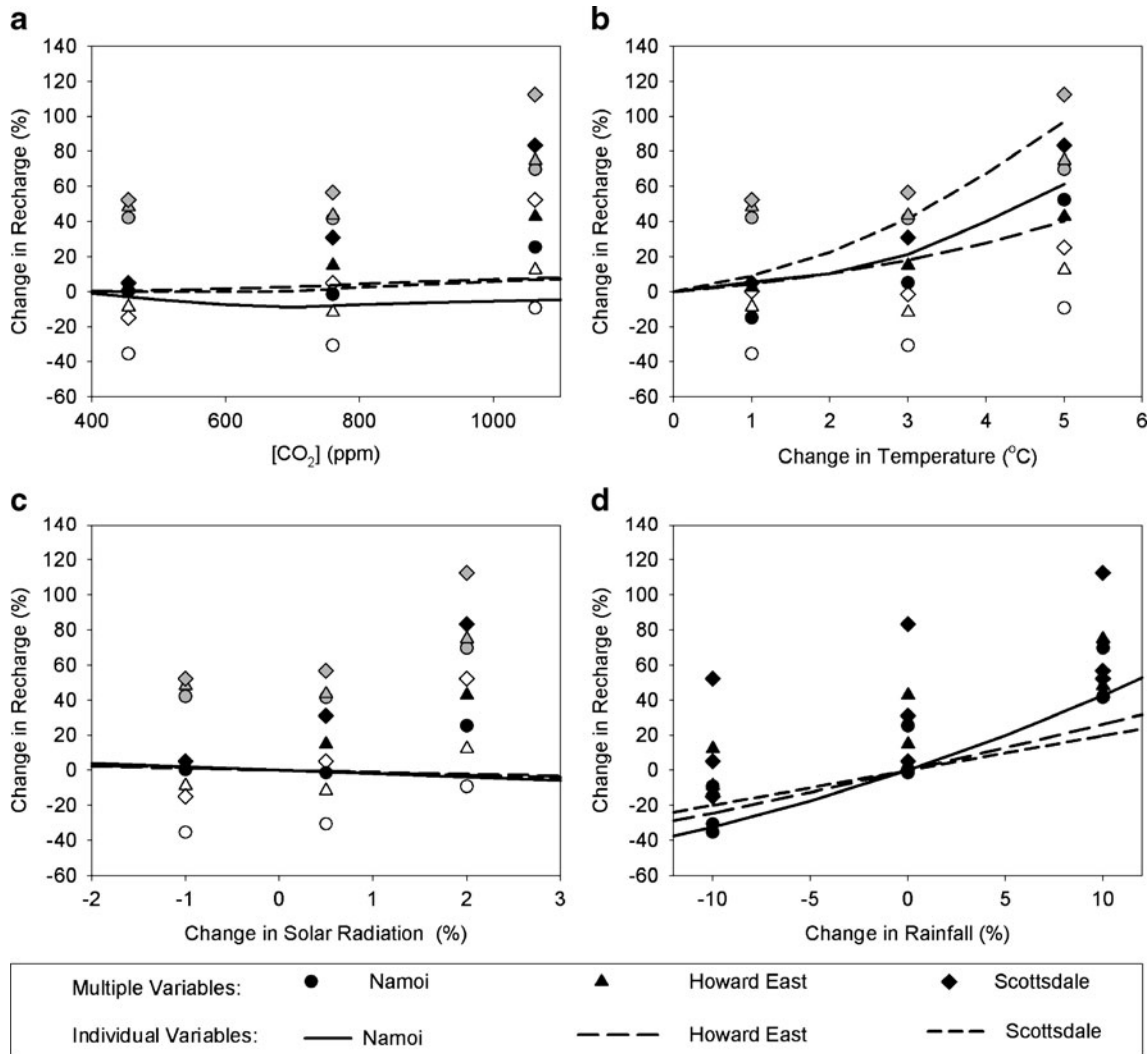


Fig. 8 Responses of modelled recharge when altering variables from the 112-year historical scenario: **a** CO₂, **b** temperature, **c** solar radiation and **d** rainfall. *Symbols* represent the results of altering multiple variables. *Solid* symbols indicate scenarios where rainfall has not been changed, *hollow* symbols indicate scenarios where rainfall has also been reduced and *gray* symbols represent scenarios where rainfall has been increased. *Lines* represent the change that would occur if individual variables were altered

example, if only changes in rainfall were considered, it is likely that changes in recharge would be estimated incorrectly. Additionally, if potential evapotranspiration were used, this may not account for the full feedbacks of the system (the results indicate that evaporation and transpiration are affected in different ways). Ideally, all the interactions between vegetation, soil and climate would be modelled to account for how climate change will affect groundwater recharge. This would provide a much better estimate of how diffuse groundwater recharge is projected to change under a changed climate.

