Drought and flooding rains: Western Australian water resources at the start of the 21st Century

D P COMMANDER

School of Earth and Environment, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
✉ *philip.commander@bigpond.com*

The drying climate of southwestern Western Australia has led to much reduced runoff and groundwater recharge, with consequent decline in groundwater levels affecting wetlands and groundwater-dependent ecosystems. Water level decline in the Gnangara Mound has been exacerbated by maturing pine plantations and groundwater pumping for public supply and horticulture, while desalination has replaced the failing surface water supplies from hills catchments. At the same time, the north and northwest of the State have an increasingly wet climate in the last decade. The challenge for the State is to optimise use of the existing water resources and make best use of the undeveloped surface and groundwater. With groundwater and surface water resources increasingly fully developed, the emphasis for the future will be on recycling and water-use efficiency.

KEYWORDS: climate variability, drought, groundwater, surface water, water resources.

INTRODUCTION

Drought and flooding rains characterise our climate, but Western Australia is experiencing prolonged drying in the southwest and contrary wetting in the north simultaneously. Water is often quoted as a limiting factor in the development of Western Australia: the State lacks major perennial rivers; rivers in the southwest are saline in those areas where their catchments extend into farmland; and much of the interior is characterised by salt lakes. Pronounced long dry seasons in the southwest and the north exacerbate the feeling of a waterless terrain and, apart from the wetlands on the Swan Coastal Plain, the presence of groundwater is rarely evident.

Settlement and development of Western Australia has been largely achieved using groundwater; there are few areas where stock water cannot be sourced, and the mining industry has adapted to use saline water. Only the Eastern Goldfields and Wheatbelt require water to be piped in from a significant distance. Dams in the Ord and the southwest, and the Gascoyne River, together with the Perth Basin's groundwater have sustained irrigated agriculture.

Water has always been high profile in the public consciousness. Perth is a groundwater-based city where many householders have their own bores and the aquifers are household names, while the symbol of rural Australia is the windmill (windpump).

The last decade has seen low rainfall and the near collapse of Perth's surface water catchments, the stalled development of the Yarragadee aquifer in the southwest, and in 2013, desalination accounts for about half of the Integrated Water Supply Scheme supplying Perth and much of the Wheatbelt and Goldfields. Climate change in the southwest has reduced the yield from surface water and strained the capacity of groundwater, especially at the time licensed groundwater use in many areas has reached allowable limits. Climate change is a topical subject, yet there has only been relatively recent recognition of the contribution of rainfall cycles to the current climate.

A hundred years ago, the southwest was about to enter a 60 year period of above-average rainfall. The environment we see today is a mismatch of vegetation grown up in the high rainfall of 1920–1974, but maturing in a low rainfall period since 1975. Perth's water supply has moved through eras of natural springs, dug wells, artesian bores, dams, protection of catchments, and is now entering an era of desalination and recycling. This has brought an inevitable cost increase, yet high-quality drinking water remains the cheapest bulk commodity, and is low priced by world standards.

Water security into the future is a major issue. Climate-change issues, managing groundwater abstraction rates, and the present-day drying trend in the populous southwest corner of the State, all present major challenges. Western Australia has the fastest growing population of any Australian State and more people inevitably leads to more water usage. Western Australians already consume more water per head for all purposes than other Australian States and the State's groundwater resources have borne the brunt of this increasing demand.

The last decade has seen a national focus on water, stimulated by the Millennium Drought of 1998–2009, with the formation of the National Water Commission and its National Water Initiative, the National Centre for Groundwater Research and Training, CSIRO's Water for a Healthy Country Flagship, the Western Australia Department of Water, the Water For Food program in the Department of Agriculture and Food, and the four year initiative of the Department of Regional Development and Lands to assess, plan and investigate regional water availability under the Royalties for Regions program.

WATER MYTHS

The Western Australian population holds some very entrenched views regarding water and water supply. In the late 1890s, myths surrounded 'artesian' water—the magic of free-flowing water, in an age without ready access to power and pumps. The Western Australian Government, in 1896, embarked on diamond drilling to 3000 feet (914 m) for artesian water in granite near Coolgardie (against the advice of its then Government Geologist H P Woodward). Newly appointed Government Geologist A G Maitland commented 'a prevailing notion in certain circles is that if a well is only carried deep enough, an abundant supply of artesian water is assured' (Maitland 1897 p. 26), and reporting on his visit to the drilling, rated the 'chances of success as so infinitesimally small that as to render it useless to proceed any further with the work' (Maitland 1897 p. 28).

With desalination of local saline groundwater in the Kalgoorlie Region consuming an increasingly unsustainable amount of wood to fire the condensers, it was Chief Engineer C Y O'Connor's bold scheme to pipe water from a reservoir in the Perth Hills to Kalgoorlie that settled the water supply problem. This feat has dominated the thinking of the population brought up on O'Connor's achievement, and led to a long-distance pipeline mentality.

Watering the desert is a great Australian dream, but Western Australia's unique myth is piping water to Perth from the Ord River. The prohibitive costs were recognised in the 1970s, but the idea was taken up again in earnest by Ernie Bridge, Member for the Kimberley and Minister for Water Resources in the early 1990s (Bridge 1991). The public revelation of the existence of the Yarragadee Aquifer below the Blackwood Plateau (an underground lake reported in 'The Australian') forced abandonment of the project, but Bridge's death at Easter 2013, still spawned a number of letters to 'The West Australian' supporting long-distance pipelines as a source for Perth.

'Bringing water from the north' surfaced again at the 2004 state election with the Fitzroy canal proposal, in spite of a complete lack of basic information about the supposed groundwater source. Among industry professionals, the joke is that these schemes would never get considered if the map was the other way up – it is easier to visualise water running downhill from north to south! Numerous studies (e.g. Department of Premier and Cabinet 2006) have shown the cost of bringing water from the north cannot compete with the energy cost of seawater desalination.

In May 2000 a press conference unleashed on incredulous reporters news of the 'discovery' of the Officer Basin – 'Mining company discovers basin the size of England with first bore' read one headline' – and showed a suggested pipeline to supply Perth (Commander 2000). As indicated in the Kalgoorlie Boulder Waterlink study from the year before (Water Corporation 1999), the Officer Basin had long been considered a brackish source, and the subsequent drilling did not alter the position.

Because hydrogeology is often not readily understood by the public, development of groundwater is surrounded by half truths. Erroneous claims that the forests and biodiversity of the southwest would be threatened by the development of the southwest Yarragadee Aquifer obscured the very real issue of the potential effect on the Blackwood River and its tributaries. The uncertainties of predicting aquifer performance prior to development have led to very conservative decisions: the shelving of the Water Corporation's southwest Yarragadee proposal, and of the Vasse Coal proposal. The Environmental Protection Authority made recommendations against the latter in May 2011, citing serious environmental risks to nearby aquifers.

Misleading newspaper reports are seldom corrected. The West Australian (18 Oct 2007 p. 16; 17 March 2008 p. 9), quoted a study from the University of New South Wales, overestimating the magnitude of subsidence caused by groundwater extraction in Perth by an order of magnitude (Featherstone *et al*. 2012), and raising the spectre of damage to infrastructure, such as railways running up hill. In fact, the subsidence due to removal of water from elastic storage in the confined aquifers below Perth has been measured as 50 mm (Jia *et al*. 2007; Featherstone *et al*. 2012), spread over a large area, and is not a serious problem. Nevertheless, there was no public retraction, so the public is left confused.

The belief in water divining, and the (usually) erroneous concept of underground streams brought from northern Europe, is still endemic in the population, but much effort has been put into educating the younger generation through groundwater programs, for instance the Children's Groundwater Festival at Whiteman Park.

The recycling and drinking of treated waste water seems to be regarded with abhorrence by Australians, used to using pristine water once then discarding it, but it is clear that perceptions will have to change. Elsewhere in the world, people have had no choice for a long time—Londoners, for instance, are brought up being told that their drinking water has already passed through seven people (though this is largely a myth too).

WATER RESOURCE ASSESSMENT

Assessment of water resources in Western Australia began a little over a hundred years ago (Aquaterra 2009) with temporary river gauging stations on the Helena and Canning Rivers, and a further nine stations on streams in the hills near Perth commissioned between 1908 and 1911. Some 19 stations were established in 1939-1940 on the principal rivers in the southwest of the State, and in the 1950s and 1960s, monitoring began in the Indian Ocean Division and Timor Sea Divisions. While the quality of these early records was sometimes poor and infrequent, they provide a starting point for measurement records, and emphasise the importance of collecting rainfall and stream flow data. A statewide stream gauging network is now in place including telemetered continuous water level and electric conductivity (a measure of salinity), providing real time data for flood prediction.

The broad features of the State's artesian basins were also known a hundred years ago (Maitland 1913, 1919) although systematic groundwater resource assessment did not begin until 1962 (Allen 1997a, b). After a short hiatus, following the recommendations of the Auditor General (2003), the Department of Water's State Groundwater Investigation Program (SGIP) was reinstated in 2006 (Johnson *et al*. 2005), and groundwater investigation is currently proceeding in the Perth Basin, Pilbara and West Kimberley. Regional groundwater monitoring of some 2500 bores is largely concentrated in the Perth Basin, and very localised elsewhere, with an additional network of 1300 bores monitoring groundwater level rise in the agricultural areas (George *et al*. 2008). Both surface water and groundwater monitoring data are available online through the Department of Water website.

CLIMATE VARIABILITY AND CLIMATE CHANGE

Rainfall is the ultimate origin of our water resources, but only relatively recently has there been recognition of the dominance of cyclicity in rainfall patterns on groundwater levels. Unlike the northern hemisphere, where tree-ring records, and hence rainfall proxies, go back thousands of years, the record in Western Australia has not until recently been extended before 1876. A reconstructed winter rainfall record showing a cyclic pattern of around 50 years duration (Figure 1) has now been proposed from a 350 year tree-ring record in *Callitris columellaris* near Lake Tay (100 km northeast of Ravensthorpe) by Cullen & Grierson (2009), and work on speleothems in southwest caves is continuing (Treble *et al*. 2003, 2008, 2013). According to this tree-ring analysis, southwestern Australia may have been settled at one of the wettest times in the last 350 years.

