Managing groundwater levels in the face of uncertainty and change: a case study from Gnangara
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ABSTRACT

The Gnangara Groundwater System meets about 50% of all water needs for the Perth–Peel region of Western Australia (population 1.7 million). Much of the water is contained in an unconfined aquifer which occurs in coastal sand dunes and supports ecologically-important throughflow wetlands. The system has been subject to significant climate change since about 1975, although the persistent and unidirectional nature of the change was not recognised for some time. As well as climate, groundwater levels are affected by land use (e.g. plantation forestry, urbanisation) and land management (e.g. how plantations and stormwater are managed) as well as by the amount of groundwater abstraction from each of several inter-connected aquifers. Land, water and forests are managed by different government agencies with their own policy objectives. Maintaining groundwater levels within an agreed range of values to protect the wetlands requires informed and early adaptation by these agencies as well as a supportive community. Adaptation was hampered because there was little or no experience of managing groundwater for climate change and the causes of declining levels were neither clear nor agreed. Even when target water level decisions were agreed, their achievement required the cooperation of parties with different priorities. This paper examines some of the lessons learned from this experience and the current approach to manage the land, water and forest resources to meet multiple objectives in a system that is undergoing transitional change rather than reaching a new equilibrium. Climate change impacts have been progressive and the concept of a system that can respond in a resilient manner after a temporary perturbation is not an appropriate concept in this example. Climate adaptation involves significant social and institutional change as well as biophysical changes to make the most of a changing system.

Key words | adaptive management, climate change, groundwater management, land use planning

INTRODUCTION

Like many coastal cities with nearby surface water catchments, Perth (population 1.7 million) in south-west Western Australia relied on streamflow into reservoirs for most of its drinking water during the 20th century. In 1975 about 84% of drinking water came from these dams with the balance coming from aquifers contained within sediments within the Perth Basin. A climate shift in 1975 resulted in a 10 to 15% reduction in annual rainfall and a 50 to 70% reduction in streamflow (Bates et al. 2008). Research has indicated that about half of the change in rainfall can be attributed to elevated greenhouse gases with the balance being due to climate variability (Cai & Cowan 2006).

Perth also had access to water from the Gnangara Groundwater System (GGS) which consists of an unconfined aquifer contained in a series of coastal dune systems and several deeper confined aquifers which contained water that in some cases is over 40,000 years old. This water source was first accessed using shallow wells soon after first settlement in 1829 when it was discovered that Rainwater....
surface water springs and lakes dried over summer making them unreliable (Hunt 1980; Lund & Martin 1996). Contamination of the unconfined aquifer with sewage resulted in drinking water being increasingly sourced from deeper artesian aquifers and, after the first hill dam was completed in 1891, from reservoirs in the Darling Range located east of the city. In 1975 only about 16% of drinking water was being supplied by groundwater. However following the sharp decline in streamflow after 1975 this proportion increased progressively to being over 60% since 2002.

Groundwater has been an important water source for non-potable uses such as peri-urban horticulture, the irrigation of parks and domestic gardens and for domestic use in areas outside the drinking water supply area. It also supports a large number of groundwater throughflow wetlands which were initially considered as impediments to economic development but are now recognised for their ecological values. Currently about 50% of all water use in the Perth–Peel area is from the GGS with additional groundwater also being accessed further south.

This paper examines the response to the decline in rainfall commencing in the mid 1970s and how the important interactions between land use, land management and water extraction became crucial to meeting competing social, economic and environmental values. Management systems are usually not designed to cope with complex and multiple value systems. This required the state government to explore new land and water management strategies.

This case study is important because the south west of Western Australia is recognised as being one of the parts of the world where climate change has most affected water resources (Hennessy et al. 2007; Bates et al. 2008; CSIRO 2009). It is likely that other areas may experience similar changes in future and lessons may be learned from an examination of what has worked and what could have been done better.

### STUDY SITE

**Climate change in south Western Australia**

The south-west of Western Australia has a Mediterranean climate characterised by cool wet winters and hot dry summers. The long-term average annual rainfall in Perth is 854 mm and over 80% falls between the months of May and October. The reliability of the rainfall has traditionally been high.

Prior to 1975, storms with high rainfall intensities and wetter than average years resulted in significant runoff into reservoirs and recharge into aquifers. There is evidence from rainfall stations around the region that extreme rainfall intensities (e.g. >30 mm/day) underwent a profound reduction since about 1965 (Li et al. 2005). Monthly rainfalls in stations that straddle the Gnangara Mound show a reduction in rainfall (Figure 1). Whereas about 17 months per decade would have rainfalls in excess of 150 mm prior to 1970, the number is now only about 7. Comparisons of annual and monthly rainfall have also shown that rainfall has decreased in the Perth region by between 10 and 15% since about 1975 (Bates et al. 2008). This has resulted in streamflow reductions in excess of 50%, initially due to the reduced rainfall and later due to groundwater levels falling below the invert of streams (Petrone et al. 2010).

