Management of groundwater in Australia: new models and approaches for adaptive management and large scale reuse

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Abstract
Historically, groundwater allocations and water rights were frequently defined using static volumetric limits, which were granted for indefinite periods of time, if groundwater was subject to any regulation at all. Growing demand and water scarcity now call for more optimised approaches in managing groundwater volume and quality. There is also growing recognition of the uncertainty in sustainable yield estimation and the limits in long term forecasting of groundwater level evolution. The sources of these uncertainties include sparsely defined distributed hydrogeological characteristics, climate variability and most of all future demand patterns. Because of these uncertainties, adaptive management strategies based on a combination of regular monitoring, modelling and flexible volumetric limits to achieve environmental targets are becoming more popular. The paper provides a selective snapshot of recent needs for adaptive groundwater management in Australia. It demonstrates an uncertainty based modelling approach for the calculation of transient water import requirements given differing environmental targets within the planned large scale reuse scheme of the Lockyer Valley, Australia. Adaptive groundwater management concepts are also the current approach for the large uncertainties of the Coal Seam Gas industry in Queensland with projected abstraction rates up to 160 GL/a.

Keywords
Adaptive management, groundwater modelling, uncertainty

INTRODUCTION

Groundwater resources in Australia

Despite being reported as the second driest continent on Earth after Antarctica, Australia has an exceptionally high per capita water availability and residents have the highest water use per capita in the world. For example in 2004-2005 Australia’s population of 20 million people consumed 18767 GL of water or 2570 litres per person per day. Much of this use was on irrigated agriculture. This resulted in an over-exploitation of many rivers and aquifer systems and the loss of wetlands. A stark example of this occurs at the mouth of the Murray River, at the end of the Murray Darling Basin, which has received virtually no flows during 2002-2009 (Grafton 2010).

As a result of the increasing competition on water resources and the increasing use of more costly water sources like desalination, as well as the increase in supply security, the average price of water nearly doubled from $0.40/kL in 2004-05 to $0.78/kL in 2008-09. However, there was large variation in the average price paid for water in 2008-09 with households paying $1.93/kL and agriculture $0.12/kL. (Australian Bureau of Statistics 2010)

Groundwater use is increasing across Australia but most of the groundwater use is extracted by individual users and is rarely metered. Only a small fraction is managed through distribution networks(Herczeg 2011). In 2004-2005, licences for groundwater use were 4700 GL/y, representing 25% of the total amount of water used in Australia (Australian Bureau of Statistics 2010).

The amount of water consumed by the mining industry in 2008-09 was 508 GL, 23% more than in 2004-05. This rise is associated with increased levels of mining activity. Water use in the mining industry is likely to increase. Recent projections of groundwater production in the Coal Seam Gas
industry were estimated to a peak use of 160-220 GL/a within the next 5 years. There was also a 15% increase from 2004-05 in the manufacturing industry.

From the above it is evident that there is a strong economic incentive to make the best use of the existing groundwater resources and to optimise the performance of aquifers as storage systems. For this reason, water rights trading schemes were introduced. Irrigators are able to buy and sell water entitlements, although restrictions are in place to limit sales outside of irrigation districts.

![Figure 1](image)

**Figure 1.** Case study locations projected on a map of groundwater recharge across Australia. Values are approximate estimates of recharge based upon extrapolation from limited measurements (Crosbie, Jolly et al. 2010; Herczeg 2011). 1= Lockyer Valley, 2=Coal Seam Gas Developments 3=Gnagara Mount, Perth

However there is substantial resistance against the new water allocation plan for the Murray Darling Basin. Studies on conflicts with Australian water allocation identified the key determinant of conflicts in a Water Allocation Plan region as (i) the social capital of the community (ii) the extent of the water allocation reductions and (iii) level of trust in the science (McKay 2011). The level of trust in the science is especially important in groundwater systems, where impacts take a long time to manifest but can be difficult to reverse once they have occurred.
Sustainable Yield & Environmental Flows

There are many ways in which sustainable yield is defined. For example, the amount of water that can be pumped over a reasonable time without causing a well to dry up is called ‘groundwater yield’ (Herczeg 2011). As the ‘reasonable time’ applied for this estimate is often just days or weeks, this definition of yield is usually not equal to the sustainable yield.