An intriguing discovery is that the recent decline in rainfall in southwest Western Australia mirrors that of North China, which has also been declining substantially since the mid-1960s. Using observed rainfall datasets in China and Australia Li *et al*. (2012) examined the relationship between the decline of southwest rainfall in early winter (May–July) and the reduction of North China rainfall in late summer (July–September) during 1951–2008, and found that a significant link exists between these two rainfall series. They suggested that poleward shifts of the Southern Subtropical High Ridge and the Northern Subtropical High Ridge over longitudes 110° to 150°E instigated by warming sea-surface temperatures in the tropical Indian–western Pacific may have partially contributed to the rainfall reduction in both regions.

This teleconnection between rainfall in the southwest of Western Australia and North China allows the use of China's long historical climate record to reconstruct the past climate in southwest Western Australia. Li *et al*. (2012) showed that the reconstructed wet and dry periods are consistent with those in the paleoclimate data from the south coast from tree rings and the speleothem record at Moondyne Cave, and consistent with historical accounts of drought and flood events in the 19th Century.

The historical record of floods in the Swan River gives information on rainfall before records began in 1875 (Bureau of Meteorology 1929). Bearing in mind that the Helena and Canning Rivers are now regulated, the accounts of flooding in Perth Water in the period 1830–1926 are quite beyond the experience of most Perth residents, and gauging shows a decline in flow peaks in the Avon since 1971 (Figure 2).

The worst floods seem to have been in 1830, 1847, 1862, 1872, 1917, 1926, 1945, 1955, 1963 and 1964 (Bekle & Gentilli 1993; Bureau of Meteorology 1929; Binnie & Partners 1985), with the three largest floods in 1862, 1872 and 1926. In 1862, three weeks of relentless heavy rain over the Swan–Avon catchment covered Perth, including

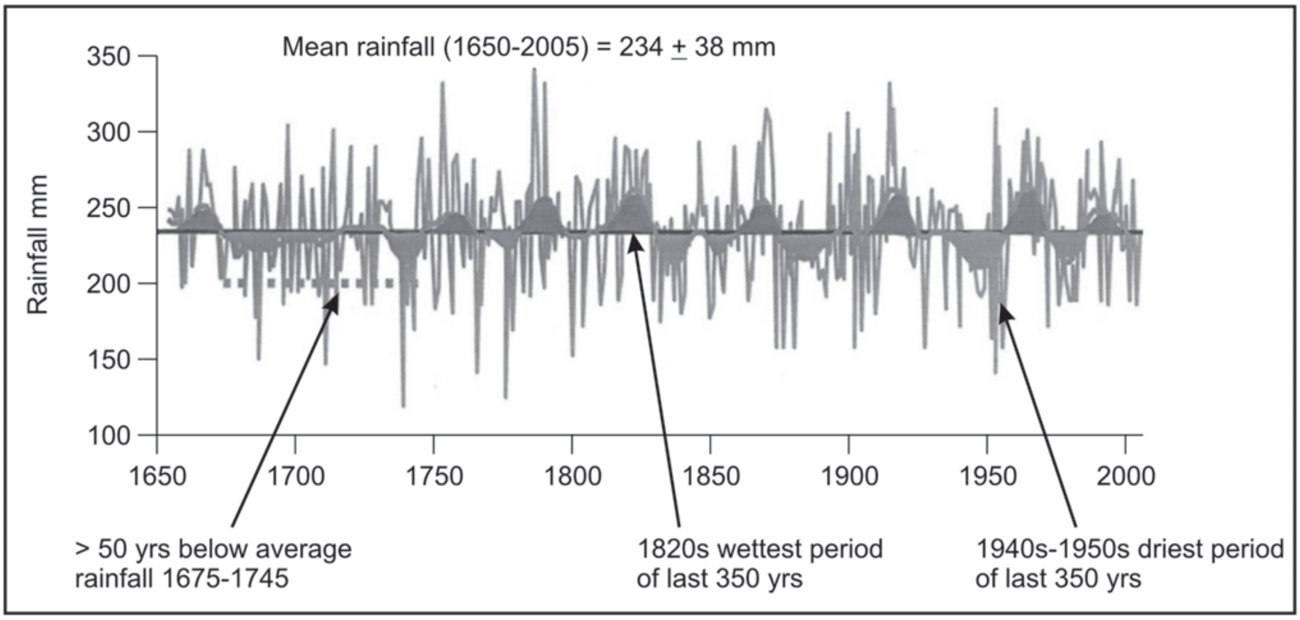

Figure 1 Reconstructed autumn–winter rainfall at Lake Tay from tree rings in *Callitris columellaris* (Cullen & Grierson 2009).

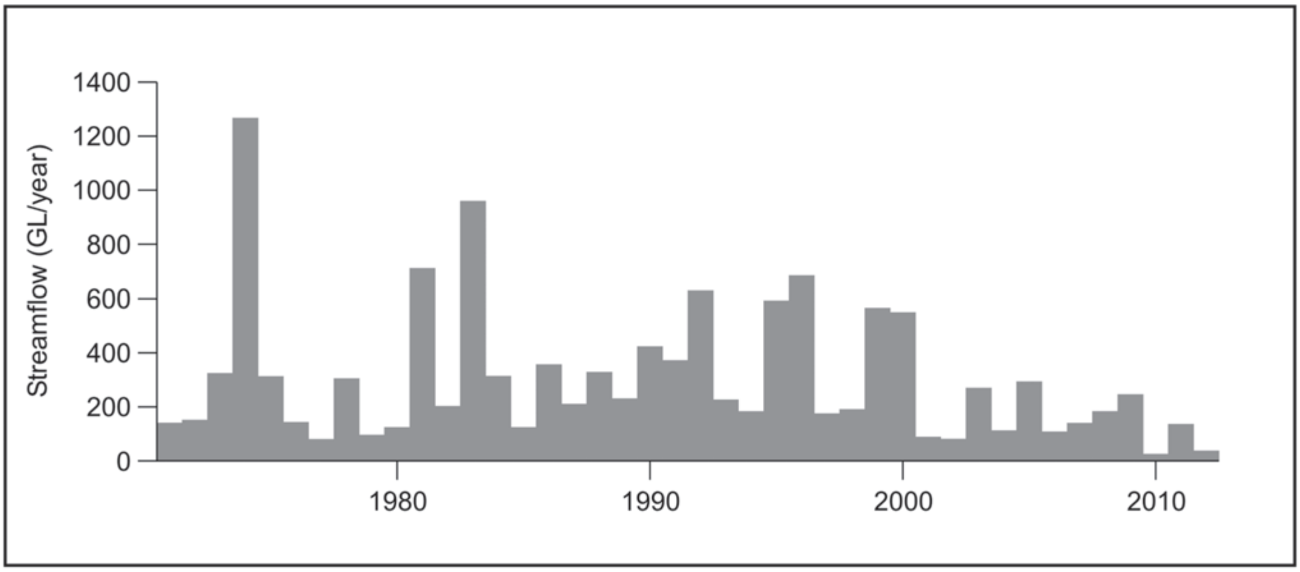

Figure 2 Annual streamflow in the Avon River at Walyunga station 616011 since 1971 (Department of Water).

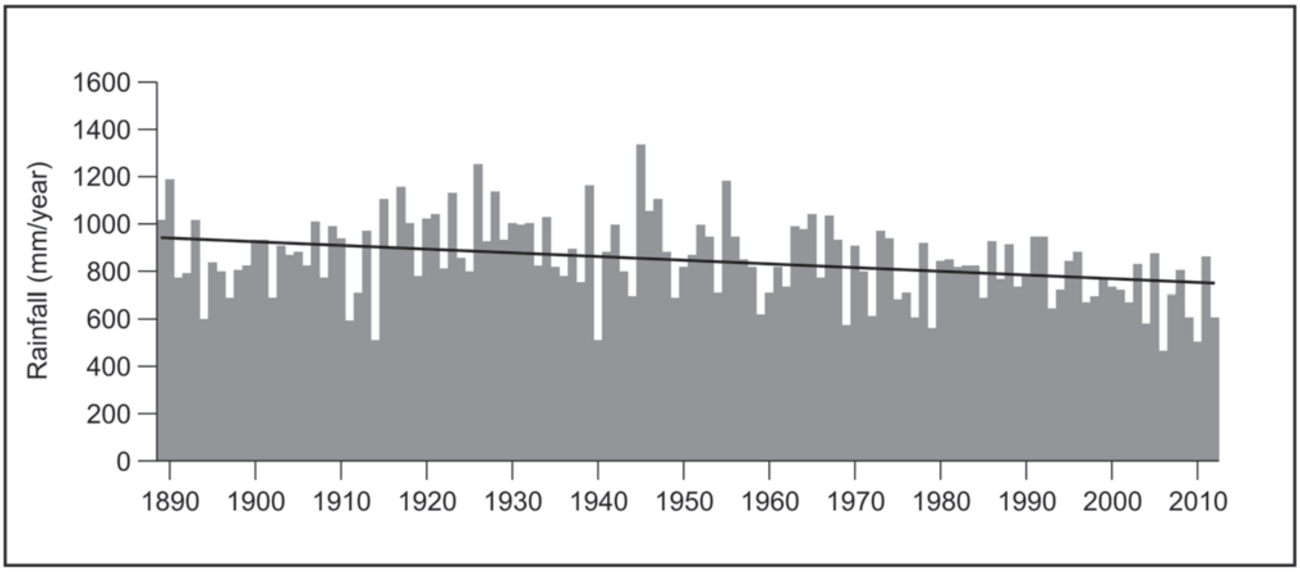

Figure 3 Perth annual rainfall 1889–2012.

the Causeway in over 2 m of flood waters for weeks. Properties and farms were destroyed and the bridge over Canning River was washed away. There were similar conditions in 1872.

In July 1926 severe and widespread flooding in the Avon, Swan and Helena River districts caused the Fremantle railway bridge and the Upper Swan bridge to collapse. The river burst its banks at Barrack Street, submerging jetties and bursting into offices. Flood waters encroached 137 m onto the foreshore. In South Perth, 14 houses were inundated between Scott Street and Mill Point. Waves surged along Mill Point Road and residents sailed a yacht up suburban streets, according to newspaper reports at the time. Market gardens along the river at Mounts Bay Road and in Belmont and Maylands were flooded by over a metre, and houses in South Guildford were submerged up to their roofs. Despite extensive reports of damage the waters did not reach the height of the 1862 floods.