### The Gnangara groundwater system

The GGS consists of several interconnected aquifers as shown in Figure 2.

1. The Superficial Aquifer is unconfined and contained within Cainozoic sand dunes which underlie about three-quarters of the city. In the north the dunes are covered by native (Banksia spp.) woodlands, pine plantations and peri-urban agriculture.

![Mean Frequency of Cumulative Monthly Rainfall per Decade](chart.png)

**Figure 1** | Incidence of monthly rainfalls in excess of 100, 150 and 200 mm over the past ten decades (Government of WA 2009a).
2. The Leederville Aquifer is contained within Cretaceous sediments and is confined when below the Osborne Formation (Figure 2). It receives recharge from the overlying Superficial Aquifer. It contains groundwater of about 5,000 years old near intake areas and between 20,000 and 30,000 years old in deeper areas.

3. The Yarragadee Aquifer is contained in Jurassic sediments and confined by overlying formations. At depth it contains water more than 40,000 years old.

The Gnangara Mound has its highest elevation in the north east where it is about 70 m above sea level (Figure 3). Recharge is by annual rainfall and discharge is by evaporation from wetlands and groundwater dependent ecosystems, and discharge to the Indian Ocean, Swan Estuary and gaining streams to the north and east. The wetlands occupy inter-dunal swales, wind deflation areas and areas underlain by clayey sediments adjacent to major rivers. Most wetlands that occur in the sand dune systems show a close correspondence between groundwater and lake levels because they are groundwater throughflow systems. This has placed limits on the amount of water than can be extracted because a fall in groundwater levels can result in wetlands drying and losing their ecological value. Extracting water from underlying confined aquifers can also exert a delayed and diffuse impact on the water table and therefore on wetlands. However, the impacts are usually attenuated and hard to distinguish from other factors that affect groundwater levels.

**History of groundwater use**

Before 1980, most groundwater for public supply was taken from the Superficial Aquifer in what is now described as environmentally sensitive areas (Figure 4). Between 1990 and the present, most water has come from the Leederville and Yarragadee confined aquifers, and an increasing amount from the Superficial Aquifer under less environmentally sensitive (mainly urban) areas. The decreased abstraction from the environmentally sensitive areas resulted from engineers working with wetland experts and also with the involvement of the newly formed...
Environmental Protection Authority. Initially, urban areas (Figure 3) were avoided because of the risk of groundwater contamination from septic tanks, industry, below-ground petrol storage tanks and stormwater runoff. Experience from abstraction from urban bore fields has been that contamination has not been a significant problem. In addition, groundwater levels have declined in areas under native vegetation and pine plantations (Figure 3), but have been more robust in urban areas because of roof and road runoff being directed into the aquifer. As a result, additional abstraction has been made from the Superficial Aquifer in urban areas since about 1996 (Figure 4).

Abstraction for drinking water represents only about 45% of use of water from the GGS aquifers, and only 25% of use from the Superficial Aquifer. Self supply home garden use (58 GL/y) and horticulture (54 GL/y) are major users of unconfined groundwater with lesser amounts for parks and recreation (31 GL/y), domestic and rural lifestyle (14 GL/y, which includes drinking water for households not receiving reticulated water) and industrial and service use (13 GL/y). The number of backyard bores in the Perth–Peel region is estimated to be about 178,000, with about a third of all private gardens and lawns using unconfined groundwater. The remaining households use reticulated drinking water on their lawns and gardens which includes groundwater from the GGS. Backyard bores have been encouraged because they use non-potable water which reduces the demand for drinking quality water.

RESULTS

Hydrological response to climate change and management

All climates are variable so changes may not be recognised as being different from climate variability for many years. Acceptance that the pre-1975 climate was not a good basis for future planning was made at different times by managers, depending on the impacts that the change had on their areas of concern. The absence of above average rainfall years resulted in surface water supplies being significantly affected at an early stage (Bates et al. 2008; Petrone et al. 2010). Rainfall reductions of between 10 and 15% since 1975 had a multiplier effect on streamflows with reductions in excess of 50% and by more that 70% since 1997. This effect was highly visible in reduced public supply surface water storage levels and led to the imposition of severe restrictions on
public supply use in the late 1970s. Public supply surface water source yield amounts were down-rated by the early 1990s in recognition that pre-1975 rainfalls were unlikely to return.

The impact of climate change on recharge was also significant but was not so obvious. Because aquifers were full where water tables were at the ground surface in wetlands, any reduction in rainfall was initially offset by reductions in evapotranspiration and surface drainage. It was only when water tables fell over summer, to an extent that winter recharge was not sufficient to fully replace the losses, that the reduced rainfall was reflected in lower net recharge and a decline in groundwater levels.

