CHAPTER 10

# Groundwater change in the Murray basin from long-term in-situ monitoring and GRACE estimates

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ABSTRACT

We present observations of groundwater change in a key, semi-arid, agricultural region of Australia, the Murray Groundwater Basin. Time series of in-situ groundwater levels archived in Government databases were compiled for all the States sharing this groundwater basin. A high quality subset of this dataset in a region affected by dryland salinity provides long-term in-situ observations on the respective impact of (1) increased recharge after deforestation and (2) the recent multi-year drought on groundwater levels. A change in the long-term dynamic of the water table is observed since the beginning of the drought in 1997 (1994 in some regions). The analysis of the bore data first showed a regional rise of the water table by ~5 cm/a from 1980 to 1992 followed by a regional decline at a rate of 17 cm/a from 1997 to 2009. Time series of groundwater storage anomalies obtained from a combination of total water storage using space gravimetry (GRACE) and soil moisture estimates from hydrological models also indicate a strong decline of the water table from 2002 to 2010. From August 2002 to December 2010, GRACE-based estimates indicate a groundwater loss of ~18 ± 1.3 mm/a which equates to a total loss of groundwater of ~45 ± 3 $km^3$ over the ~300,000 $km^2$ hydrogeological basin. These observations suggest that the impact of the drought on groundwater recharge counterbalanced and surpassed the impacts of past land-clearing and has brought a temporary halt to dryland salinity.

## 10.1 INTRODUCTION

### 10.1.1 Purpose and scope

The Murray Groundwater Basin is a very valuable but equally sensitive water resource that covers about a third of the Murray-Darling drainage basin (Fig. 10.1). There are two main pressing issues relating to groundwater management in this region. First, increased groundwater recharge inherited from the historical clearing of the region continues to influence groundwater levels leading to dryland salinity in many areas. Second, the demand for groundwater is currently increasing, mostly to paliate for the low reliability of surface water resources. However, sustainable yields are already exceeded in some aquifers and it is not well known how resilient the aquifers of the region are to prolonged droughts. The main aim of this study is to provide long-term observations of groundwater dynamics in the Murray Groundwater Basin. These observations are then used to estimate the respective impact from past land clearing and the recent drought on groundwater resources in the basin. For this we used two main sources of information: (1)

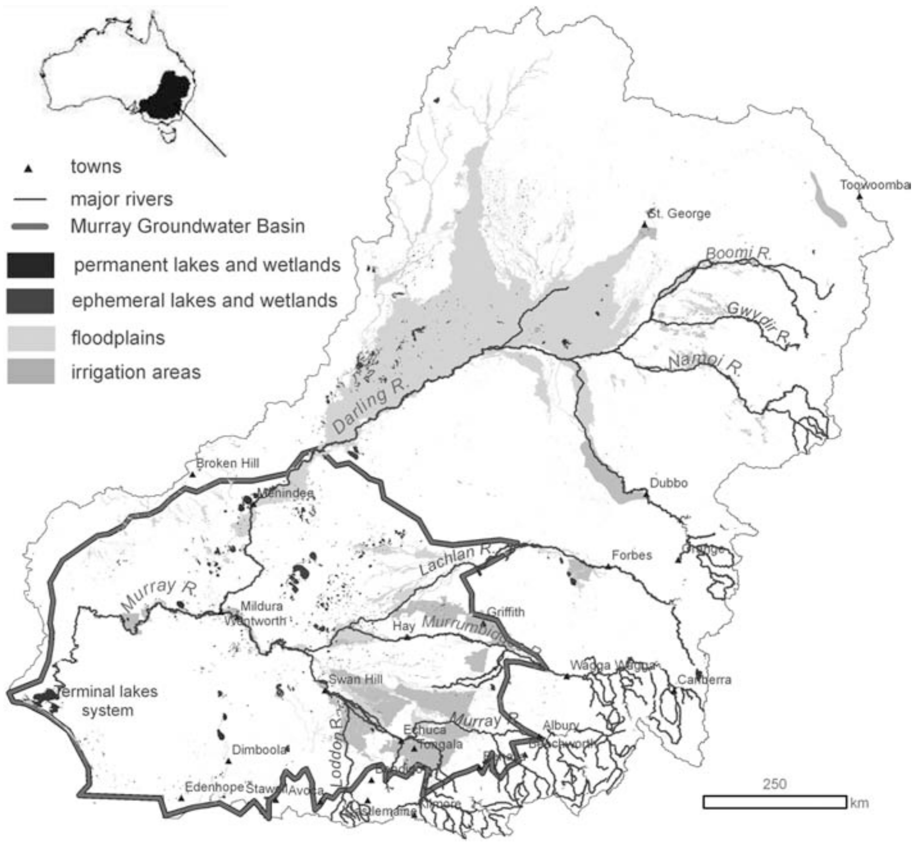


Figure 10.1. Location of the Murray Groundwater Basin in the Murray-Darling drainage Basin, Australia.

in-situ point observations of groundwater levels at monitoring bores and (2) regional estimates of variations in water storage from space gravimetry GRACE (GRGS) and a hydrological model (GLDAS).

### 10.1.2 Study area description

***Water resources in the Murray-Darling Basin***

The Murray-Darling Basin (MDB) covers 1.06 M km$^2$ or approximately one-seventh (14%) of Australia (Fig. 10.1). The topography of the MDB is dominated by vast plains, bounded to the east and south by the Great Dividing Range that has undulating hills reaching an elevation of up to ~2200 m above sea level. The MDB is the nation's food bowl; agriculture is the dominant economic activity covering ~80% of the basin and accounting for ~40% of Australia's total agricultural production (Pink 2008). Land use across the basin is dominated by farming land (67%), native and plantation forests. The main agricultural activity is livestock production (cattle and sheep) while other key land uses include irrigated dairy, cotton, rice, wheat, corn, and horticulture (grapes, citrus and other fruit trees). There is a wide range of climatic conditions in the MDB that follow north-south and east-west gradients. In the eastern uplands (Great Dividing Range), the climate varies from temperate in the south to mountainous and subtropical in the north. The vast plains of the west, which occupy most of the MDB, have a hot semi-arid to arid climate. Rainfall is summer dominated in the north and winter dominated in the south. Fig. 10.2 shows the spatial distribution of mean annual rainfall across the MDB and highlights the strong influence of the topography (high rainfall along Great Dividing Range to the east). The inter-annual variability in rainfall is noticeably large (Fig. 10.2).