Early maps of Perth show extensive wetlands, but by the late 1800s, there appear to be generally dry conditions. In the early 1900s though, rising groundwater levels were recorded from numerous locations including Lake Claremont (Butlers Swamp), Shenton Park Lake (Dysons Swamp), Mabel Talbot Reserve and Perry Lakes. It is difficult to separate the effects of clearing and rainfall but following high rainfall in 1917 and succeeding years (Figure 3), seasonal wetlands (previously named swamps) became permanent lakes. In the 1920s, drainage was a preoccupation in Perth, with the building of the tunnel outfall from Herdsman Lake and draining of Shenton Park Lake which had flooded adjacent houses. From historical evidence, Rich (2004) believed that Herdsman Lake experienced a unique period of higher water levels in 1920–1960 not experienced during 1847–1915, or after 1960. While the effects of clearing cannot be discounted as an additional factor, it appears our view of the vegetation systems and groundwater-fed wetlands around Perth are coloured by a historically wet period.

By plotting the rainfall (Figure 4) expressed as Cumulative Departure from Mean (CDFM) Yesertener (2005, 2008) showed how the cyclic rainfall pattern controls shallow groundwater levels in the Gnangara Groundwater Mound, explaining the historical evidence from wetlands. Most recorded groundwater levels in the Gnangara Mound start in the early 1970s, and thus reflect the overall decline in response to the rainfall cycle.

SURFACE WATER RESOURCES

Darling Range runoff

Following the completion of the Victoria Reservoir in 1891, nearly all the suitable rivers in the Darling Range have been dammed, but in the last decade, successive drought years (2001, 2006, 2010 and 2012) have severely impacted on streamflow (Figure 5). Streams which had flowed continuously from the 1960s ceased in the summer of 2011. It has been shown that evapotranspiration from deeply rooted eucalypts increases following drought years, lowering groundwater levels below streambed elevations, thereby reducing catchment water yield and dam inflows (Hughes *et al*. 2012). Rainfall that once generated significant flow during the winter months is now absorbed into dry soil horizons and more readily transpired.

The long-term groundwater and streamflow records, partly collected as a result of concerns about bauxite mining impacting on stream-water quality, have been invaluable in highlighting the interplay of vegetation, groundwater and streamflow in a drying climate with

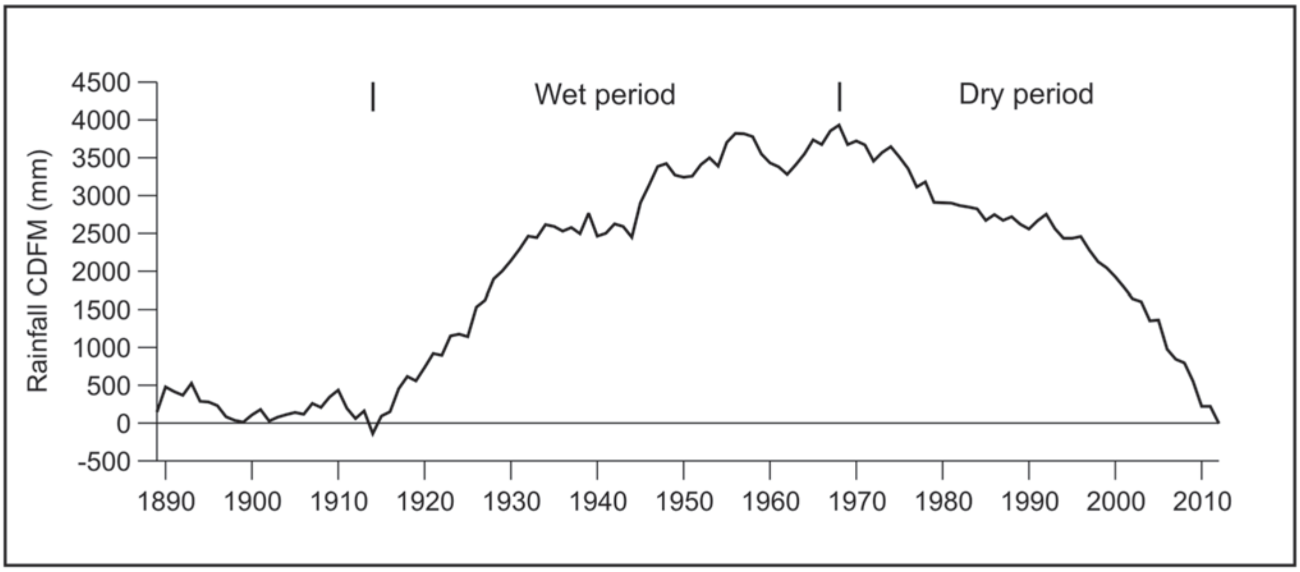

Figure 4 Perth rainfall plotted as cumulative departure from mean (CDFM). The period to 1913 is slightly below the long-term average. The period from 1917 to 1935 is well above and to 1969 somewhat above, whereas the period from 1975 is well below. Shallow groundwater levels mirror these trends.

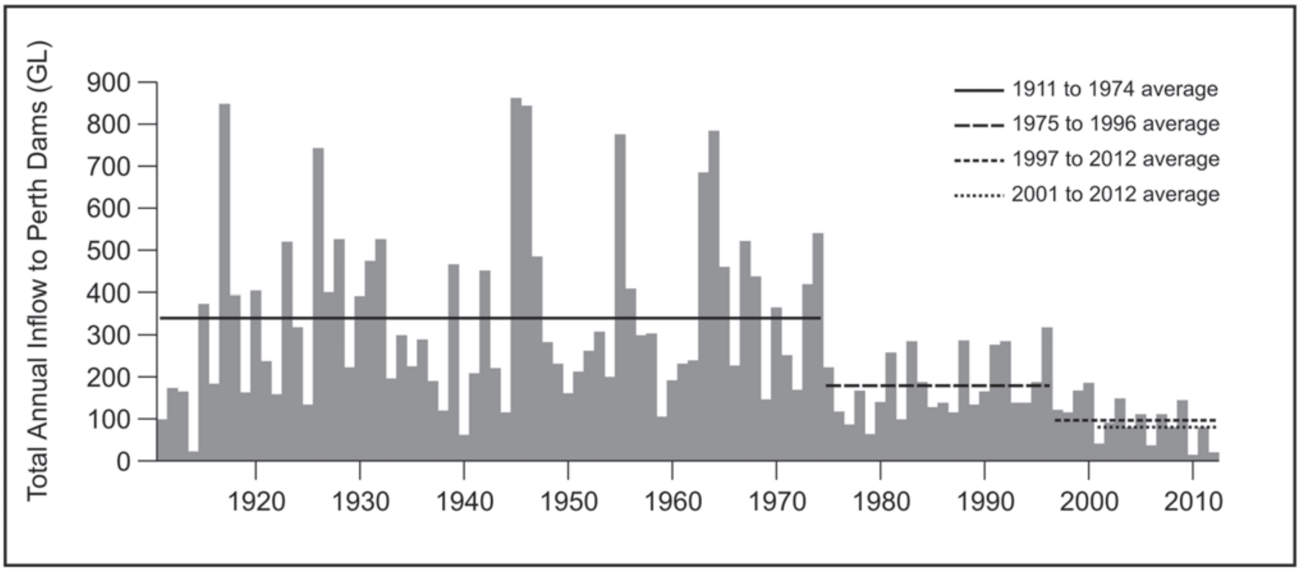

Figure 5 Annual streamflow into major surface water reservoirs in the Darling Range (Water Corporation).

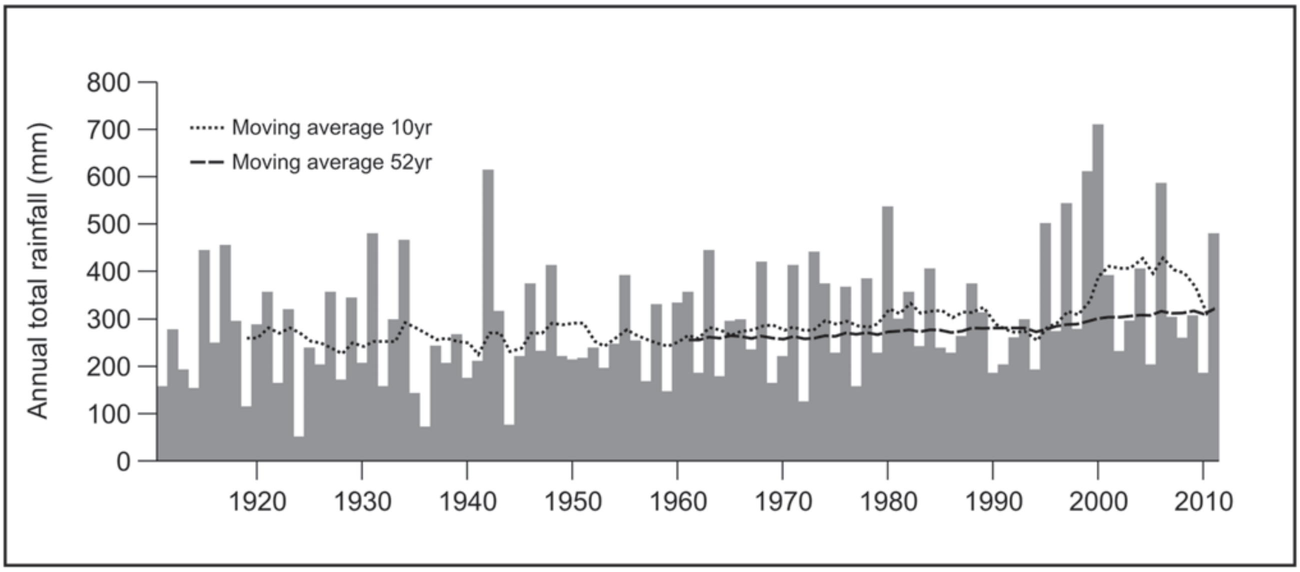

Figure 6 Averaged annual rainfall for the Pilbara for 1910–2012, along with backward moving averages of 10 and 52 years (Charles *et al*. 2013)

important implications for future water supply and the function of aquatic ecosystems.

Durrant (2009) reported on the difficulty of analysing trends in rainfall–runoff relationships since the step-change in rainfall in 1975, which could not be attributed solely to the lower rainfall. Several factors affect individual catchments: increased surface-water and groundwater use, declining groundwater levels, land-use changes, farm dams and regulation. She noted that the rainfall analysis post-1975 showed a reduction in maximum daily rainfalls averaged over the last decade, which could impact on infiltration rates and general 'wetting up' of the catchment, resulting in a reduction of baseflow contribution to streams. These decreases in rainfall take time to reach equilibrium in the groundwater signature. Evidence of a change in the streamflow regime is seen with the shift in the peak flow month (one month later) that has been observed across all sites in the southwest.