Groundwater storage levels are not easily measured and reported, unlike dam storages, and the multiplier effect of reduced rainfall on groundwater recharge is less than that on surface water streamflows. An estimate of groundwater storage changes since 1979 was made using levels from 194 monitoring bores located across the Gnangara Mound. A specific yield of 0.25 was assumed. A strong downward trend in groundwater storage is evident since 1992 (Figure 5). However, these trends and their causes were not so clear at the time. The situation was also complicated by changes to the levels of extraction (Figure 4), the maturing of the 220 km² of pine plantations, changes to the frequency with which the Banksia woodland was burned, and by urbanisation of south western parts of the Mound. Development of a sophisticated groundwater model helped identify the separate and combined effects on different parts of the Mound (De Silva 2009). The first version of the Perth Regional Aquifer Modelling System was developed in the early 2000s and the model has been used and periodically upgraded ever since.

Over a number of years of analysis and debate it was accepted that reduced rainfall had a widespread impact on groundwater levels but local impacts were important. Maturing pine plantations effectively stopped all recharge and, where the water table was within about 10 m, there was the likelihood that the pines were net extractors of water (Silberstein et al. 2010). Native vegetation, the main land use on the Mound, can also be managed to influence groundwater levels. Fuel reduction burns in spring or autumn, to reduce the risk of damaging wildfires, reduces leaf areas and increases recharge for a few years afterwards (Yesertener 2006). Such burns need to be carefully managed so that nature conservation values are not impacted. While the impact on recharge is modest, the large areas under this land use results in a significant volume of recharge.

Management response to falling groundwater levels

Dry years between 1975 and 1977 resulted in salt water intrusion of the Superficial Aquifer in coastal and estuarine areas and a significant decline in surface water storage levels. This led to a complete sprinkler ban for people who used potable water on their gardens. The number of

Figure 5 | Reduction in groundwater storage in the Superficial Aquifer between 1979 and 2009 GL – Gigalitre or 10⁹ L.
householders who had private bores accessing the shallow aquifer to irrigate their gardens increased from about 25,000 in 1975 to about 65,000 in 1980 as a result of these restrictions.

Wellfields at Mirrabooka, Wanneroo, East Mirrabooka, Lexia and Pinjar were developed to augment the declining surface water source yields and bolster the public supply system capacity. These wellfields were designed to intercept a proportion of groundwater throughput up-gradient of urban development. They were located on public land used for nature conservation and pine plantations. Efforts were made to avoid important wetlands but their ubiquity meant that it was inevitable that some would be impacted by pumping.

After the Environmental Protection Act 1986 was promulgated there was a requirement that new wellfields commit to managing groundwater or lake levels around important groundwater dependent ecosystems. Estimates of groundwater levels required to support dependent ecosystems were used to establish minimum desirable levels and minimum absolute levels, below which there were increasing risks that ecological damage to the wetlands would occur. Given variability, exceeding these levels was acceptable for short periods but continued exceedence of the levels was deemed a breach of Ministerial Conditions set on the operator of the wellfield (the Water Authority of WA until 1995) or the state water manager (the Water and Rivers Commission from 1996, and now the Department of Water). The criteria levels are used in conjunction with an extensive ecological monitoring program to guide abstraction away from the most ecologically sensitive areas on an annual basis. After 1998, about 43 public water production bores were closed as their continued use may have affected important groundwater dependent ecosystems.

The levels were set based on an understanding of the range in groundwater levels in the preceding few decades and on the likelihood that vegetation would be stressed and unable to respond to significant falls in levels and rates of change. In recognition of the importance of pine management, a requirement that pines in ecologically sensitive areas be managed such that their basal areas was less than 11 m²/ha was established. This density of plantation was thought to enable a similar amount of recharge as Banksia woodland, based on measurements made in the 1980s.

However, in practice this level of thinning was not often achieved due to practical difficulties and limited resources for plantation management. Also it is possible that the decline in rainfall amount and intensity after the 1980s resulted in limited recharge even when the thinning target had been achieved. By the early 2000s it was agreed that the pines would be progressively removed from the Mound. A laminated veneer lumber plant was established in 2004 to improve the value of the pine wood that will be progressively harvested until 2028. Depending on the future climate and what replaces the pines, groundwater levels around areas with Ministerial Conditions may increase by up to a metre after pine removal compared with a continuing decline if they were to remain (De Silva 2009).

A further reduction in rainfall in the early 2000s caused a rapid decline in public supply surface water storage levels. This triggered preparation of a ‘drought response’ strategy to counter the storage decline and to try and prevent the need for severe water restrictions. A major part of the strategy was a significant increase in groundwater abstraction from the confined aquifers (Figure 4). This increased use of confined aquifer storage water was to be replenished assuming that rainfall would returned to pre-1998 levels. However, the rainfall did not recover and confined aquifer abstraction continued at the higher rate to offset reduced surface water yields. This resulted in increased groundwater abstraction during a period of reduced recharge.