After European settlement in the early 1800s, much of the land in the MDB was cleared for new farming areas. Land clearing was associated with an increase in drainage and groundwater recharge, resulting in a subsequent rise of the water table. For example, in the south-eastern Murray Groundwater Basin, where annual rainfall is between 600–800 mm, groundwater recharge increased from <1 to 4–90 mm/a after land clearance (Cartwright et al. 2007). In areas of secondary salinity, saline water is remobilised and brought to the surface by the rising water table or by lateral flow in the unsaturated zone. This can lead to the degradation of soil and surface water resources through the formation of salt scalds at the surface and increased river salinity (Fig. 10.3). Land clearance in much of the MDB happened more than 50–100 years ago but, due to the slow nature of unsaturated zone and groundwater flow, human induced salinization has continued to expand. Affected land in the MDB (not necessarily all in the MDB) was estimated at 640,000 ha in 1997 (NLWRA 1997). Such widespread impacts mean that in addition to the degradation of water and land resources, the consequent impacts from dryland salinity, including economic (decline in capital value of land and infrastructure damage) and biodiversity (loss of flora and habitats for fauna) costs, are felt at both local and regional levels (ANRA 2010). Some catchment mitigation strategies for salinity have involved revegetation of agricultural areas and saline groundwater interception schemes.

### *The Murray Groundwater Basin*

The MB is a closed groundwater basin covering an area of ~300,000 km$^2$ (Brown 1989). The groundwater flows towards the Murray River, which acts as the only outlet for groundwater transport from the basin (Evans and Kellett 1989). The saucer-shaped basin comprises 200–600 m of Cainozoic unconsolidated sediments and sedimentary rocks forming the major aquifers; Renmark Group, Murray Group, Pliocene Sands and Shepparton Formation (Evans and Kellett 1989). In this study we examine three of these aquifers (Murray Group, Pliocene Sands and Shepparton Formation), in regions where they are the water table aquifers. The extent of these water table aquifers are presented in Fig. 10.4a, and a cross-section illustrating the relationship between the different aquifers of the Murray Basin is shown in Fig. 10.4b.

### *Pliocene Sands Aquifers*

In the western region of the MB the Pliocene Sands aquifer is the Loxton-Parilla Sands, and in the east it is the Calivil Formation. The generally unconfined aquifer of the Loxton-Parilla Sands comprises fine to medium sand with minor clay and silt, and averages 60 m in thickness (Evans and Kellett 1989). In the north-western MB this aquifer is confined in areas by the overlying Quaternary Blanchetown clay (Evans and Kellett 1989). The upper parts of the Loxton-Parilla Sands laterally grade into the Shepparton Formation in the eastern MB. The Loxton-Parilla Sands also overly and laterally grade

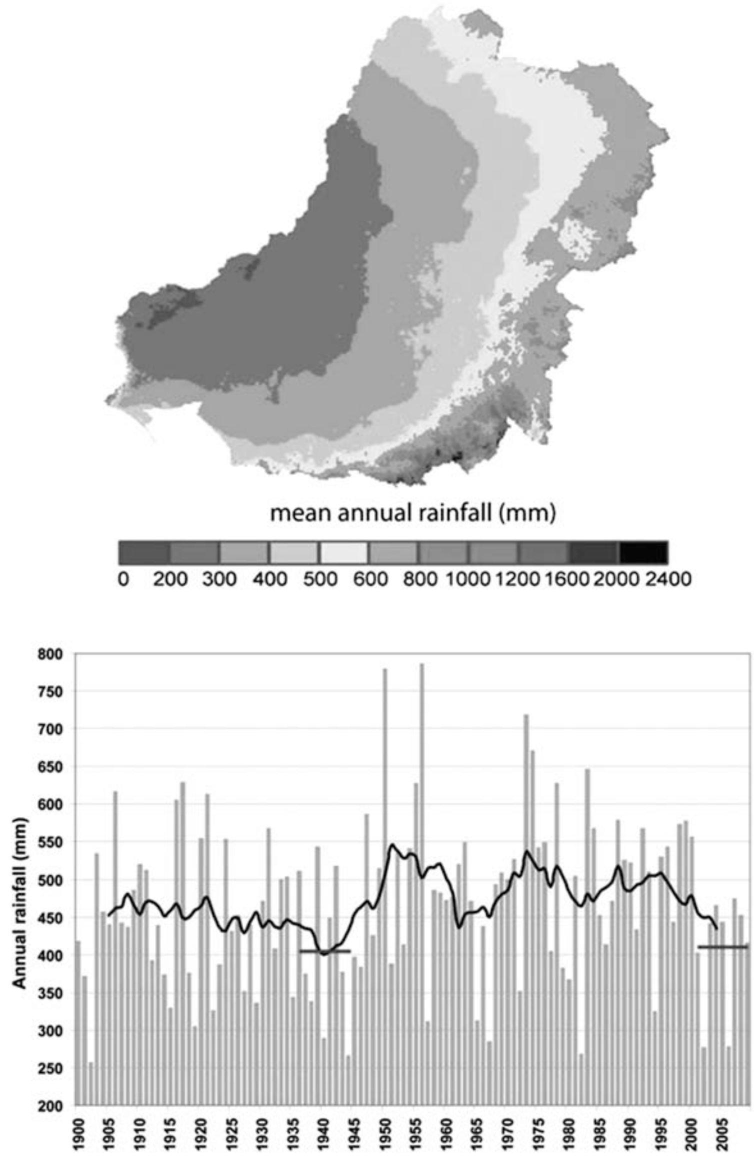


Figure 10.2. Top: spatial distribution of average annual rainfall for the 1900–2009 period. Bottom: mean annual rainfall over the Murray-Darling Basin for individual years from 1900 to 2009. Also shown are the 11-year running mean (solid black) and the two lowest 9-year means on record: 1937–1945 (395 mm) and 2001–2009 (406 mm). Data courtesy of the National Climate Centre, Australian Bureau of Meteorology, Melbourne, Australia.

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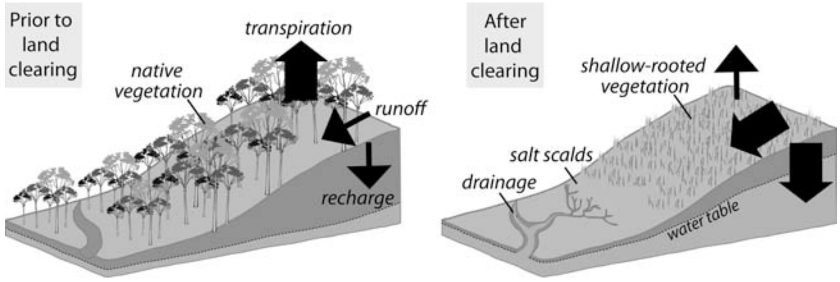


Figure 10.3. Schematic diagram (after DARA 1989) of processes leading to dryland salinity after the clearance of native vegetation for agricultural practices.