Pilbara and Kimberley runoff

In contrast to the declining rainfall in the southwest, annual rainfall in Pilbara (Figure 6), and especially the central and east Pilbara has increased since about 1960 (Charles *et al*. 2013).

Systematic records of runoff in the Pilbara and Kimberley only commenced in the 1960s, though there is historical evidence from flood marks. The pattern of most northern rivers, both Pilbara and Kimberley, is one of increased runoff after 1999 (Figure 7). Devastating floods in the Gascoyne River at Carnarvon in 2010 and 2011 destroyed horticultural crops, cut off transport links and damaged homes and major infrastructure, and a new levee system is being built 10 km east of the town to mitigate the effect of flooding.

An unexpected feature of the increased runoff in the Pilbara was that of increases in groundwater salinity in bores adjacent to or recharged from rivers (Commander *et al*. 2004). This is possibly due to wetter catchments subject to evaporation, and denser vegetation close to the rivers, with the salts being recharged into groundwater with the first flush of succeeding runoff events. This effect has also been noted by Bennett & George (2011) in the Keep River, on the Northern Territory border. The river had been intermittent from 1965 until the initiation of the mid-1990s wet phase, becoming perennial (around 30 ML/day) in 2000, with a consequent increase in salinity from 100 mg/L to around 350 mg/L, forecast to increase to 1000 mg/L.

CLIMATE CHANGE EFFECT ON WATER RESOURCES

Surface water in the Darling Range

Silberstein *et al*. (2012) noted that the 16% rainfall reduction in the southwest after the mid-1970s resulted in declines of more than 50% in streamflows into the major water supply reservoirs in the Darling Range. They looked at projections from 15 global climate models (GCM) which suggest that the climate will be drier and hotter by 2030. Fourteen of the fifteen GCMs project further rainfall declines over the region, with a median decline of 8% resulting in a median decline in runoff of 25%, and continuing the downward trend in runoff. Projected runoff declines under a dry future scenario vary from 53% in the northern part of the Darling Range to 40% in the southern region. While proportional decline in runoff is greatest in the northern part of the area, the greatest volumetric declines are in the wetter basins in the southern part. The projections are also for a substantial reduction in the frequency of high runoff yielding years and a reduction in the area producing high levels of runoff. The results indicate the already large reductions in runoff recorded since 1975 are likely to continue under future climate projections.

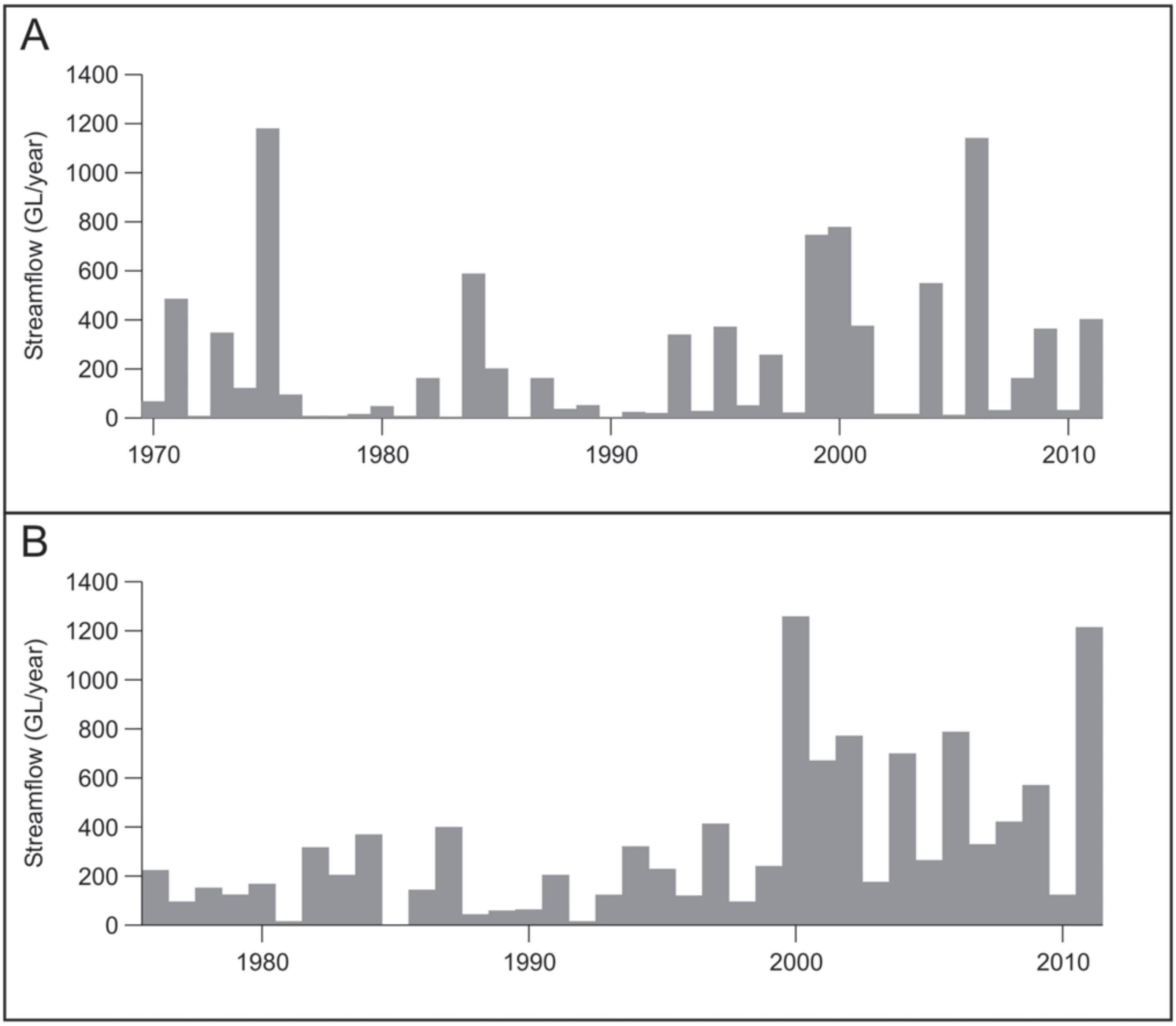

Figure 7 Annual streamflow in (a) Fortescue River at Gregory Gorge station 708002; (b) Dunham River at Dunham Gorge station 809321 (Department of Water).

Groundwater in the southern Perth Basin

Groundwater systems such as the Gnangara Mound have been shown to be very sensitive to rainfall changes (Yesertener 2005). Ali *et al*. (2012a) mapped out areas where groundwater levels may be most affected by a future drier climate and found that levels were most stable under areas with high water tables used for cleared dryland agriculture. McFarlane *et al*. (2012) concluded that in some cleared farming areas, groundwater levels would continue to rise, even under a dry climate scenario [the rate of groundwater level rise under farmland in the agricultural areas had slowed markedly since 2001, but are generally continuing (George *et al*. 2008)].

Ali *et al*. (2012b) assessed climate change impacts on water balance components of the regional unconfined aquifer systems in southwest coastal catchments. Compared with the historical period of 1975–2007, reductions in the mean annual rainfall of between 15 and 18% are expected under a dry variant of the 2030 climate, which will reduce recharge rates by between 33 and 49% relative to that under the historical period climate. Relative to the historical climate, reductions of up to 50% in groundwater discharge to the ocean and drainage systems are also expected. They suggested that seawater intrusion is likely in the Peel–Harvey Area under the dry future climate and net leakage to confined systems is projected to decrease by up to 35% which will cause reduction in pressures in confined systems under current abstraction.

WATER RESOURCE MANAGEMENT

The current State Water Plan (Department of Premier and Cabinet 2007) followed the 2001 low-rainfall year, and its development period included the investigation and shelving of the southwest Yarragadee proposal, the decision to build a seawater desalination plant, the Fitzroy canal proposal, the National Water Initiative, and the reconstitution of water management into the newly created Department of Water. The plan recognised the need to adapt to climate change, and the need for more metering and monitoring to improve the integrated management of water for the environment and other public values. It recognised that water use had tripled over 25 years, with groundwater accounting for over three-quarters of water used, and recognised that increasing demand for water would be met through water conservation, efficiency and recycling.

The plan outlined a water policy framework, among other things ensuring water management plans address issues in context of whole-of-State objectives, and facilitating the implementation of the National Water Initiative in a 'manner appropriate' for Western Australia. Where possible, planning was to be integrated to address the sustainability of the resource, water use, protection of catchments and drinking water sources and management of other impacts. One of the seven priority activities for 2007–2011 was to 'invest in science, innovation and education' specifically including 'groundwater investigation' (which had been previously addressed in the 2003 Auditor General's report).

The National Water Initiative was born out of issues affecting the Murray Darling Basin, but there are fundamental differences between the Murray Darling Basin and the variety of groundwater systems in Western Australia. Unlike the Murray Darling Basin, where groundwater and surface water resources are intimately connected, surface and groundwater in Western Australia are generally geographically separate, and the problem of double accounting, where the same water was allocated as both groundwater and surface water, does not generally apply in Western Australia. In an economic context, groundwater in Western Australia was already more often being used for high-value crops and the former Water Authority of Western Australia had already been leading Australia in capping groundwater abstraction and defining environmental water provisions.

Full allocation, the amount the Department of Water is prepared to let licensed users pump, has now been reached in a number of groundwater sub-areas, and is likely to be reached throughout in the Perth Basin within a decade or so. Some areas are also over-allocated under the current drier climate, and programs have commenced to alleviate the situation. However, allocation limits are a management tool to control impacts, and questions such as 'how much water do we have?' or 'will it run out?' should really be reframed as 'at what rate are we prepared to use it, considering the impacts?' More intensive groundwater level monitoring and assessment of ecological dependencies are needed to assess whether impacts from groundwater abstraction are acceptable, and owing to the large groundwater storages, it may be many years before the effects of abstraction become apparent.

In the State's fractured rock provinces, where mining is by far the major user, it is not likely that usage will be severely restricted, given that mines are dispersed, though locally mines may wish to pump at rates exceeding a sustainable yield for a defined timeframe.

WATER RESOURCE DEVELOPMENT

Development of the State's water resources has risen rapidly in the last few decades (Figure 8). Much of the expansion in groundwater use has been in the Perth Basin for urban and irrigation supplies. Groundwater use shown in Figure 8 also includes hypersaline groundwater pumped in the goldfields for carbon-in-pulp processing of gold ores, saline and brackish groundwater used in nickel ore processing, and groundwater pumped to dewater mine pits. In the Pilbara, where most of the dewatering takes place, much of the water is fresh, and excess water not required for processing is mainly discharged to the environment, reinjected, or used for irrigation.