Limitations

Whilst this study has investigated a number of climate variables, there are some limitations to this work. The impact of changes in seasonality has not been considered, as all variables were augmented by the same fraction or absolute value. Changes to variables related to plant growing seasons would likely have some impact on plant water use resulting in changes to recharge.

As stated in the previous, the issue of ecological succession was not investigated. This has been investigated by Lasch et al. (2002). They found, through simulations with a forestation model, that there was a shift in natural vegetation composition to more drought tolerant species. Changes in vegetation type due to changes in climate in Australia were also investigated by Donohue et al. (2009). It was observed that there has been a trend over recent decades for more persistent vegetation and less recurrent vegetation independent of rainfall. (This is consistent with the findings of differing changes to leaf area index for the understorey and overstorey at the Howard East site.) It was speculated that this was due to increasing CO₂ concentrations. Different vegetation types would have different water-use properties and, therefore, predicting the effects on recharge due to this is not simple. It is fair to reiterate, however, that for extreme scenarios, where temperature is increased by more than two degrees, the results reported here are unlikely to represent an actual future climate as vegetation and crop types may change.

Although the effects of changing the magnitude of events has been investigated, the effects of changing the frequency of events (where the time between events is altered) has not been investigated. This could have significant impacts on both recharge and vegetation.

Additionally, changes using a one-dimensional model have been simulated, better results would be obtained from a holistic approach to simulating the water cycle. Changes in runoff and groundwater levels will provide important feedback to the recharge process, and on a more important scale, water resources as a whole.

Conclusion

The unsaturated-zone-model WAVES was used to investigate how projected changes to climate variables based on

climate change may impact on diffuse groundwater recharge. Through altering individual variables it was found that:

- Increases in CO₂ concentrations could result in changes to recharge of the order of 10%.
- Increases in temperature are likely to result in substantial increases to recharge; however, this may be negated by land use change or ecological succession.
- A 1% change in rainfall results in approximately a 2% change in recharge; however, this may be amplified in water limited environments
- Changes in recharge due to changes in vapour-pressure deficit are fairly minor, with a 10% increase only decreasing recharge by 1%.
- Changes in recharge due to solar radiation show that recharge decreases 1–2% for a 1% increase in solar radiation.
- Changes in recharge due to changes in rainfall intensity are specific to the environment being modelled.

When multiple climate variables are altered, changes in recharge appear to follow trends in rainfall; however, the predicted recharge appears to be always larger than would be expected from just accounting for changes in rainfall. The role of all climate variables should be considered when projecting changes in recharge due to changes in climate. This has implications for how GCM outputs are used to project changes in diffuse groundwater recharge.

Acknowledgements This work is part of the Murray-Darling Basin Sustainable Yields project that was funded by the National Water Commission. The authors wish to thank G. Harrington, R. Silberstein, X. Zhang, N. Tuteja, I. Cartwright and two anonymous reviewers for reviews of this manuscript.

References

- Allen DM, Mackie DC, Wei M (2004) Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. *Hydrogeol J* 12(3):270–290
- Arnold JG, Srinivasan R, Mutiah RS, Williams JR (1998) Large area hydrologic modeling and assessment, part 1: model development. *J Am Water Resour Assoc* 34(1):73–89
- Ball JT, Woodrow IE, Berry JA (1987) A model predicting stomatal conductances and its contribution to the control of photosynthesis under different environmental conditions. In: Nijhoff M (ed) *Progress in photosynthesis research*. Dordrecht, The Netherlands, pp 221–224
- Berhane D (2001) Groundwater recharge estimation for zone 7: Upper Namoi Alluvium Groundwater Management area. Department of Land and Water Conservation Centre for Natural Resources, Gunnedah, Australia
- Bouraoui F, Vachaud G, Li LZ, Le Treut H, Chen T (1999) Evaluation of the impact of climate changes on water storage and groundwater recharge at the watershed scale. *Clim Dynam* 15(2):153–161
- Broadbridge P, White I (1988) Constant rate rainfall infiltration: a versatile nonlinear model. 1. Analytic solution. *Water Resour Res* 24(1):145–154
- Brouyère S, Carabin G, Dassargues A (2004) Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. *Hydrogeol J* 12(2):123–134