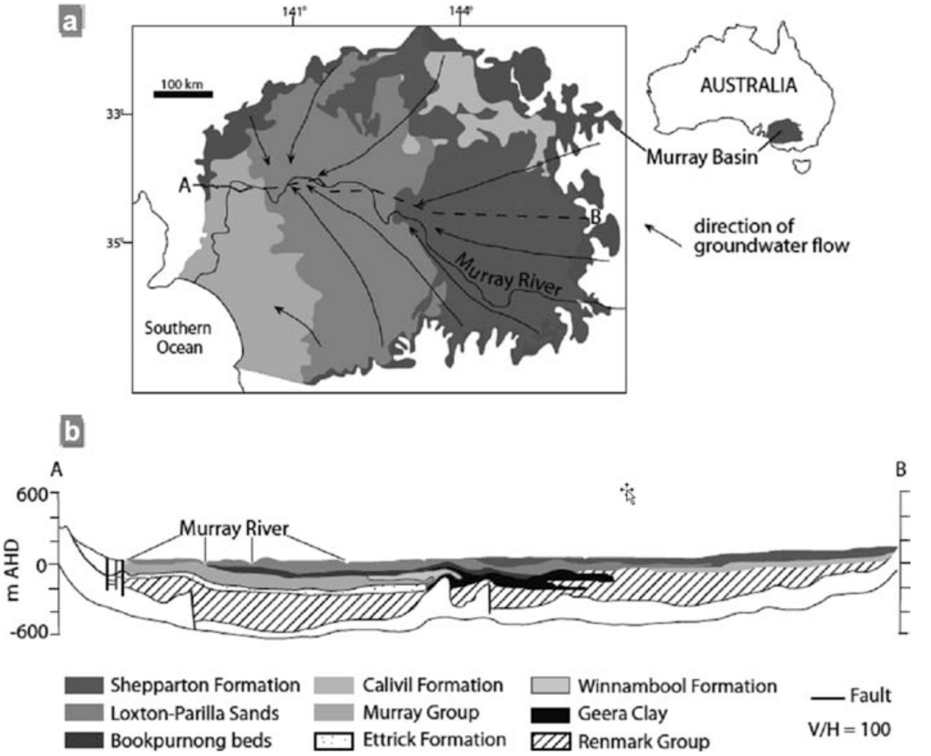


Figure 10.4. a) Location of the major water table aquifers within the Murray Groundwater Basin and groundwater flow directions. b) cross section showing the relationship between the different aquifers and confining units from west to east in the Murray Groundwater Basin (after Evans and Kellet 1989).

into the Calivil Formation in the eastern MB. The water table is present in the Loxton Parilla Sands except in the western region where the sands overly the unconfined Murray Group aquifer and the water table lowers below the base of the Loxton Parilla Sands (Evans and Kellett 1989). The Calivil Formation consists predominantly of coarse to granular quartz sands with lenses of kaolin and carbonaceous clay (Hennessy et al. 1994), and has an average thickness of 60 m, but can range up to 100 m (Brown 1989).

This formation is hydraulically connected to the underlying Renmark Group aquifer and the lateral deposits of the Loxton-Parilla Sands. In areas where the Calivil has coarser grained deposits, the aquifer is hydraulically connected to the overlying Shepparton Formation, and these regions generally coincide with the basin margins (Evans and Kellett 1989). In the northeastern margin of the MB, the Shepparton is unsaturated and the water table is within the Calivil aquifer.

**Shepparton Formation**

Conformably overlying the Calivil Formation in the eastern MB are the Pliocene to Quaternary fluvio-lacustrine deposits of the Shepparton Formation. In order of abundance, this aquifer comprises clay, slit, and sand (Evans and Kellett 1989). Hydraulic connectivity between the sand lenses is non-continuous resulting in vertical and horizontal heterogeneity of flow. This regional aquifer increases in thickness towards the basin's centre, from 10's meters up to 70–80 m (Brown and Stephensen 1991).

**Murray Group Aquifer**

The Murray Group aquifer is a middle Tertiary marine limestone and calcarenite aquifer located in the western MB (Evans and Kellett 1989). The limestone is over 100 m thick in most areas (Brown 1989), and previous work shows data from bores screened in the aquifer up to 150 m depth (Leaney et al. 2003). This aquifer overlies a confining layer formed by the clay and marl of the Winnambool and Ettrick Formations (Evans and Kellett 1989), and is laterally separated from the Renmark Group aquifer by the Geera Clay (Brown 1989). The eastern section of this aquifer is confined to semi-confined predominantly by the clay and silt deposits of the Pliocene Bookpurnong beds (Evans and Kellett 1989). The western section of this aquifer is unconfined beneath the Pliocene Sands aquifer; which are largely unsaturated (Leaney et al. 2003).

### 10.1.3 Methodology

**In-situ groundwater levels**

***Regional decadal trends***

Archive groundwater level data were sourced from the Government departments of the States in the Murray Groundwater Basin (NSW, Department of Water and Energy; VIC, Department of Sustainability and Environment; and SA, Department of Water Land and Biodiversity Conservation) and collated in a common database. We used this database to generate decadal trends of groundwater levels across the entire Murray Groundwater Basin. Using a least square fit, linear trends were calculated at each monitoring bore for two periods: 1980–1992 and 1997–2009. The time between the two periods (1993–1996) was not analysed because of the spatial inconsistency for the onset of the drought across the basin (Leblanc et al. 2012; Leblanc et al. in press). The trend analysis was performed on a subset of bores matching the follow criteria: 1) each selected bore must have, at least, 75% of the years represented in each 13 year epoch; and 2) only Government observation bores (production bores excluded) with an average saturated zone $\leq 30$ m from the bottom of the screened interval were analysed. Deeper bores were excluded as they can reflect processes occurring on longer time scales (Fetter 2001). In total, 354 representative bores for the unconfined aquifers across the Murray Groundwater Basin were used for the decadal trend analysis.

***Detailed observations at selected sites***

We also used this database to find high quality point observations that showed the respective longt-erm impacts of past land clearance and of the recent drought on groundwater levels. Accordingly, we searched the database for a selection of bore hydrographs that met the following criteria: 1) be a long time series; 2) be located at the edge of the Murray Groundwater basin where the problems of dryland salinity were clearly identified. We also searched for an updated time series of groundwater levels of the bores used by Allison et al. (1990) to demonstrate increase in groundwater recharge due to land clearing.

**GRACE estimates of changes in groundwater storage**

Since its launch in March 2002, the Gravity Recovery and Climate Experiment (GRACE) mission has been acquiring data on continental water storage anomalies which have been increasingly used for large-scale hydrological and hydrogeological applications. GRACE provides global mapping of the time-variations of the gravity field at an unprecedented resolution of ~300 km (for harmonics coefficients of the geopotential developed up to degree 60) and a precision of 1.5 cm of water equivalent thickness when averaged over regions of a few hundreds square-kilometres (Ramillien et al. 2008; Schmitt et al. 2008). These small temporal changes in the Earth's gravity field are mainly due to the redistribution of mass inside the fluid envelope of the Earth caused, at daily to decade timescales, by tectonic or glacial isostatic adjustment signals but also changes in surface loads such as atmosphere, oceans and continental water storage (Tapley et al. 2004). The effects of atmospheric mass, ocean tides and barotropic signals are accounted for using oceanic and atmospheric models in the reduction of the raw observations (Bettadpur 2007). In large regions like Australia where there are no significant tectonic or glacial isostatic adjustment signals, the remaining GRACE data should mainly correspond to changes in total continental water storage (TWS) which is an integrated measure of all the major water stores: reservoirs and lakes, soil moisture, groundwater, snow, ice and biomass. In the semi-arid Murray Groundwater Basin variations in biomass, snow and ice are negligible compared to other stores and are well below the detection threshold GRACE satellites (Rodell et al. 2005). Similarly there are no major surface water reservoirs in the Murray Groundwater Basin; hence the GRACE TWS signal over this region corresponds mostly to change in soil moisture and groundwater storage.