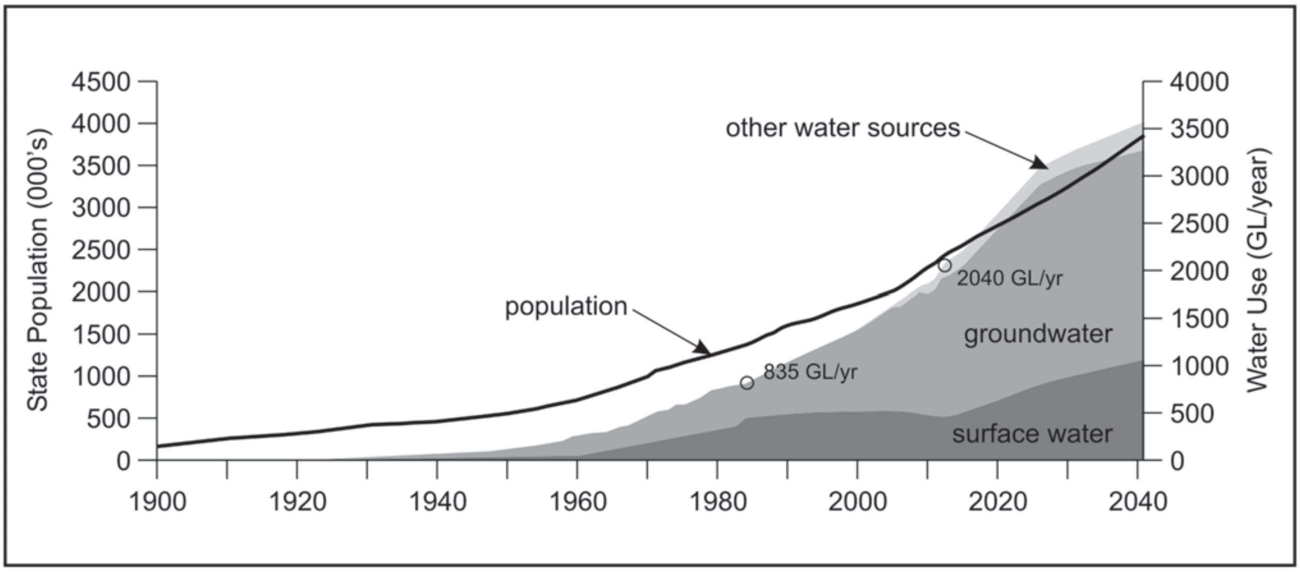

Figure 8 Water use in Western Australia, historical and projected to 2040 (Department of Water).

Irrigation

The current 'Water for Food' program of the Department of Agriculture and Food is aimed at stimulating irrigated agriculture in the Ord River Irrigation Area, Fitzroy Valley, La Grange (south of Broome), Pilbara, Carnarvon, West Midlands and Myalup. The project forecasts that about 1000 GL/a of low salinity (< 1000 mg/L TDS) water will be available to provide a base for 100 000 ha of irrigated agriculture. Some 7500 ha on the Weaber Plain, an area occupying a former channel of the Ord River extending across the Northern Territory border is currently being developed, following extensive investigation to assess the rising water table below the existing irrigation areas on the Ivanhoe and Packsaddle Plains, and to determine the suitability of the new land, which may require future groundwater pumping from the paleochannel aquifer. A program of land and water investigations commenced in 2012 across the sandplain soils surrounding Kununurra and the La Grange aquifer, and includes work with traditional owners coupled with an analysis of land tenure and markets for irrigated agricultural developments. Trials of cotton, and successful growing of melons, corn and cattle hay have demonstrated the potential of the La Grange area for irrigation.

Development of new crops has often proved difficult. In the Ord River Irrigation Area phases of development have included cotton, rice, sugar cane and sandalwood. In the northern Perth Basin, there has been recent expansion of vines, olives and almonds. Investigation of potential groundwater resources in the Birdrong Aquifer at Medo Station on the Wooramel River recently proved a resource of low salinity groundwater, but with poor recharge potential.

Mining

Development of the Goldfields was certainly hampered by lack of water in the first decade after 1892, leading to the abandonment of diggings, and the unsustainable use of wood-fired condensers to desalinate saline groundwater. The building of the Goldfields pipeline sufficed for the Kalgoorlie region until the 1980s when use of hypersaline groundwater from paleochannel aquifers enabled the current cycle of gold processing. Predictions made in the 1990s that groundwater from paleochannels in the Eastern Goldfields would run short, based on original estimates of groundwater storage, have not materialised, as paleochannel borefields have performed better than expected and yields have been maintained (Johnson 2007).

In the Pilbara, large-scale dewatering as mines go deeper below the water table has led to water surplus, and discharge of fresh groundwater to watercourses. Dewatering from the Woodie Woodie manganese mine is discharged to the Oakover River; from Yandi and Yandicoogina iron ore operations into Marillana Creek; and from Hope Downs iron ore mine to Weeli Wolli Creek. At the Marandoo iron ore mine, excess mine dewatering is being used to irrigate cattle fodder, rather than discharge it. Saline water at the Cloudbreak iron ore mine is re-injected into suitable aquifers. Potential iron mines in the Midwest are actively exploring for groundwater in the Murchison Catchment and the Permian sandstones in the eastern Carnarvon Basin.

Public water supply

Some 80 towns and numerous indigenous communities throughout the State depend on local groundwater supplies (Allen 1997b). In recent years, the supply from Geraldton's Allanooka borefield has been extended to Northampton and Yuna, replacing unsatisfactory local groundwater supplies, and groundwater from the Yarragadee Aquifer is being piped to Dunsborough, Margaret River and Bridgetown.

A significant water supply, discovered in the channel iron deposits of Bungaroo Creek, a tributary of the Robe River south of Pannawonica, is currently being pumped to Millstream for the West Pilbara Water Supply to be used in conjunction with the Harding Dam.

Garden bores

There are estimated to be about 170 000 garden bores in Perth, particularly located where blocks are large, the strata are sandy and the water table shallow, and less numerous in areas of clay, greater depth to water, hard limestone or high salinity.These are generally not licensed.

Lindsay (2004) assessed groundwater monitoring records in the urban area and concluded that in half of the 46 monitoring bores the water table had fallen an average of 0.8 m in 30 years. However, changes around the river and coast are small and greater changes occur inland. He concluded that water-level changes could be consistent with rainfall, though the bore network is not necessarily representative, with bores located preferentially near drains and wetlands. Smith *et al.* (2005) determined that groundwater levels had fallen under most of Perth in the previous 10 years period and that there was limited opportunity for additional backyard bores. Gaps in the bore monitoring record were identified, and have been subsequently filled using federal government funding.

The general fall in groundwater levels in many inner suburban areas has been tempered by urban infill, with increased infiltration via soakwells from greater roof and paving areas.

Superficial Aquifer

The Gnangara Groundwater System is the largest single groundwater source in Western Australia, servicing Perth's public water supply, parks and gardens, garden bores, horticulture and vineyards. Usage is around 321 GL/a (2009) close to one-fifth of Western Australia's groundwater use. It also supports wetlands, groundwater-dependent vegetation and stygofauna. The groundwater system encompasses the Superficial Aquifer (unconfined aquifer) between the Swan River and Gingin Book together with the underlying Leederville and Yarragadee Aquifers (the confined aquifers).

Of the total groundwater abstraction, 65% abstraction is from the Superficial Aquifer, of which 42% is for public water supply, 22% for horticulture, 18% for unlicensed garden bores and 9% for parks and gardens (Gallardo 2011).

The development of public supply borefields on the Gnangara Mound during the 1970s coincided with a major planting of pines and a decline in rainfall after

1975, and the combination of these three factors has resulted in declining water table levels of as much as 8 m, and consequent drying of wetlands. Ministerial conditions set for water levels around a number of wetlands in public wellfields in the 1990s have been breached, leading to 43 nearby production bores being turned off, though this measure has met with limited success.

A whole-of-government approach to managing the groundwater resources of the mound was set out in the Gnangara Sustainability Strategy. The Gnangara groundwater areas allocation plan (Department of Water 2009) sets out the approach to allocation and licensing for all water users on the Gnangara Mound. Through the plan, the Department of Water aims to achieve a reduction in the total abstraction from the Superficial Aquifer to address the trend of declining groundwater levels. The Forest Products Commission is responsible for modifying harvesting strategies of the pines to assist in increasing groundwater recharge, within the constraints of commitments to supply wood.

One of the management responses to declining groundwater levels on the Gnangara Mound has been the artificial maintenance of wetlands, using bores in either the superficial or underlying Leederville Aquifer. This has been attempted at Lake Jandabup, Lake Nowergup (Searle *et al*. 2011), Hyde Park and Perry Lakes and also, below the ground, in Yanchep Caves (Yesertener 2006), where seven of the estimated 300 caves previously had permanent groundwater-fed streams and pools supporting stygofauna associated with tuart root mat communities.

Lake Nowergup has been supplemented with groundwater from the Leederville Aquifer since 1989. With the continuing regional water table decline, supplementation has not been successful in meeting Ministerial water level criteria nor in maintaining a number of the lake's ecological values, including its vegetation, though the slower rate of decline in lake levels has protected the lake from acidification and possibly from eutrophication. Seale *et al*. (2011) suggested it is unlikely that the current Ministerial conditions will be met by the continuation even of artificial maintenance, and recommended that the current criteria were no longer appropriate for the site.

Yarragadee and Leederville Aquifers

The Yarragadee Aquifer has been used in Perth since the early 1900s (Davidson 1995) and is now used almost exclusively for public water supply. Most of the 'independent artesian bores' were drilled at reservoir sites in the urban area so that the water could meet peak demand periods, the water not requiring treatment for iron, unlike the Leederville Aquifer. Expansion of use took place at the end of the 1990s with the Wanneroo and Pinjar borefields and three new bores in the Gwelup borefield (Scarborough, Carine and Gwelup). Figure 9 shows a typical response of water levels to the expansion in production. The drawdown cone in the Yarragadee now extends from Mandurah to beyond Gingin Brook (Figure 10).