Alternatively, the recharge rate of the aquifer can be considered the absolute maximum amount of groundwater that can be used sustainably, but in reality, only a small fraction of the recharge can be used in the long term, without causing significant impacts on natural environments. As a simple rule of thumb, extraction should not exceed 50-70% of groundwater recharge without very careful assessment (Herczeg, 2011), and even that might be too much in areas which strongly depend on groundwater baseflow in rivers. This precaution is required because rates of recharge are highly uncertain and the actual rate may be lower than estimated. This accounts especially for areas with irrigated agriculture. As an example, detailed deep drainage modelling on a farm land block in the Lockyer valley provided estimates which ranged between 59-262 mm/year (Wolf, Moore et al. 2011).

Australia has adopted strategies toward the achievement of Ecologically Sustainable Development (ESD) in water allocation; several states had begun to require this prior to 2004. The National Strategy for Ecologically Sustainable Development, endorsed in 1992, defines the goal of ESD as: 'development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends.'

Despite the commitment to ESD, past norms of water allocation in Australia have created a legacy of over-allocation in many regions (Australian Water Resources 2005). The return of all over-allocated or over-used systems to environmentally sustainable levels of extraction was, and is, a key requirement of the National Water Initiative (NWI) in 2004 (Grafton 2010). The process of implementing a radical policy change to use ESD in water allocation in Australia is ongoing but has an active history of 20 or so years. There are over 190 water plans in Australia, and most of these have reduced the amount of water allocated to growers in any year. This has been met by opposition from some groups, but the more subtle change is that there has been a change of the type of crops grown (McKay 2011) and increased irrigation efficiency.

Groundwater Allocations

As shown in Figure 2, there are basically 4 concepts for groundwater regulation which go along with different levels of uncertainty:

Unregulated use

Unregulated use was widespread in Australia and is still continuing in many areas. As an example, unregulated groundwater use in the Great Artesian Basin lead to peak groundwater abstractions of 750 GL/a in 1915, and has since fallen by approximately 25% (Cox and Barron 1998). Individual bores in the confined aquifers showed water level dropped by more than 80 m. Still, stock and domestic use of groundwater from the Great Artesian Basin is not regulated.

Unlicensed use of groundwater, mainly for stock and domestic uses, is estimated to consume an additional 1100 GL/y (Herczeg, 2011). In view of the goals of environmental sustainable development, the practice of unregulated use is only applicable in areas where it is evident that the groundwater abstraction is very small compared to the available resources. In those situations, the
required investigation effort is low and a high uncertainty in the estimation of groundwater recharge is appropriate.

**Figure 2:** Different allocation concepts and the associated uncertainty, competition and regulatory effort.

*Fixed allocation based on groundwater recharge estimates*
In this case, groundwater recharge estimates which are for example derived by chloride mass balance, water table fluctuation methods or unsaturated zone modelling are used to define permanent water licenses or water rights. This method is still utilised in many countries worldwide, especially in areas where the strong competition around water resources leads to a low priority of environmental water demands (e.g. at the Lower Jordan River Basin) (Wolf and Hoetzl 2011). The drawback of the fixed character of the allocations is that uncertainties or methodological changes in the recharge assessment or water balance frameworks require later adjustments of the fixed water rights. As an example, too many water allocations were provided in the Murray-Darling basin, partly due to double accounting of interconnected surface- and groundwater resources. Now the Murray Darsling Basin was forced into an adaptive management scheme as well. It was discussed that a minimum of 3.1 billion $AU is required to buy water entitlements from willing sellers in the Murray Darling Basin in order to achieve healthy and working rivers again (Grafton 2010). To be successful, fixed allocation models should have a very low uncertainty or operate with large precautionary buffers.