A number of public water supply and demand measures were adopted, especially after 2001, including the building of a 45 GL per year desalination plant which was commissioned in 2006. Perth’s rapid growth made the need for more water a matter of timing with the dry climate resulting in increased groundwater abstraction and developments being brought forward much more rapidly than anticipated.

In response to the need to coordinate government agency policies and plans, the Gnangara Sustainability Strategy (GSS) was established to link land use changes and groundwater abstraction in such a way that social, economic and environmental values associated with groundwater would be considered in a balanced manner (Government of WA 2009b). The availability of global climate models and regional and local groundwater models helped identify the separate and combined impacts of climate, land use and abstraction. This improved the ability to set conditions
on both land and water management actions that affects groundwater levels. The GSS recommended land use and land management changes that may improve groundwater levels and, where these were not enough, changes to abstraction limits were considered. In some cases the inevitability of falling groundwater levels was accepted because the cost of their maintenance was unacceptably high.

After pine removal, native vegetation will be re-established to create ecological linkages with other areas managed to protect the groundwater resource and increase recharge around bore fields. The frequency with which the native vegetation is burned will balance the need to protect fire-sensitive terrestrial communities while also enabling sufficient recharge to maintain groundwater dependent ecosystems.

The GSS recognised that public water supply was the most highly valued social and economic use of water from the Gnangara Groundwater System (Government of WA 2009b). However, private groundwater users such as peri-urban horticulturalists have access to only one water supply option – groundwater. The greater flexibility of supplying drinking water from other sources, including desalination, has resulted in the public utility being asked to make more adjustment to their extraction than users with less flexibility.

A water allocation plan was developed to reflect the directions of the GSS by reducing groundwater abstraction, supporting more effective use of water and limiting the direct impacts of abstraction and use on wetlands and water quality (Government of WA 2009c). Current work is monitoring the groundwater resources against management objectives and using water accounting to better understand how the resource is responding to climate, abstraction and land use regimes. Management triggers and responses are set out in the current water allocation plan. Part of the work in the new management plan involves research on how to determine ecological water requirements in a declining rainfall situation.

CONCLUSIONS

The lessons learned from about 30 years of managing groundwater levels on Gnangara Mound under climate change and development pressures have been:

- Climate shifts can be sudden but not recognised for many years because it is hard to distinguish them from climate variability. In south-western Australia, a specialist group (the Indian Ocean Climate Initiative) was formed to help distinguish between these two influences. More than a decade before the science was clear that there had been a climate shift in 1975, water managers were planning on the assumption that the climate would not return to its pre-1975 condition. This decision was helped by rapid population growth and economic development that was increasing water demands and reducing the risk of an over investment in new sources had the climate reverted to a wetter form.
- Surface water resources were affected relatively quickly with highly visible storage declines, but declines in groundwater storages were more gradual, cumulative and less obvious.
- Because there were a number of factors affecting groundwater levels (namely climate, pine plantations, abstraction, urbanisation and fuel reduction burning of native vegetation) it was difficult to understand and then get agreement as to each factor’s relative and cumulative impacts. Getting wide agreement was made difficult by the significant social, economic and environmental values associated with each use.
- In general, private uses of groundwater were given priority over public uses, despite drinking water being the highest valued consumptive use, because it is possible for a water utility to source their water from elsewhere (e.g. desalination) whereas private groundwater users have no option other than groundwater beneath their property.
- Maintaining agreed groundwater levels to meet environmental requirements was complicated by an assumption that the water manager could influence levels in the face of climate change and an inability to direct land use, especially pine management. Also, climate change had a progressive impact and agreed minimum levels were breached irrespective of the management approach adopted. Often, the environmental values were lost before environmental conditions were lifted, since to amend them beforehand was to admit that they could not be saved.
- Single resource and issue management, which work well when there is limited or no conflict, requires a
multi-agency approach to land and water planning when there are multiple values being impacted.

Many management systems assume that the environment is in a quasi equilibrium and development will impose a stress which needs to be managed through regulation to reduce the risk of impact or to enable the impacted system to return to an earlier state if perturbed (e.g. resilience). With major changes in climate such as experienced in south-west Western Australia, the change is often progressive and regulatory ‘lines in the sand’ can be breached despite implementing the accepted best management practice. Changes to policies and regulatory mechanisms are often hard to achieve, as accepting breaches can be construed as failure and requires an acceptance that values have been permanently lost. Gnangara has required water and land managers to agree a transitional path which tries to balance values as systems adjust to a changing climate.

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