Abstraction from the Yarragadee Aquifer exceeds natural recharge, therefore groundwater is being taken from storage (GHD *et al*. 2012), with induced recharge occurring in the 'recharge window' southwest of Gingin (Pigois 2009) where the Yarragadee Aquifer is directly overlain by the Superficial Aquifer. This is a relatively small area of around 30km^2 which gives rise to the lobe of low salinity groundwater in the Yarragadee Aquifer extending southwest to City Beach. The abstraction from the newer bores was intended to be a short-term measure, but the shortage of surface water supplies after 2001 has meant the bores have been continuously pumped.

The change in water levels in the Leederville Aquifer is similar, with induced recharge from the

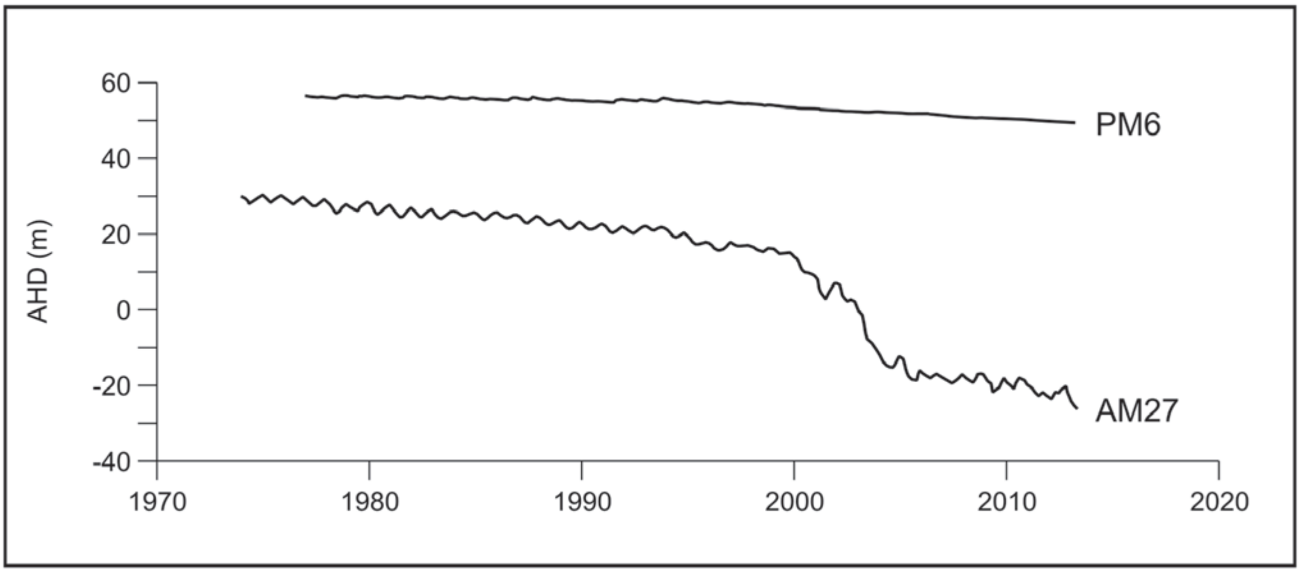

Figure 9 Water levels in the Superficial Aquifer at Pinjar Monitoring Bore PM6 on the central Gnangara Mound, and in the Yarragadee Aquifer Artesian Monitoring Bore AM 27 near Hillarys showing effect of increased production from confined aquifers in the late 1990s to early 2000s (Department of Water).

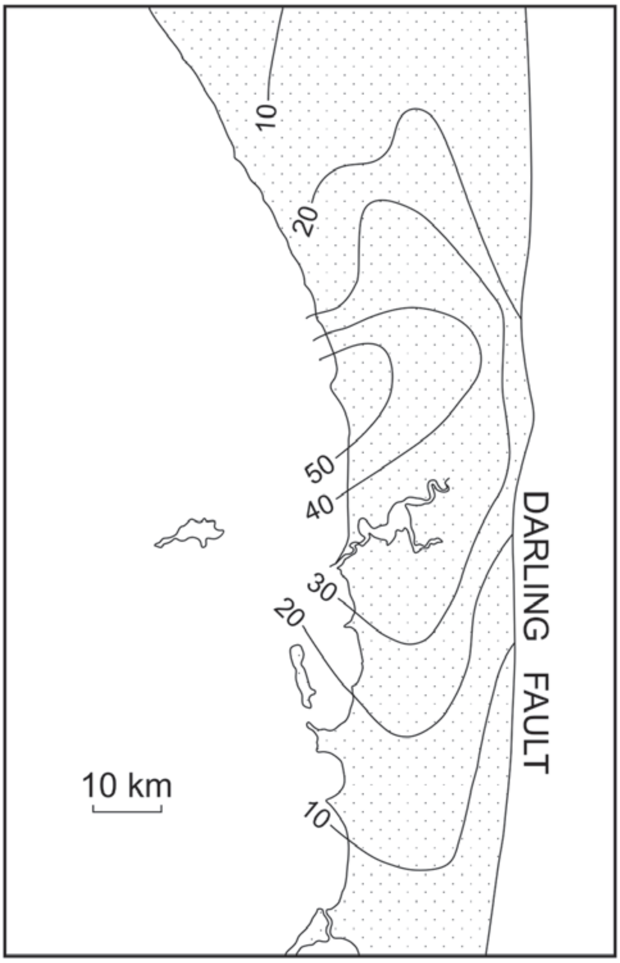

Figure 10 Change in water level (in metres) in Yarragadee Aquifer monitoring bores between 1977 and 2012 in the Perth region (Department of Water data). The Yarragadee Aquifer includes the Cattamarra Coal Measures adjacent to the Darling Fault in the southeast.

Superficial Aquifer indicated by the increased rate of water table decline near Leederville Aquifer production bores after increased pumping from the Leederville Aquifer (Figure 9).

Southwest Yarragadee case study

Exploration of the Yarragadee Aquifer in the southern Perth Basin started with the Quindalup Borehole Line in the 1960s. Subsequent drilling demonstrated greater thicknesses and lower salinity groundwater progressively to the south beneath the Blackwood Plateau. Following the low runoff in 2001 to the hills reservoirs, and lack of recovery to dam storage in the years after, the Water Corporation embarked on a comprehensive groundwater investigation involving some 12 000 m of drilling on the Blackwood Plateau with the aim of constructing a 45 GL/a scheme to augment the Integrated Water Supply Scheme. The difficulty of carrying out long-term pumping tests meant that there was a high degree of uncertainty about drawdown and effects on the Blackwood River and tributaries, supported by Yarragadee discharge, and the necessity of building a full capacity scheme at the outset prevented a staged approach.

Public opposition from local water users, who had expectation the resources would be used for the benefit of local farming and industry, and from environmental groups (including 'Friends of the Yarragadee'), made the decision too political, and a second desalination plant was a more certain option. The end results are that it will be difficult in future to contemplate such a groundwater scheme, given the likely opposition; the management of the aquifer has become more conservative, and the public is left ill-informed about the effects of pumping (Commander 2009).

Geothermal use of aquifers

A number of geothermal exploration permits, with a view to power generation, have been taken up in the Perth Basin, but to date use of geothermal heat has been limited to heating swimming pools. The first use of hot groundwater in Perth is reputed to be at the Zoological Gardens bore (1898) to heat the reptile house. The Dalkeith 'hot spring' was used for bathing, though on an unregulated basis, and was closed when the Sunset Home bore (in the Yarragadee Aquifer) was capped in the 1950s. In the modern era, the Melville Pool bore (1996) was the first of a number of bores to be drilled specifically into the Yarragadee Aquifer for heating a swimming pool. By 2013 there were pairs of bores, a deep abstraction bore and a shallower reinjection bore, at nine installations (Melville, Christchurch, Claremont, Challenge, St Hilda's, Beatty Park, Cannington, Craigie and Hale). The St Hilda's project in Mosman Park is 1007 m deep and provides water at 49°C.

The most favourable sites for geothermal bores are in Perth's western suburbs where the Kings Park Formation is thick, providing a thermal insulator, resulting in higher temperatures in the underlying Yarragadee Aquifer. Groundwater is also being used for cooling the Pawsley Centre supercomputer in Kensington, in this case reinjecting heated water into the Mullaloo Sandstone at 100 m depth.

RESPONSES TO WATER SCARCITY IN THE SOUTHWEST

In the face of much reduced runoff into the hills reservoirs and the declining water levels on the Gnangara Mound, the Water Corporation has adopted a policy of 'Security through diversity' utilising a range of ways of closing the demand–supply gap: groundwater, surface water, desalination, efficiency and recycling, catchment management, and water trading. These measures have largely enabled the Integrated Water Supply Scheme to avoid the severe restrictions suffered by other state capitals, although Western Australia's situation is ongoing.

The decision to build Australia's first large-scale (45 GL/a) seawater desalination plant at Kwinana for public consumption followed the low rainfall in 2001, and the complications of carrying out the southwest Yarragadee investigation in a tight timeframe. Opening in 2006, the plant provided some 17% of the Metropolitan area's supply needs. Shortly after in 2007, the decision was made to proceed with a second desalination plant at Binningup. This opened at the end of 2011, with a second stage opening in early 2013 giving an ultimate capacity of 100 GL/a, and contributing about half of the water supply to the Integrated Water Supply Scheme from desalinated seawater.

Groundwater desalination plants also exist elsewhere in the State, supplying the towns of Denham (from saline artesian water), Ravensthorpe, Hopetoun, Yalgoo and Rottnest (brackish shallow groundwater). Desalination plants supply water for mining across the State, and for industrial uses on the Burrup Peninsula.

An increasing emphasis on water use efficiency starting in the 1990s, has promoted the concept of water auditing—gaining an understanding of water use in industry and mining (Sturman *et al*. 2005). In 2001 the Water Corporation commenced a Water Wise Water Auditors Program which was tested in Kalgoorlie, where the capacity of the pipeline and storage at Kalgoorlie is limited. It involved such measures as replacing plumbing (eg dual-flush toilets and low-flow showerheads) and promoting brick paving over grass.

A $6 million metering program on the Gnangara Mound to meter horticultural bores has also made growers more aware of their water use, and together with other measures has increased water use efficiency.

Promotion of garden bores in Perth, to reduce demand on scheme water, resulted in more drilling after the 2001 low rainfall year, and was encouraged by a subsidy scheme, and online publication of the Perth Groundwater Atlas, whereby landowners could easily calculate the depth to the water table on their property. A further incentive was the two-day-a-week roster for garden watering with scheme water, though later garden bores were subject to a three-day-a-week roster, to achieve equity and general water conservation. The Water Corporation has also run a 'Save 60' campaign aimed at reducing each person's use by 60 L per week. In the Metropolitan area, these measures have resulted in per capita scheme water consumption dropping by 30% in the last 10 years.