*Fixed allocation considering environmental flows*
This is an extension of the before mentioned concept. The key difference is that environmental goals like a minimum flow of a river system were defined. Thus the complexity requirements for hydrological and hydrogeological models are higher. The National Strategy for Ecologically Sustainable Development (ESD) initiated a strong movement into this direction. However, large scale river basin modelling exercises still lack sufficient detail on groundwater–surface water interaction for making allocation impact predictions with acceptable reliability. Consequently, fixed allocation models considering environmental flows should have a very low uncertainty or operate
with large precautionary buffers.

Adaptive management with variable allocations

Adaptive Management is a process to cope with uncertainty in understanding centred on a learning model where natural resource ‘management actions are taken not only to manage, but also explicitly to learn about the processes governing the system’ (Shea et al. 1998)(Pahl-Wostl 2011). This implies a paradigm shift in water management from a prediction and control to a management as learning approach(Pahl-Wostl 2007). Adaptive management strategies with variable allocations have two distinctive advantages: (i) the potential for optimum resource use also during wet periods (ii) the legislation is more robust against deficiencies of hydrological models. However appropriate operational rules are consequently more complex and must be defined and tested for their long term ability to keep the system within the set environmental targets while resulting in maximum water availability to the users. A promising development is to integrate operational rules into groundwater models, e.g. the adjustment of pumping rates in a defined area based on water levels at trigger locations which fall over a given time period (e.g. Schoups et al. 2006; Srinivasan et al. 2010). For this purpose the Groundwater Operational Management Package (GWOMP) was recently developed (Gallagher and Leach 2010). GWOMP runs seamlessly with MODFLOW and produces a detailed account of the extractive deficits recorded within management areas over the simulation period, as well as the history of trigger activation and operational decisions. Thus it allows, when examined in association with the model simulated head and flow response under the operating rules, a robust statistical assessment to be made of the potential impacts on groundwater-dependent ecosystems and the reliability of water supply (Gallagher and Leach 2010).

Predictive Uncertainty Analysis

Predictive uncertainty analysis in groundwater modelling is slowly gaining popularity in Australia since it allows model benchmarking, quality control. It can provide efficient yet robust analysis for optimizing both existing monitoring networks and future data acquisition strategies to support model based environmental management. Robust in a relative sense, because of the particular characterization of model predictive variance in the problem formulation employed (Moore 2006), which includes the contributions to this variance made by both measurement error and environmental heterogeneity that cannot be captured by the calibration process. Efficiency is gained via a linearity assumption in the equation, which allows the calculation to be made sufficiently rapidly, so that it can be repeated at many alternative existing or proposed monitoring sites and times. Furthermore, this analysis has no cost barriers, as the software for such analyses is in the public domain(Doherty 2011; Doherty 2011). These are particularly important benefits in the large scale regional model context, where monitoring is typically a significant effort and is subject to public scrutiny in terms of both cost and rigour. Recent applications areas of application are the Lockyer Valley, Queensland (Moore, Woehling et al. 2011), the Namoi Valley, NSW and the Surat Basin, Queensland.

Innovative Modelling Tools

Other model frameworks could be used for this analysis in future. A comprehensive hydro-economic modelling framework to estimate impact of different water policies on the economic return from agriculture under the consideration of groundwater availability was demonstrated for the Ogallala Aquifer (Bulatewicz 2010). Detailed modelling of conjunctive use using
MODFLOW’s Farm Process was demonstrated for the Pajero Valley (Hanson, Schmid et al. 2010). Since 2010, publication records indicate the growing popularity of hydro-economic modelling which is attributable to their ability to directly inform policy making (George 2011; George 2011; Pena-Haro 2011; Varela-Ortega, Blanco-Gutiérrez et al. 2011).

CASE STUDIES

Two case studies for new groundwater management challenges are detailed in this paper: (i) large scale reuse in the Lockyer Valley (South East Queensland) and large scale groundwater abstraction due to Coal Seam Gas development in Queensland. Another instructive example in Australia are the well documented schemes adaptive groundwater management in Australia is the Gnagara mound in Perth (Bekesi 2009). Applications of GWOMP exist for North Stradbroke Island, QLD but are not yet a publicly documented (Gallagher and Leach 2010).