We obtained a GRACE TWS time series over the Murray Groundwater Basin from solutions produced by the Groupe de Recherche en Géodesie Spatiale (GRGS). These solutions are an average of 10 days of GRACE observations (Bruinsma et al. 2010). Atmospheric mass, ocean tides and barotropic signals are accounted for in the GRGS solutions using the European Centre for Meteorological Weather Forecasting reanalysis, Finite Element Solution 2004 (FES2004) (Le Provost et al. 1998) and the MOG2D-G barotropic models (Carrère and Lyard 2003). GRACE estimates of changes in groundwater storage were obtained by subtracting soil moisture storage from the GRACE TWS time series. Variations in soil moisture storage were estimated for the groundwater basin using the NOAH land surface model (Ek et al. 2003), with the simulations being driven (parameterization and forcing) by the Global Land Data Assimilation System. The NOAH model simulates surface energy and water fluxes/budgets (including soil moisture) in response to near-surface atmospheric forcing and depending on surface conditions (e.g. vegetation state, soil texture and slope) (Ek et al. 2003). The NOAH model outputs of soil moisture estimates have a 1° spatial resolution and, using four soil layers, are representative of the top 2 m of the soil.

### 10.1.4 Relevance to GRAPHIC

This chapter contributes to GRAPHIC project by providing an Australian case study which gives insights into major water resources issues in the Australian continent and materials for comparison with other countries or regions.

First, the Murray Groundwater Basin has experienced a general rise of the water table after land clearing. This rise of the water table induced widespread dryland salinity problems degrading vast areas of farming land and surface water bodies. Second, this key agricultural region has experienced a continued increase in water demand which is increasingly difficult to supply given the very high hydroclimatic variability. Third, it is often considered that groundwater has the capacity to help meet water needs during periods of drought when surface water resources are dwindling. This region has recently been affected by one of the most severe and prolonged multi-year droughts on record for the 20th and 21st centuries. It offers a unique opportunity to study the effects of a prolonged rainfall deficit, and the coupled pressures of climate variability (drought) and human activities (land clearing) on groundwater resources. Finally, the Murray Groundwater Basin is also one of the few semi-arid regions equipped with a relatively good monitoring network for groundwater at a regional scale. We therefore used this opportunity to test the capability of the GRACE mission to provide regional estimate of change in groundwater storage so that it can be applied for the monitoring of insufficiently instrumented regions.

## 10.2 RESULTS AND DISCUSSION

### 10.2.1 Long-term observations from in situ hydrographs

***Regional trends across the basin***

Long-term trends in groundwater levels across the Murray Groundwater Basin highlight a regional rise of the water table during the period 1980–1992; linear trends for this period range from −0.16 to 0.63 m/a with a median value of 0.05 m/a (Fig. 10.5). This regional rise is attributed to the increase of groundwater recharge after land clearance. Following the onset of the drought in 1994–1997, trends in groundwater elevations clearly reversed across the basin. Linear trends for the 1997–2009 period range from −0.88 to 0.50 m/a with a median value of −0.17 m/a (Fig. 10.5). Local examples from two regions in the Murray Groundwater Basin are presented below.

***South eastern Murray Groundwater Basin***

We found in the Government databases a cluster of monitoring bores in an area affected by dryland salinity that provides long-term continuous groundwater hydrographs showing the respective impacts from past land clearance and the recent drought on groundwater dynamics. This cluster of monitoring bores is located in the Benalla region close to the south-eastern border of the Murray Groundwater Basin (Fig. 10.6). Groundwater hydrograph data during ~1974–2010 (from VWRDW 2010), indicate most groundwater levels in the Benalla region show a steady increase of 0.05–0.42 m/a

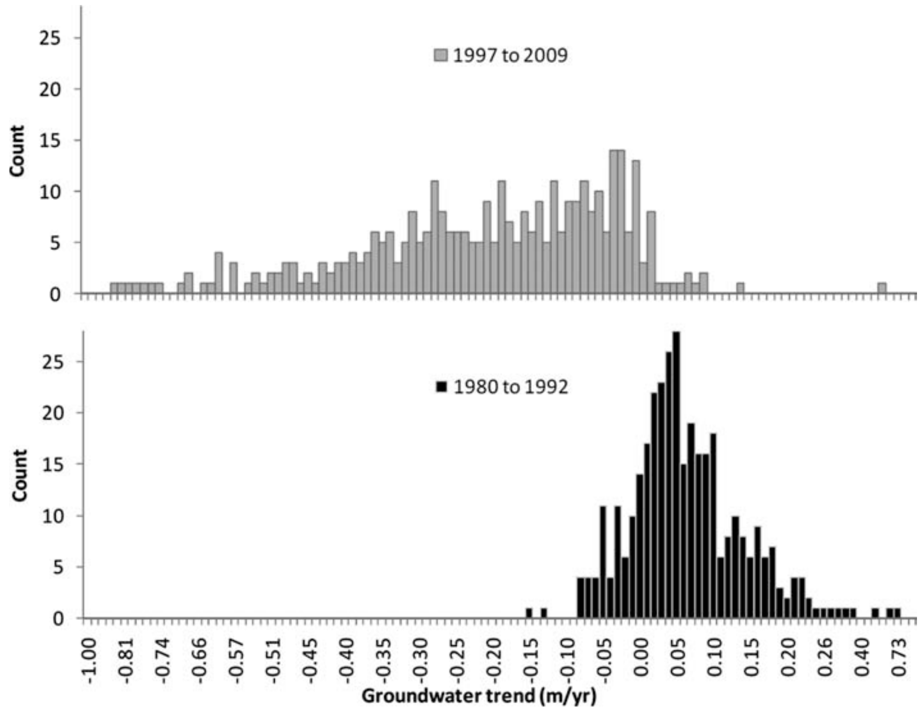


Figure 10.5. Histogram of groundwater trends between the years 1980-1992 and 1997-2009 for bores located in the Murray Groundwater Basin.

up until ~1994/7, when the first impacts of drought conditions are reflected in the groundwater system (Fig. 10.7). Typical of many regions in the Murray Groundwater Basin, the increases in groundwater elevations, observed in both shallow and deeper aquifer systems prior to 1994/7, reflect the long term impacts of land clearance in the region throughout the last century (e.g. Allison et al. 1990). The rising water tables resulted in salt scalds often observed along the foothills (Fig. 10.6). From 1997–present (2010), the groundwater elevations of shallow and hydraulically well-connected deeper groundwater systems declined due to drought conditions by 0.20–0.38 m/a. Local variations in the stratigraphy (highlighted in Fig. 10.6b) cause heterogeneous connectivity between shallow and deep aquifers in the region. Some deeper bores presented in Figure 10.7 show a continued increase in groundwater elevations during the drought (e.g. bores 9–12). This continued rise in deeper bores could be due to a much slower response time of the groundwater system as the depth increase.