A greater awareness of the value of water has led to the concept of water sensitive urban design (Western Australian Planning Commission 2006, 2008; Department of Water 2013), making use of the geography and soils in Perth that are mostly favourable to recharge of stormwater, whether from roofs and paved areas, into soakwells, or road runoff into sumps and wetlands, which can then, fortuitously, be used by garden bores.

The move toward water use efficiency (recognised in the State Water Plan 2007) has extended to the Carnarvon Basin, where free-flowing artesian water had been discharged into 'bore drains' to water stock. It was estimated that 95% of the water was wasted, contributing to overgrazing and inability to control feral animals, and by the 1990s some 40 out of the 120 flowing bores drilled between 1910 and 1930 had ceased to flow. The Carnarvon Artesian Basin Rehabilitation Project was set up as voluntary program of capping and controlling the flowing bores, piping the water to troughs instead of open bore drains, with a subsidy of 80% cost to pastoralists. By 2003, 45 bores had been decommissioned, and a further 12 by 2007, saving 8 GL/a at the surface and an estimated 35 GL/a in subsurface leakage, and allowing an overall rise in hydraulic head throughout the basin.

Treated waste water that is discharged to the ocean represents a significant resource. The Water Corporation has trialled Managed Aquifer Recharge from treated waste water at the Beenyup Waste Water Treatment Plant in Craigie, returning water to a high standard through microfiltration, ultraviolet radiation and a reverse-osmosis plant, prior to injection into the Leederville Aquifer, with intense monitoring and studies of the aquifer chemistry. The immediate benefit will be to raise hydraulic head in the aquifer, and it will be several decades before the injected water reaches nearby production bores. The decision to proceed with larger scale Managed Aquifer Recharge was made in August 2013.

Significant social consideration and education are required to increase water re-use for potable use, although reuse for non-potable use is already in place. The Kwinana Water Recycling Plant was commissioned in 2004 and processes about 24 ML/day of treated wastewater from the Woodman Point Waste Water Treatment Plant to produce high-quality, industrial-grade water for several local industries. The plant makes a significant contribution to the Water Corporation's 'climate resilience' target of achieving 30% wastewater re-use in the Perth metropolitan area by 2030. Importantly, it has significantly reduced industry demand in the area for scheme and bore water. In addition, all coastal waste water treatment plants that lack an ocean outfall (about 90%) dispose of their treated wastewater to a land site—often infiltration to the aquifer or a woodlot.

As the city's cheaper water sources have been developed, it is inevitable that costs of providing additional water will be progressively greater. The impact of higher cost desalination, and rebalancing fixed-consumption costs, has been felt by customers of the Integrated Water Supply Scheme with the base price of water per kL rising from around 50c per kL in 2007 to $1.30 in 2013, with the top rate of $2.60 per kL for household consumption over 550 kL/a. The sliding scale encourages lower water use, and reflects the cost of desalination compared with relatively cheap groundwater. Nevertheless, this is still inexpensive on a world comparison, and tap water is still a thousand times cheaper than bottled water.

While drinking water catchments have been maintained in a more or less pristine condition, to protect water quality, management of vegetation is being carried out to increase water flows. Pine tree removal on the Gnangara Mound should increase groundwater recharge, and thinning in hills catchments should increase runoff. However, a contrary program of revegetation in the Denmark catchment has been carried out to return the salinity to potable levels below 500 mg/L.

The increased awareness of the value of water is apparent in water trading. Commitments are made in the National Water Initiative to 'expand the trade in water'. This may be simple in a surface water system where sellers and buyers share the same water conduit, or can easily transfer water; it is not so straightforward for self-supply groundwater users with their own infrastructure on their own property. Moreover, groundwater users are permitted to take water from a defined aquifer at a point where the effects of withdrawal are judged to be acceptable. Moving the point of withdrawal could have undesired effects, drawdown at wetlands, for instance, and therefore each trade needs to be separately assessed under the *Rights in Water and Irrigation Act 1914.* Skurray *et al*. (2013) identified the impediments to groundwater trading in the Superficial Aquifer on the Gnangara Mound and found that facilitating infrastructure was lacking, and price information unavailable. Moreover, limiting trading to within management areas, and over-allocation and weak monitoring also impede the development of a market. Nonetheless, in terms of the National Water Initiative aim to 'bring about more productive water use' in the horticultural areas surrounding Perth, water is already used for high-value crops.

Another National Water Initiative objective is effective water accounting, providing information on how much water there is, as well as information on who is using it and for what purposes. The Department of Water has commenced annual water accounting, trialling the Gnangara Mound. It is intended to report on changes in groundwater levels from year to year, rather than reporting on quantities. Average groundwater levels for the Gnangara Mound have already been reported since 1997, similar to reporting of reservoir storage levels.

ISSUES ASSOCIATED WITH GROUNDWATER ABSTRACTION

Appleyard & Cook (2009) found that acidification was taking place in the Mirrabooka Borefield, with aeration and oxidation due to the lowered watertable leading to low pH (typically <5 at the water table) and elevated concentrations of heavy metals. This is likely to be widespread over the Gnangara Mound, but is not apparent in deeper monitoring bores. A program of mapping acid sulfate soils has been carried out in the Murray River area of the Swan Coastal Plain, and on the Scott Coastal Plain, to identify areas which might be at risk of acidification owing to watertable decline.

Seawater intrusion is a potential issue for all coastal borefields in unconfined aquifers, affecting Esperance, Albany, Bunbury, Kwinana, Perth, Exmouth, Broome and Derby. Bores have already had to be abandoned in peninsula suburbs in Perth, and it is a potential issue in Perth's northern coastal suburbs. Kretchmer & Degans (2012) documented the inland movement of the seawater interface in the Superficial Aquifer as a result of pumping from the Water Corporation's north coastal scheme, though there is no evidence yet of increased salinity in production bores.

Production of groundwater from confined aquifers releases water from elastic storage, and is accompanied by a volume reduction as the aquifer matrix compacts. In Perth, subsidence had been too small to measure until the advent of highly accurate Global Positioning Systems (GPS), and large declines in hydraulic head. In 1996, a high resolution GPS, part of Geoscience Australia's Australia-wide network, was installed at the Hillarys tide gauge, and this registered the change in elevation due to pumping the Yarragadee Aquifer (Figure 9). The total decline between 1996 and 2006 was about 50 mm (Jia *et al*. 2007; Featherstone *et al*. 2013), consistent with the head change of around 50 m in the Yarragadee (although the Leederville Aquifer also has an effect), and land subsidence over the Perth region can be inferred to mirror the change in head in the Yarragadee Aquifer (Figure 10).

Interest in shale and tight gas has caused concern among landowners worried about their groundwater supplies. Likely targets in the Perth Basin are the Kockatea Shale and Carynginia Formation several thousand metres deep, and below saline stagnant groundwater in overlying aquifers. The potential for fracking (hydraulic fracturing of shale and injecting sand and various chemicals) to affect the fresh groundwater flow systems in the overlying Yarragadee Aquifer is low, but a proliferation of deep wells crossing many strata increases the chances of a casing or grouting failure and leakage between aquifers. Nevertheless, various aquicludes separate the Kockatea Shale and Carynginia Formation from aquifers containing low-salinity groundwater.

Storage of carbon dioxide also has the potential to concern groundwater, mainly from the point of view of casing integrity, but there are unknown effects of pressurisation beyond natural levels. Current research on carbon capture and storage in aquifers is focussed on the Lesueur Sandstone on the Harvey Ridge west of Harvey. The Geological Survey of Western Australia drilled Harvey 1 in 2012 to depth of 2945 m where the aquifer is relatively shallow (Department of Mines and Petroleum 2012). Further evaluation and research is proceeding.

FUTURE FOR WATER RESOURCES

Increased demand for drinking water in the southwest is likely to be met by recycling and further desalination. Increased competition for horticultural water will see trading, higher prices and water use efficiencies. Pressure of urban development will continue to displace horticulture, and pressure will be placed on water catchments, when the cost of keeping the catchments pristine is weighed against the alternative costs of water treatment and seawater desalination.

In the north, the challenge for the State is to complete the irrigation developments in the Ord, develop groundwater in the Canning Basin, and use the untapped flows of the Fitzroy River, which have not been utilised since the failed Camballin irrigation project of the 1960s. While ever increasing quantities of water will be produced in the course of mining below the water table in the Pilbara, there is unlikely to be significant competition from or between mines as these are generally separated by considerable distances.

A drying climate is now built into water planning, and the era of low-cost surface water from hills' dams and groundwater is over, with desalination the new yardstick for price, and recycling the next opportunity, with public perception the greatest challenge.

Groundwater management has become more complex, with a need for more intense water-level monitoring and increasingly better understanding of hydrogeology as full allocation is reached, and the effects of variable climate incorporated. Water managers face the challenge of managing a dynamic environment undergoing change due to a drying climate, and understanding what can and what cannot be protected.

While surface water resources and groundwater recharge have declined in the southwest, there still remains vast storage of groundwater in the Perth Basin, though the widespread effects of increased pumping the Yarragadee and Leederville Aquifers (originally for short-term drought relief) is now becoming apparent. Continuing groundwater investigation is needed to improve the monitoring network in the Perth Basin.

There still remain large areas of the State where the groundwater resource is poorly known. The Canning Basin, Western Australia's largest sedimentary basin, is inferred to contain large groundwater resources but only the extreme southwest and northwest coastal portions of the basin have been investigated. As one of the largest supposed shale gas resources in the world, access and need for water will stimulate groundwater investigation and use. The Officer Basin, the subject of much media attention in 2000, remains 99% unexplored, yet there are likely to be significant fresh or brackish water resources in the basin waiting to be discovered.

While some water information is becoming more accessible with the Bureau of Meteorology's responsibility to keep and disseminate data, other sources, for instance the vast treasury of consultants' reports that are held by Government, are not yet open file and the hydrogeological mapping program, which came to a halt, has not been replaced by public access to digital information. Reporting in the form of water accounting will bring a greater transparency, and as more information becomes available it will be ever more important to integrate and consolidate the public and private knowledge.

ACKNOWLEDGEMENTS

Don McFarlane, Richard George and Chris O'Boy made significant contributions to the paper and Jacqui Durrant and Simon Rogers assisted with provision of surface water information and figure preparation. Colin Branch and Roger Hocking suggested substantial improvements to the text. Craig Miskell drafted the figures.