Case study 1: Lockyer Valley

The Lockyer Valley has the potential to become an example of conjunctive use management with an urban area, since major volumes of treated water from the downgradient metropolis of Brisbane could be used to supplement the natural water resources of the valley. The Lockyer Valley (approx. 80 km west of Brisbane) is an intensively used agricultural catchment and a major contributor to the vegetable supply for Brisbane. Over 1,500 bores are estimated to be currently servicing the Valley and 21 weirs for groundwater recharge, storage of water for direct surface water access and management of releases from the major dams. During the 1980s, average annual groundwater withdrawal in the Lockyer Valley was estimated to be 46,500 ML, while safe annual yield is estimated to be 27,000 ML (DPI, 1994). It is estimated that at least one-third of productive land in the valley has already been withdrawn temporarily from cultivation due to lack of water. Over-allocation of groundwater, particularly in 2007, has exacerbated salinity in some aquifers, as saline water seeps in from adjacent sandstone areas to replace the higher quality water taken from alluvial aquifers or more salt is washed down from the unsaturated zone due to irrigation and dry land clearing.

With a maximum combined production capacity of 232 million litres (0.232 GL) of Purified Recycled Water (PRW) a day, the South East Queensland (SEQ) Water Grid operates the third largest recycled water scheme in the world and the largest in the southern hemisphere. The additional water volumes are critical to provide supply security during drought conditions, but are under-utilised in wet periods. The option to supply a significant amount (ca. 15-25 GL/a) of the PRW to augment the over-utilised groundwater resources of the Lockyer Valley (approx. 80 km west of Brisbane) is currently being explored in detail by government agencies and the water grid managers.

The intended scheme is special in that it unites urban and rural water systems in one engineering solution to the expected benefit of both. Three major supply scenarios are currently discussed:

1 Delivery of PRW to the individual farm gates;
2 Delivery of PRW to major reservoirs, distribution via existing pipes to selected farmers and releases to the creek (see Figure 4 a); and
3 Direct injection of PRW into the groundwater via wells.

Recent developments show that the complexity of common pool resource management (options 2
and 3) is a barrier to farmer’s acceptance of the PWR supply. As a consequence, a delivery to farm gates is favoured by the local water users. While requiring a more costly pipe network, it provides farmers with full control of their PRW use.

A starting point for all models on environmental impact is the knowledge of future demand for PRW. In this case however, the future demand for PRW depends on finding a society consensus on ecosystem services and environmental flows.

![Figure 3.](image)

**Figure 3.** a) Schematic cross section through the Lockyer Valley including pre-development groundwater levels and modern drought conditions; b) Future management scenario with time variant PRW supply to keep groundwater levels between upper and lower target level. Sand and gravel dominated aquifer sequences shown with dot texture.

The supply of PRW into the Lockyer Valley provides the opportunity to actively steer the currently overused ecosystem to any desired state, i.e., to to keep groundwater levels between upper and lower target level (Figure 3) by importing variable amounts of PRW depending on the current climate and demand. This can be achieved with all three supply scenarios (farm gate/reservoir release/injection). Due to the extensive treatment aimed at indirect potable reuse, the purified recycled water comes at a high production cost (> $AUD 500 per megalitre), compared to current water charges of a maximum of $AUD 30 per megalitre. For this reason, irrigators will go a long way to avoid using PRW if possible. Only if creeks have dried up or groundwater wells run dry or turn salty, will there be a business case for them to use PRW. From an environmental, regulator or water users perspective, clearly, the decision of where the target groundwater levels are set will govern future PRW demand.

A transient regional groundwater flow model (Arunakumaren 2003) has been expanded for this purpose, and has been calibrated to data from 1991 to 2010 (Wolf, Cresswell et al. 2010). The model domain area is depicted in Figure 4.
Figure 4. a) Overview of the Lockyer Valley with a common pool supply scenario. b) Spatial distribution of groundwater level surface (m AHD) used as the environmental target for high groundwater levels.