### *South western Murray Groundwater Basin*

A study by Allison et al. (1990) in the south western Murray Basin observed that the land clearing from 50 to 100 years ago resulted in increased recharge rates, which is reflected in the rising groundwater elevations. The original bores used in the study by Allison et al. (1990) are presented here (Fig. 10.8) with the time series of groundwater elevations extended to include the more recent drought impacts. Four groundwater bores are

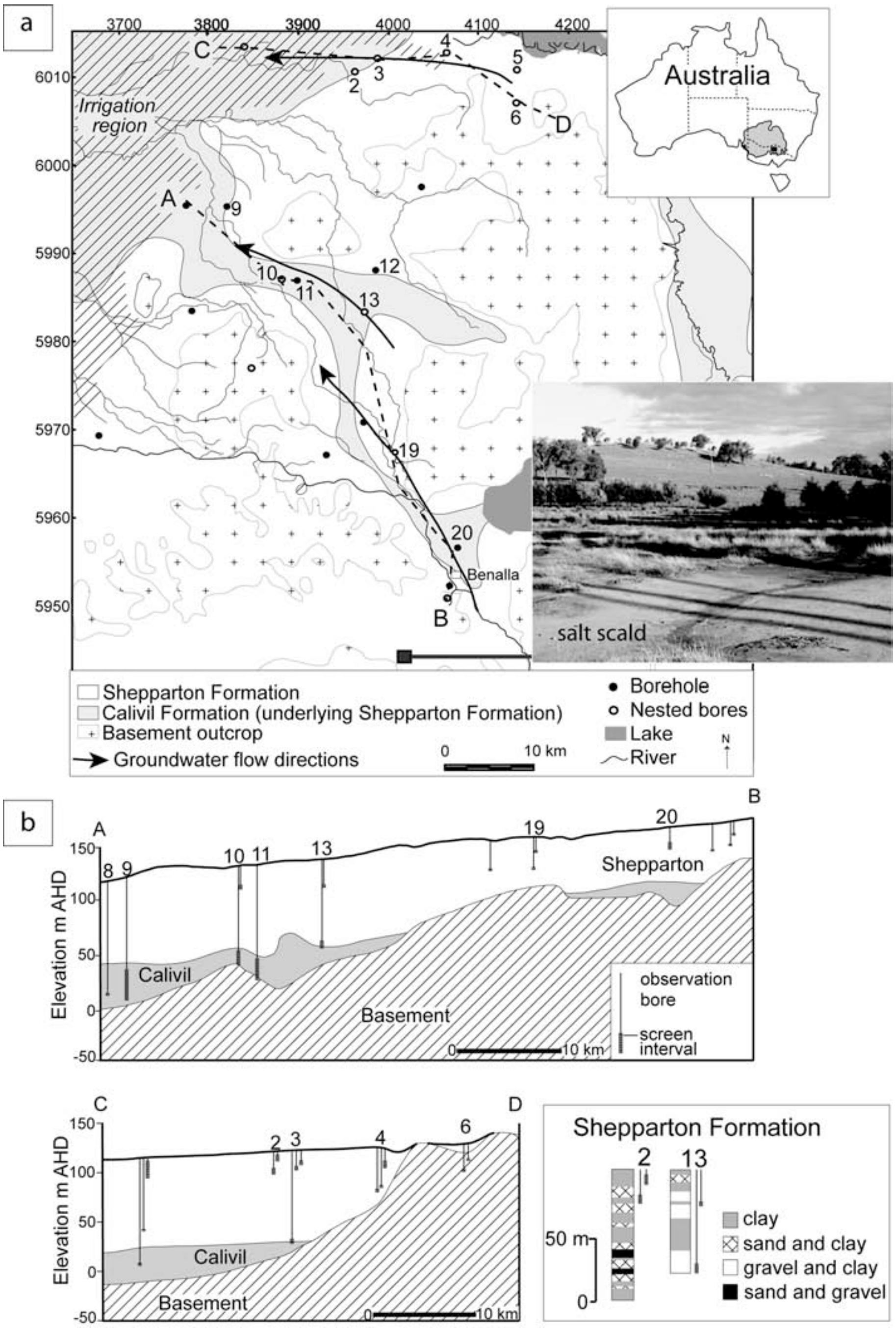


Figure 10.6. (a) Geology (after Hennessy et al. 1994), general groundwater flow directions for June-August 2003, and locations of bores (inserts: location of the Murray Groundwater Basin and Benalla region in south-eastern Australia; and local example of a salt scald due to dryland salinity (photo from English et al. 2004)). (b) Cross sections of the region and stratigraphic logs for two bores in the Shepparton aquifer, shows examples of the heterogeneous stratigraphy resulting in locally variable connection between shallow and deeper aquifer systems.

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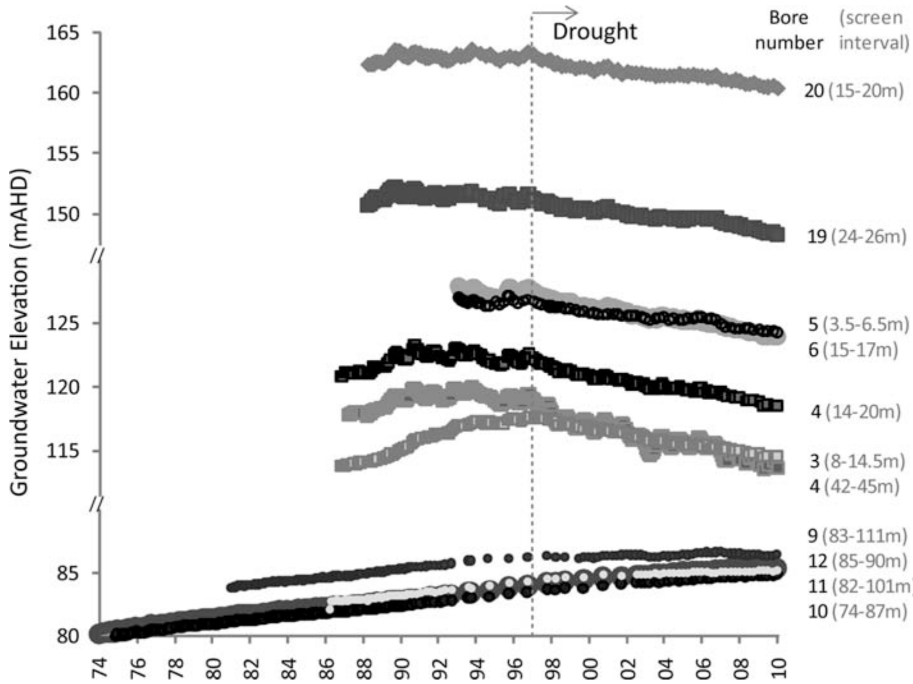


Figure 10.7. Groundwater hydrographs for selected bores in the south-west of the Murray Groundwater Basin (Benalla region).

presented, each highlighting variations in the response to environmental change. PAG 6 bore is located within a unit of low recharge rates (Renmark Group; Allison et al. 1990) and therefore showed relatively small increases due to land clearing between 1973–1994 (<0.03 m/a), and shows a continued rising trend during drought conditions. All other bores are screened in limestone aquifers. The shallow bore ARC 5, shows rising groundwater elevations to 1994, and a large decline during the drought. In comparison CTN 5 and SHG 7, which have deeper screen intervals, show little change and an increasing trend respectively. These bores highlight local variations in the trend and magnitude of changes in groundwater levels in response to regional stressors (ie. land clearing and drought).