REFERENCES

Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I & Hodgson G 2012b. Potential climate change impacts on the water balance of regional unconfined aquifer systems in south-western Australia. *Hydrological Earth Systems Science* **16**, 4581–4601.

Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I, Hodgson G & Charles S 2012a. Potential climate change impacts on groundwater resources of south-western Australia. *Journal of Hydrology* **475**, 456–472.

Allen A D 1997a. A history of hydrogeology in the Geological Survey of Western Australia 1988–1995. *Geological Survey of Western Australia Annual Review for 1995–96*, 11–21.

Allen A D 1997b. Groundwater: the strategic resource—a geological perspective of groundwater occurrence and importance in Western Australia. *Geological Survey of Western Australia Report* **50**.

Appleyard S & Cook T 2009. Reassessing the management of groundwater use from sandy aquifers: acidification and base cation depletion exacerbated by drought and groundwater withdrawal on the Gnangara Mound, Western Australia. *Hydrogeology Journal* **17**, 579–588.

Aquaterra 2009. *Strategic review of the surface monitoring network report*. Report for Department of Water.

Auditor General 2003. Second Public Sector Performance report 2003. *Western Australia Auditor General Report* **7**.

Bekle H & Gentilli J 1993. History of the Perth Lakes. *Early Days* **10,** 442–460.

Bennett D L & George R J 2011. Surface water characteristics of the Weaber Plain and lower Keep River Catchments: data review and preliminary results. *Department of Agriculture and Food, Resource Management, Technical Report* **370**.

Binnie and Partners 1985. *Avon River flood study*. Report for Public Works Department, Western Australia.

Bridge E 1991. *The Great Australian Dream*. Private publication of Minister for Water Resources, Western Australia.

Bureau of Metereorology 1929. Results of rainfall observations made in Western Australia. Government Printer, Melbourne.

Charles S P, Fu G, Silberstein R P, Mpelasoka F, McFarlane D, Hodgson G, Teng J, Gabrovsek C, Ali R, Barron O, Aryal S K, Dawes W, Van Neil T & Chiew F H S 2013. Interim report of the hydro climate of the Pilbara: past, present and future. A report to the Western Australia Government and industry partners from the CSIRO Pilbara Water Resources Assessment, CSIRO Water for a Healthy Country, Australia.

Commander D P 2000. Massive water find in the Officer Basin: *Western Australian Geologist* **396**, 6–8.

Commander D P 2009. New water from old sources: case study of the south-west Yarragadee aquifer. *The Australian Geologist* **151**, 20–22.

Commander D P, Martin M W & Doherty R 2004. Increasing groundwater salinity in north-west Australia – a result of exceptionally wet years. *In:* Dogramaci S & Waterhouse A (eds) *Engineering salinity solutions*: *1st National Salinity Engineering Conference 2004. Barton, ACT*, pp. 73–77. Engineers Australia, 2004

Cullen L E & Grierson P F 2009. Multi-decadal scale variability in autumn-winter rainfall in south-western Australia since 1655 AD as reconstructed from tree rings of *Callitris columellaris*. *Climate Dynamics* **33**, 433–444.

Davidson W A 1995. Hydrogeology and groundwater resources of the Perth region WA. *Geological Survey of Western Australia Bulletin* **142**.

Department of the Premier and Cabinet 2006. *Options for bringing water to Perth from the Kimberley: an independent review*. <http://www.water.wa.gov.au/PublicationStore/first/64772.pdf>

Department of the Premier and Cabinet 2007. *State Water Plan 2007*. <http://www.water.wa.gov.au/PublicationStore/first/74923.pdf>

Department of Mines and Petroleum 2012. *South West CO_2 Geosequestration Hub: project and activity progress report for the Global Carbon Capture and Storage Institute*. <http://www.dmp.wa.gov.au/documents/South_West_Hub.pdf>.

Department of Water 2009. Gnangara groundwater areas allocation plan. *Department of Water Western Australia Water Resource Planning Series* **30**.

Department of Water 2013. *Water resource considerations when controlling groundwater levels in urban development*. Department of Water Western Australia.

Durrant J 2009. Streamflow trends in south west Western Australia. *Department of Water Western Australia Surface Water Hydrology Series* **HY32**.

Featherstone W E, Filmer M S, Penna N T, Morgan L M & Schenk A 2012. Anthropogenic land subsidence in the Perth Basin: challenges for its retrospective geodetic detection. *Journal of the Royal Society of Western Australia* **95**, 53–62.

GALLARDO A 2011. Resource evaluation report Gnangara groundwater areas allocation plan. *Department of Water Western Australia Hydrogeological Report Series* **HR 312**.

GEORGE R J, SPEED R J, SIMONS J A, SMITH R H, FERDOWSIAN R, RAPER G P & BENNETT D L 2008. Long term groundwater trends and their impact on the future extent of dryland salinity in WA in a variable climate. Proceedings of the 2nd International Salinity Forum, Adelaide 30 March-3 April 2008 (CD).

GHD, ECOSEAL, VANESSA O'KEEFE & HAMSTEAD CONSULTING 2012. Guidance for groundwater storage utilisation in water planning. *National Water Commission Canberra, Waterlines Report Series* **81**.

HUGHES J D, PETRONE K C & SILBERSTEIN R P 2012. Drought, groundwater storage and streamflow decline in southwestern Australia. *Geophysical Research Letters* **39**, DOI: 10.1029/2011GL050797.

JIA M, ENGLISH P, COMMANDER D P & JOHNSTON G 2007. GPS observation of compaction or expansion of the Perth Basin aquifer system. *American Geophysical Union Fall Meeting 2007 Abstract* **G43B-1212**.

JOHNSON S L 2007. Groundwater abstraction and aquifer response in the Roe Palaeodrainage (1990 - 2001). *Department of Water Western Australia Hydrogeological Record* **HG23**.

JOHNSON S L, COMMANDER D P, O'BOY C A & LINDSAY R P 2005. Proposed groundwater investigation program in Western Australia (2005 to 2020). *Department of Environment Western Australia Hydrogeology Record* **HG 10**.

KRETSCHMER P & DEGANS B 2012. Review of available groundwater in the Superficial aquifer for the Yanchep, Eglinton and Quinns groundwater subareas. *Department of Water Western Australia Hydrogeological Report* **HR330**.

LINDSAY R P 2004. Water level monitoring results for the superficial aquifer in the Perth Urban Area. *Department of Environment Western Australia Hydrogeology Report* **HR 225**.

LI Y, LI J & FENG J 2012. A teleconnection between the reduction of rainfall in southwest Western Australia and North China. *Journal of Climate* **25**, 8444–8461.

MAITLAND A G 1897. Annual progress report of the Geological Survey for the year 1896. Department of Mines Western Australia.

MAITLAND A G 1913. *Appendix M. The artesian water resources of Western Australia*. Report of Proceedings Interstate Conference on Artesian Water, Sydney, 1912.

MAITLAND A G 1919. The artesian water resources of Western Australia. *Geological Survey of Western Australia Memoir* **1**, Part II, Section 24, pp. 5–7.

MCFARLANE D, STONE R, MARTENS S, THOMAS J, SILBERSTEIN R, ALI R & HODGSON G 2012. Climate change impacts on water yields and demands in south-western Australia. *Journal of Hydrology* **475**, 488–498.

PIGOIS J-P 2009. Conceptual geology of the north Gnangara Mound. *Department of Water Western Australia Hydrogeological Report* **HR 228**.

RICH J F 2004. Integrated mass, solute, isotopic and thermal balances of a coastal wetland. PhD thesis, Murdoch University, Murdoch (unpubl.).

SEARLE J A, HAMMOND M J & BATHOLS G 2011. Perth Shallow Groundwater Systems Investigation: Lake Nowergup. *Department of Water Western Australia Hydrogeological Record* **HG 40**.

SILBERSTEIN R, ARYAL S, DURRANT J, PEARCEY M, BRACCIA M, CHARLES S, BONIECKA L, HODGSON G, BARI M & MCFARLANE D 2012. Climate change and runoff in south-western Australia. *Journal of Hydrology* **475**, 441–455.

SKURRAY J, PANDIT R & PANNELL D J 2013. Institutional impediments to groundwater trading: the case of the Gnangara groundwater system of Western Australia. *Journal of Environmental Planning and Management* **56**, 1046–1072.

SMITH A, POLLOCK D & MCFARLANE D 2005. *Opportunity for additional self supply of groundwater from the superficial aquifer beneath Metropolitan Perth*. Client Report, CSIRO: Water for a Healthy Country National Research Flagship, Canberra.

STURMAN J, HO G & MATTHEW K. 2005. *Water auditing and water conservation*. IWA Publishing, London.

TREBLE P C, BRADLEY C, WOOD A, BAKER A, JEX C N, FAIRCHILD I J, GAGAN M K, COWLEY J & AZCURRA C 2013. An isotopic and modelling study of flow paths and storage in Quaternary calcarenite, SW Australia: implications for speleothem paleoclimate records. *Quaternary Science Reviews* **64**, 90–103.

TREBLE P C, FAIRCHILD I J & FISCHER M J 2008. Understanding climate proxies in southwest-Australian speleothems. *PAGES News* **16**, 17–19.

TREBLE P C, SHELLEY J M G & CHAPPELL J 2003. Comparison of high resolution sub-annual records of trace elements in a modern (1911-1992) speleothem with instrumental climate data from southwest Australia. *Earth and Planetary Science Letters* **216**, 141–153.

WATER CORPORATION 1999. *Kalgoorlie Boulder WaterLink Final Report*. Water Corporation Western Australia, Perth.

WESTERN AUSTRALIAN PLANNING COMMISSION 2006. *State planning policy 2.9: Water Resources*. Western Australian Planning Commission, Perth.

WESTERN AUSTRALIAN PLANNING COMMISSION 2008. *Better urban water management.* Western Australian Planning Commission. Perth.

YESERTENER C 2005. Impacts of climate, land and water use on declining groundwater levels in the Gnangara Groundwater Mound, Perth, Australia. *Australian Journal of Water Resources* **8**, 143–152.

YESERTENER C 2006. Assessment of the artificial maintenance of groundwater in Yanchep caves—groundwater flow modelling. *Department of Water Western Australia Hydrogeological Record* **HG13**.

YESERTENER C 2008. Assessment of the declining groundwater levels in the Gnangara Groundwater Mound. *Department of Water Western Australia Hydrogeological Record Series* **HG14**.

Received 13 August 2013; accepted 14 February 2014