- Cartwright I, Simmonds I (2008) Impact of changing climate and land use on the hydrogeology of southeast Australia. *Aust J Earth Sci* 55(8):1009–1021
- Cook PG et al (1998) Water balance of a tropical woodland ecosystem, Northern Australia: a combination of micro-meteorological, soil physical and groundwater chemical approaches. *J Hydrol* 210:161–177
- Crosbie RS, Wilson B, Hughes JD, McCulloch C, King WM (2008) A comparison of the water use of tree belts and pasture in recharge and discharge zones in a saline catchment in the Central West of NSW, Australia. *Agric Water Manage* 95(3):211–223
- Crosbie RS, McCallum JL, Walker GR, Chiew FHS (2010) Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. *Hydrogeol J*. doi:10.1007/s10040-010-0625-x
- CSIRO and BOM (2007) Climate change in Australia. Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Canberra, Australia
- Dawes WR, Gilfedder M, Stauffacher M, Coram J, Hajkovicz S, Walker GR, Young M (2002) Assessing the viability of recharge reduction for dryland salinity control: Wanilla, Eyre Peninsula. *Aust J Soil Res* 40(8):1407–1424
- Dawes W, Zhang L, Dyce P (1998) WAVES V3.5 user manual. CSIRO Land and Water, Canberra, Australia
- Donohue RJ, McVicar TR, Roderick ML (2009) Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. *Glob Change Biol* 15(4):1025–1039
- Eckhardt K, Ulbrich U (2003) Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *J Hydrol* 236:244–252
- Ghannoum O, Caemmerer S, Conroy JP (2001) Plant water use efficiency of 17 Australian NAD-ME and NADP-ME C4 grasses at ambient and elevated CO₂ partial pressure. *Aust J Plant Physiol* 28(12):1207–1217
- Green TR, Bates BC, Charles SP, Flemming MP (2007) Physically based simulation of potential effects of carbon dioxide-altered climates on groundwater recharge. *Vadose Zone J* 6(3):597–609
- Harrington GA, Currie D (2008) Development of models for tasmanian groundwater resources: conceptual model report for Scottsdale. Resource and Environmental Management, Adelaide, Australia
- Hatton TJ, Walker J, Dawes WR, Dunin FX (1992) Simulations of hydroecological responses to elevated CO₂ at the catchment scale. *Aust J Bot* 40(5):679–696
- Hsu KC, Wang CH, Chen KC, Chen CT, Ma KW (2007) Climate-induced hydrological impacts on the groundwater system of the Pingtung Plain, Taiwan. *Hydrogeol J* 15(5):903–913
- Hutley LB, O'Grady AP, Eamus D (2000) Evapotranspiration from Eucalypt open-forest savanna of Northern Australia. *Funct Ecol* 14(2):183–194
- IPCC (2007) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environ Model Softw Environ Data News* 16(4):309–330
- Johnston RM et al (2003) ASRIS: the database. *Aust J Soil Res* 41(6):1021–1036
- Kirshen PH (2002) Potential impacts of global warming on groundwater in eastern Massachusetts. *J Water Resour Plann Manage* 128(3):216–226
- Lasch P, Lindner M, Erhard M, Suckow F, Wenzel A (2002) Regional impact assessment on forest structure and functions under climate change: the Brandenburg case study. *For Ecol Manage* 162(1):73–86
- Leuning R (1995) A critical appraisal of combined stomatal-photosynthesis model for C3 plants. *Plant Cell Environ* 18:339–355
- Loaiciga HA, Maidment DR, Valdes JB (2000) Climate-change impacts in a regional karst aquifer, Texas, USA. *J Hydrol* 227:173–194
- Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR (2006) Food for thought: lower-than-expected crop yield simulation with rising CO₂ concentrations. *Science* 312:4