### 10.2.2 GRACE observations

***Spatial average of Total Water Storage from GRACE***

We used GRACE level-2 solutions from GRGS that are lists of Stokes coefficients (i.e., dimensionles spherical harmonics of the geopotential) from August 2002 to December 2010. They are estimated over 10-day intervals from Level-1 GRACE measurements, and especially the accurate inter-satellite distance and velocity variations. After removing the temporal mean over 2003–2010, the corresponding residuals should represent the vertically-integrated variations of the Total Water Storage (TWS) over continents, that include changes in surface waters, snow coverage, soil wetness and

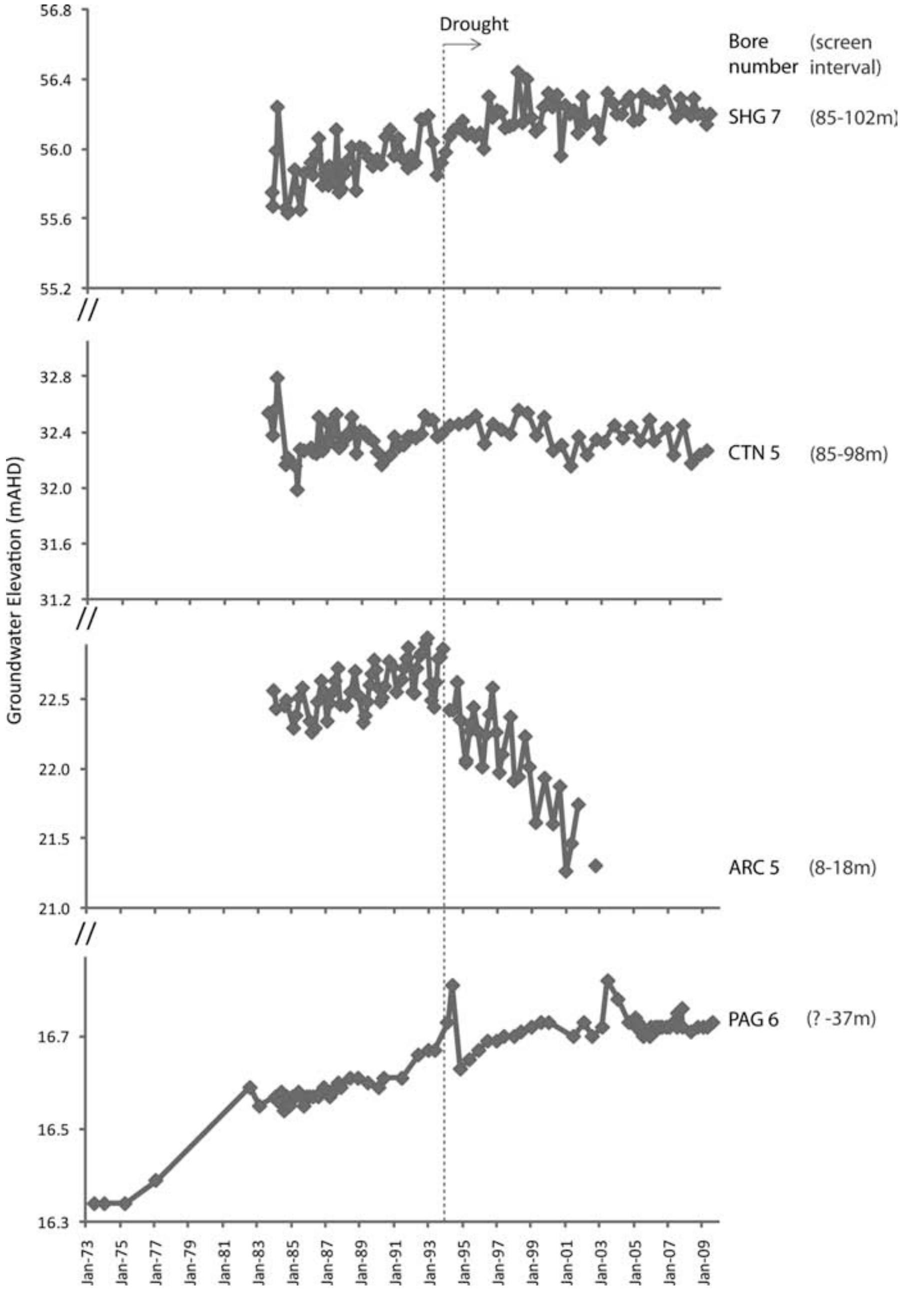


Figure 10.8. Groundwater hydrographs for selected bores in the south-west of the Murray Groundwater Basin – update on reference bores used in Allison et al. (1990).

groundwater (Figure 10.9). Stokes coefficients are converted into water mass coefficients in unit of equivalent-water height by simple linear filtering. Spatial averages in a given basin are computed as the scalar product of the water mass coefficients for each period and the coefficients of the geographical mask of the basin. GRGS solutions are provided up to degree N = 50, so their spatial resolution remains about 400 km.

***Error budget***

In order to establish the error balance of estimated regional averages over the Murray Groundwater Basin, different types of error are computed from the GRACE data. The formal errors are determined from the formal uncertainties on the Stokes coefficients that are adjusted using the Level-1 GRACE observations. Averaged over the Murray Groundwater Basin, these errors are typically less than ±25 mm of equivalent-water height (see also Llubes et al. 2007; Brown & Tregoning 2010). We computed the omission errors induced by the truncation of the gravity coefficients at degree and order 50–60. These errors represent the missing high-frequency signals that GRACE solutions cannot describe. Once they are averaged over basins, errors of truncation do not exceed ±2 mm of equivalent-water height. Leakage (contamination) errors are mostly caused by hydrological signals mostly in tropical regions and other strong geophysical signals (e.g. melting of Greenland icesheet) outside the considered basin. By using monthly outputs from the WaterGAP Global Hydrological Model (WGHM) over the period 2002–2006 (Döll et al. 2003; Ramillien et al. 2006), we found that leakage of continental water storage into the Murray-Darling basin create seasonal variations which amplitudes reach a maximum of ±25 mm. To summarize, the balance of the error for the Murray-Darling drainage basin is around ±52 mm of equivalent-water height for each period of time.

***Groundwater estimates***

Regional estimates of changes in groundwater storage were obtained by subtracting soil moisture storage from the GRACE TWS time series (Fig. 10.10). These satellite-based

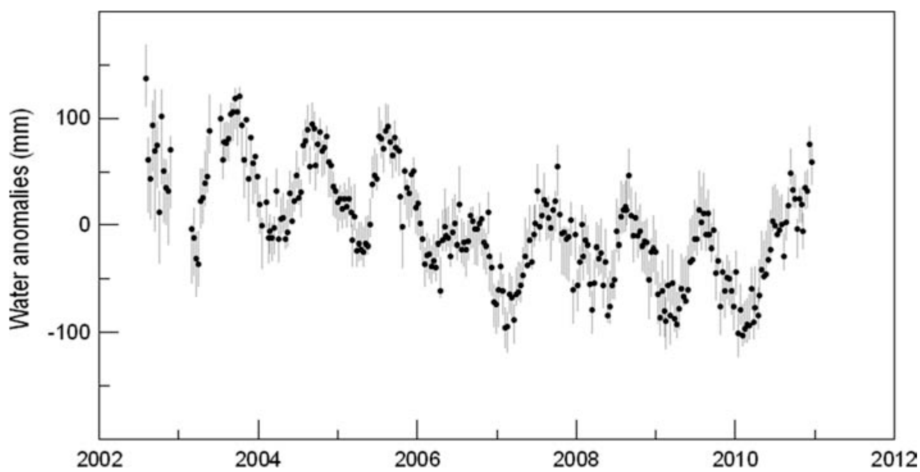


Figure 10.9. Terrestrial water storage anomalies in the Murray Groundwater Basin from the GRGS RL02 solutions in mm from August 2002 to December 2010.

estimates indicate a seasonal amplitude of the groundwater storage ranging from 60 to 90 mm with an average of 80 mm. These regional space observations also indicate a strong and continuous decline in groundwater storage across the basin since the beginning of record in 2002. The linear trend using least squares on the GRACE-based estimates indicates a groundwater loss of 17.8 ± 1.3 mm/a or 5.3 ± 0.4 km$^3$/a from 2002 to 2010 (Fig. 10.10).

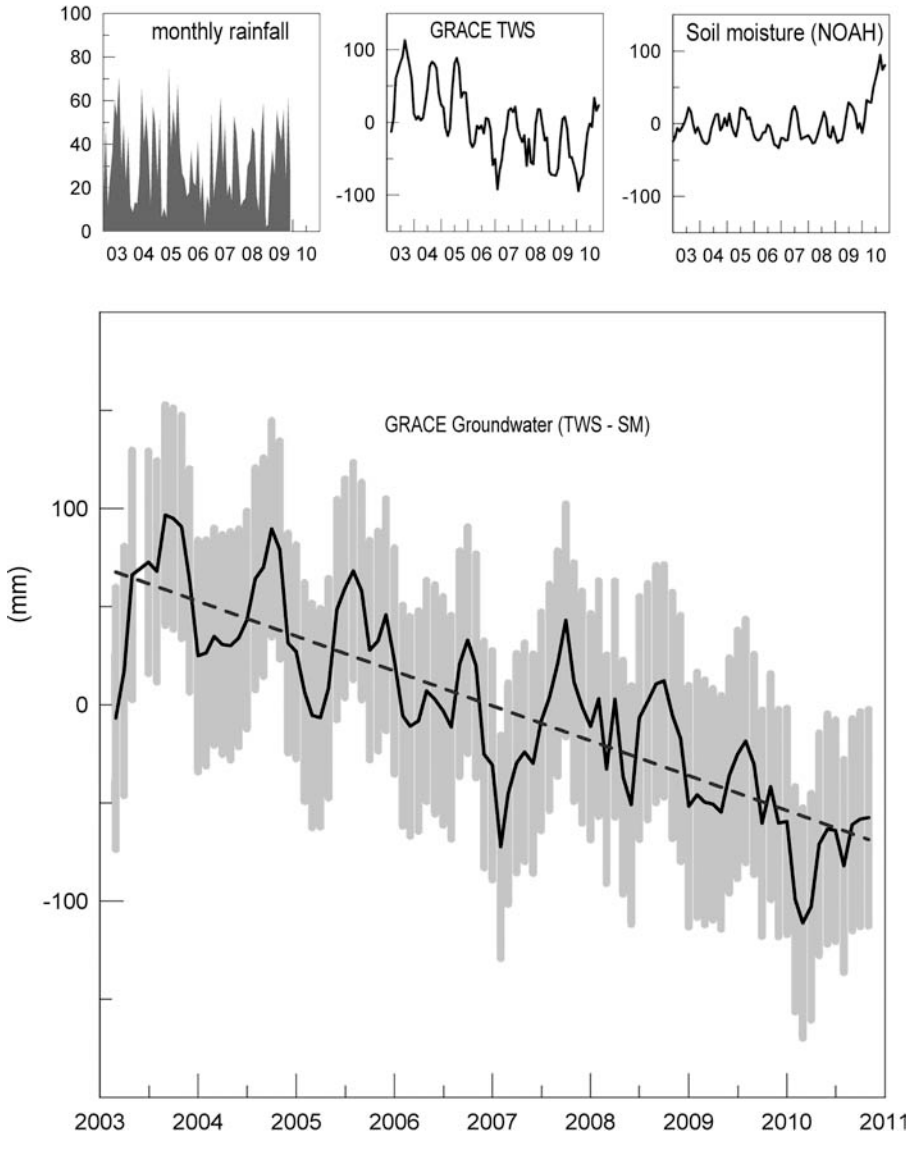


Figure 10.10. (a) Monthly rainfall in mm from the Australian Bureau of Meteorology. Monthly anomalies of (b) total water storage (TWS; GRGS solutions); (c) soil moisture (SM; GLDAS ensemble mean); and GRACE groundwater (TWS – SM) in mm from March 2003 to November 2010.

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### 10.2.3 Discussion

*Attribution of the groundwater loss during the recent drought*

Total groundwater pumping in the MGB was estimated to be below 0.4 $km^3/a$ in 2004–2005 (CSIRO 2008). This pumping rate represents only less than 10% of the decline rate in groundwater storage observed from 2003 to 2008 in the GRACE-based observations. In the absence of an important increase in pumping during the drought, the observed decline can only be explained by a reduction of the groundwater recharge while a strong natural discharge is maintained to create a deficit in the groundwater storage. Capillary rise from the saturated to the unsaturated zone and subsequent evapotranspiration may go a long way in explaining strong natural discharge. Deep rooted trees are widespread across the MGB and they could explain why a vast amount of groundwater may still be transpired during the drought.

The average annual rainfall deficit of the recent drought is similar to the one observed during the 1935–1945 drought. However the recent drought has, in comparison, led to a much stronger decrease in runoff values. This additional decrease in runoff during the recent drought can be explained by a change in rainfall patterns at various time scales: lower inter-annual variability, lower autumn and winter rainfall (Potter et al. 2010). This change in the rainfall pattern has most probably also induced a strong reduction in the groundwater recharge, and explains why the loss of groundwater during the drought is so high.