- Petheram C, Walker G, Grayson R, Thierfelder T, Zhang L (2002) Towards a framework for predicting impacts of land-use on recharge: 1, a review of recharge studies in Australia. *Aust J Soil Res* 40(3):397–417
- Pritchard SG, Rogers HH, Prior SA, Peterson CM (1999) Elevated CO₂ and plant structure: a review. *Glob Change Biol* 5:30
- Ramirez JA, Finnerty B (1996) CO₂ and temperature effects on evapotranspiration and irrigated agriculture. *J Irrig Drainage Eng* 122(3):155–163
- Rosenberg NJ et al (1999) Possible impacts of global warming on the hydrology of the Ogallala Aquifer Region. *Climatic Change* 42(4):677–692
- Salama R, Hatton T, Dawes W (1999) Predicting land use impacts on regional scale groundwater recharge and discharge. *J Environ Qual* 28(2):446–460
- Sellers PJ, Berry JA, Collatz GL, Field CB, Hall FG (1992) Canopy reflectance, photosynthesis and transpiration, part III: a reanalysis using enzyme kinetics—electron transport models of leaf physiology. *Remote Sens Environ* 42:187–216
- Slavich PG, Walker GR, Jolly ID, Hatton TJ, Dawes WR (1999) Dynamics of Eucalyptus largiflorens growth and water use in response to modified watertable and flooding regimes on a saline floodplain. *Agric Water Manage* 39(2–3):245–264
- Smith M et al (1992) Expert consultation on revision of FAO methodologies for crop water requirements. FAO, Rome
- Wand SJE, Midgley GF, Jones MH, Curtis PS (1999) Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO₂ concentration: a meta-analytic test of current theories and perceptions. *Glob Change Biol* 5(6):19
- Wand SJE, Midgley GF, Stock WD (2001) Growth responses to elevated CO₂ in NADP-ME, NAD-ME and PCK C4 grasses and a C3 grass from South Africa. *Aust J Plant Physiol* 28(1):13–25
- Wang HX, Zhang L, Dawes WR, Liu CM (2001) Improving water use efficiency of irrigated crops in the North China Plain - measurements and modelling. *Agric Water Manage* 48(2):151–167
- Woldeamlak ST, Batelaan O, De Smedt F (2007) Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium. *Hydrogeol J* 15(5):891–901
- Wong SC, Dunin FX (1987) Photosynthesis and transpiration of trees in a Eucalypt forest stand: CO₂, light and humidity responses. *Funct Plant Biol* 14(6):619–632
- Wu H, Rykiel EH, Hatton TJ, Walker J (1994) An integrated rate methodology (IRM) for multi factor growth rate modelling. *Ecol Model* 73:97–116
- Xu C, Martin M, Silberstein R, Smetten K (2008) Identifying sources of uncertainty in groundwater recharge estimates using the biophysical model WAVES, Water Down Under, Adelaide, Australia
- Yang YH, Watanabe M, Wang ZP, Sakura Y, Tang CY (2003) Prediction of changes in soil moisture associated with climatic changes and their implications for vegetation changes: Waves model simulation on Taihang Mountain, China. *Clim Change* 57(1–2):163–183
- York JP, Person M, Gutowski WJ, Winter TC (2002) Putting aquifers into atmospheric simulation models: an example from the Mill Creek Watershed, northeastern Kansas. *Adv Water Resour* 25(2):221–238
- Zhang L, Dawes W (1998) WAVES: an integrated energy and water balance model. CSIRO Land and Water, Canberra, Australia
- Zhang L, Dawes WR, Hatton TJ (1996) Modelling hydrologic processes using a biophysically based model—application of WAVES to FIFE and HAPEX-MOBILHY. *J Hydrol* 185(1–4):147–169
- Zhang L, Dawes WR, Hatton TJ, Hume IH, O'Connell MG, Mitchell DC, Milthorpe PL, Yee M (1999) Estimating episodic recharge under different crop/pasture rotations in the Mallee region. Part 2. Recharge control by agronomic practices. *Agric Water Manage* 42(2):237–249