Since our study, above average rainfall in 2010 and 2011 brings the end to this prolonged drought; large flooding events occurred in south west Queensland and Victoria in early 2011 and public water storage across the MDB are now around full capacity in mid-2011.

***Land surface versus climatic controls on groundwater***

The respective impact of land use change and hydroclimatic variability on water resources can be complex. In a large region of West Africa in the Sahel it was found that, despite the long lasting droughts of the 1970s and 1980s, surface and groundwater resources increased following intensive land clearing (*Leduc* et al. 2001; *Leblanc* et al. 2008; Favreau et al. 2009; Favreau et al. this book). Land clearing in the Murray-Darling Basin, which started with European settlement in the early 1800s caused a general rise of the water table that is still observed during the second half of the 20th century, and subsequently led to the appearance of dryland salinity (Allison et al. 1990). The observed decline of groundwater levels and TWS show that the ongoing multi-year drought in the Murray-Darling Basin has, at least temporarily, reversed and surpasses the long-term groundwater trend inherited from land clearance and may induce a temporary halt of secondary salinity processes.

## 10.3 POLICY-RELEVANT RECOMMENDATIONS

Following from the high rainfall variability and largely arid conditions described above, water resources in the Murray-Darling are scarce and highly unreliable. The five Australian States and Territory that share this vast drainage system (Queensland, New South Wales, Victoria, South Australia and the Australian Capital Territory) have extensively exploited the basin's water resources since the second half of the 20th Century. To support agricultural activities, the MDB uses ~60% of Australia's total agricultural water consumption. The basin also meets the water needs of ~2 million people in addition to contributing to the water supply of Adelaide (population 1.4 M.). Most water used in the MDB is sourced from surface water (84%). To satisfy high water demands a vast network of public and private infrastructure, including large reservoirs, weirs, diversion channels as well as farm dams has progressively been established across the entire basin. Today, the total surface water storage capacity (including farm storages) has reached ~35 $km^3$; that is 150% of the average annual water availability in the basin (GLOPACHA; WWDR). Total storage capacity was only ~2 $km^3$ in 1930 and most of the infrastructure development took place in the second half of the 20th Century. Groundwater currently represents the remaining 16% of total water use in the MDB but, under current water sharing arrangements, groundwater use could increase to be over 25% of total water use by 2030.

Maintaining a healthy basin and environmental flows has long been a challenge in the Murray-Darling Basin with intense water diversions (large reservoirs, dams, weirs), increasing demands from irrigation and urban areas, and the difficulties in sharing water allocations within the five States governed by separate legislation and policies. In addition, the current status of water resources is dire due to the impacts of probably the most severe hydrological drought since records began in the late 19th Century. Experts and Governments agree that urgent actions are required to save this important water system; for its cultural, ecological, and economic value. In an unprecedented effort in the history of Australia, the Australian Government is attempting to save the basin's health and to prepare the region for climate change by introducing a new integrated and sustainable approach to the management of the basin's water resources (http://www.thebasinplan.mdba.gov.au/). As a first step towards that plan, a discussion document – the "Guide to the proposed Basin Plan" was released in October 2010 in combination with a series of community meetings. The document outlined plans to return a long-term average of 3,000–4,000 GL/a back to the environment through 22–37% reductions in water use. The proposed range was at the lower end of the estimated environmental needs (3,000–7,600 GL/a) and represented an explicit compromise designed to avoid unacceptable social and economical consequences. In 'The Basin Plan', a cut in groundwater extraction of 186 GL/a was proposed to bring all extraction from all managed groundwater systems back to acceptable extraction rates. This total number includes widely ranging cuts, from possible increases in groundwater use to 40% reductions, reflecting the variable degree of overexploitation in the different aquifers. The proposed targets generally appeared to be accepted as more or less appropriate by environmentalists and ecologists, but were poorly received by irrigation interest groups and farming communities. While the hydrological modelling underpinning the proposed plan generally appears to be accepted, the estimation of the ecological benefits and socio-economic implications appear to have been met with much scepticism. In view of recent protests, it is clear that the 'Basin Plan' has become a contentious political issue for the Governments. Significant delays and most probably a 'watering down' of the proposed measures can be expected for the 'Basin Plan'. This is not so surprising, and in fact there is a long history of complex interactions between politics and water management in the Murray-Darling Basin (Connell 2007).

Achieving the right balance between environmental flows and socio-economic needs is proving difficult. Successful water planning will need to balance cultural and ecological values with food production, account for high natural variability and uncertainty in climate change projections, as well as address past mistakes and be cognisant of hydrological change.

## 10.4 FUTURE WORK

A key scientific challenge in the Murray Groundwater Basin is to assess the future impact of climate change on groundwater. If global climate models (GCM) remain the best tool to assist us in assessing future climate change, our case study is a good example of the difficulties in obtaining reliable estimates from these models. For the region, climate models are fairly consistent in predicting the change in annual average temperature. However, after the first half of the 21st century this estimate depends strongly on the emission scenarios for greenhouse gases (CSIRO and BoM 2007). Failure to establish policies and reduce global greenhouse gases emissions is one possible scenario. In fact, since 1990, observed fossil fuel emissions are at the upper limit of all emission scenarios and climate change and associated hydroclimatic impacts under such scenario will be stronger than most projections currently available (Meinshausen et al. 2009). Modelling rainfall is harder than temperature so the range of uncertainties attached to future rainfall projections is even larger. The pattern of floods and droughts in the MDB and other parts of Australia may often be linked to sea surface temperature anomalies in the Pacific (oscillation between El Niño and La Niña conditions or ENSO) and Indian Ocean. Climate models do not currently have the capability to predict these interannual oceanic anomalies (Meyers et al. 2007).

The effects of climate change on groundwater resources do not necessarily mirror those of surface water resources. In particular in drier environments, groundwater recharge can be a highly episodic event associated with a small number of large storms. Therefore, even when a GCM predicts a drier average climate, increased rainfall intensity could potentially lead to an increase in groundwater recharge rates (McCallum et al. 2010). Crosbie et al. (2010) estimated that, under emission scenarios adopted for the IPCC 4th assessment, average recharge across the Murray-Darling Basin would increase by 5%; with results ranging from −12% to +32% depending on the GCM used. Only the very southern margin of the basin was predicted to experience an actual decrease in recharge. This was despite a generally predicted reduced mean annual rainfall, and reflects the fact that GCMs generally predict greater rainfall intensity associated with intensification of the hydrologic cycle. Increases in rainfall intensity have indeed been observed in other regions (e.g. Huntington 2006). Trend analyses for Australia are more ambiguous, partly because of the additional influence of ocean circulation patterns on rainfall intensity. Dryland and river salinity are primarily attributed to increased groundwater recharge, and therefore might be expected to show similar changes. This stands in contrast to the analysis of Austin et al. (2010), which did not account for any effect of changed rainfall intensity and predicted a salt load reduction of 34–49%. It is noted however that in either case the expected recharge change is smaller than that which would accompany the removal or introduction of deep-rooted vegetation (Crosbie et al. 2010).

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