As a proof of concept, a modified Modflow model with a customised script was used to determine the required volumes of PRW to meet different target groundwater levels in a variable climate (Moore, Woehling et al. 2011) (Figure 5). PRW demand was defined as the amount of water required to top up the aquifer. In this simplified form, the augmentation is provided directly to every model cell which indicates a deficit. In a real world sense the PRW would not have to be injected into the aquifer. Rather it would be delivered to farmers via piped supply and reduce their need for groundwater pumping. This reduction of pumping rates leads to increased water availability in the aquifer. The figures modelled do however not account for the spatial dimension of this substitution yet, e.g. if dominantly farmers in the lower Lockyer will be supplied with PRW, this will not lead to the compliance with set environmental goals for the upper Lockyer valley. Predictive uncertainty analysis was applied in considering an uncertainty of +/-50 % in groundwater recharge, hydraulic conductivity, groundwater abstraction and specific yield. The current projection of PRW demand is based on a very limited economic analysis with no consideration of environmental benefits. Thus, the next model generation needs to specify which areas are likely to receive PRW substitution under the consideration of the costs to build supply networks. Possibly it will be cheaper to install more efficient irrigation systems instead.
Figure 5: Proof-of concept time series of PRW import requirement to match groundwater levels from June 1992 over the entire period.

Figure 6: PRW imports or water savings required for different target water levels and hypothetical costs for two water prices.

Figure 6 also demonstrates that a multi-stakeholder decision needs to be made as to the desired target water level, since these are governing the costs for the PRW import. Figure 4 displays hypothetical cost for maintaining the target water level under the assumption of a PRW water price of 500 AUS as well as under the assumption of 120 AUS as the average price for agricultural water in Australia(Australian Bureau of Statistics 2010).

It will be the subject of further economic modelling to determine if the increased supply security and extension of agricultural farmland will result in sufficient economic return to make the PRW scheme viable.

Case study 2: Coal Seam Gas Water Management in Queensland
As an example for a very uncertain system requiring major decisions, the adaptive regulations for groundwater impact of the coal seam gas industry in Queensland are described. Currently, the abstraction of water in the course of the development of coal seam gas (or coal bed methane) is at the centre stage of a politicised public discussion in Australia. With uncertainty in the future impacts of this process, an adaptive management scheme is currently favoured. This links regulation and water licences to continuous updated groundwater monitoring information and thus tries to avoid a complete stop of the industry which might result from a very strict application of the precautionary principle.

The water abstraction from CSG production in Queensland today is 16.9 GL/y for a produced gas volume of 212.11 Million m³/y (http://mines.industry.qld.gov.au/mining/production-reserves-statistics.htm). Estimates of water extraction were initially predicted to peak at 261 GL/y for a 40 Mt/y industry (with a range of 227 to 419 GL/y) but have been reduced to a peak of 160 GL/y and may be reduced further as the process proves to be more efficient than expected.

Figure 5. Schematic cross section through the Surat Basin.

This compares to the current bore discharge of 630 GL/year (including sub-artesian bores) (Hillier, 2011) for the Great Artesian Basin. There is approximately 1000 GL/a of water entering and exiting the GAB system each year (Cox and Barron). The total area of the Great Artesian Basin is 1.711 Million km² and the volume in storage estimated as 8,700,000 GL. Despite this very large storage volume, individual head levels in bores have fallen up to 80 m over the time period from 1880-1990 (Rolfe 2010).

In order to allow gas production from wells drilled into the Walloon Coal Seams, the piezometric head needs to be lowered to approximately 35 m above the seam. As the Wallon coal measures are exploited also in depth down to 700 m, this results in very large pressure differentials of more than 500 m hydraulic head between the coal seams and the over- and underlying aquifers of the Great Artesian Basin.
Artesian Basin. Given the paucity of observation wells in the Great Artesian Basin and the low hydraulic conductivity of the strata no published impacts have been observed so far outside the Walloon coal measures. Combined with the overall scarcity of transient water level information in the Great Artesian Basin, model calibration and validation are extremely difficult and a considerable uncertainty with regard to inter-aquifer leakage remains. As up to 40000 extraction wells are planned, indicated drawdown zones of the first impact assessment models indicate areas of 100 x 200 km to be affected by more than 5 m in head. However, this is associated with a large uncertainty, especially with regard to the timing of the impact.

In this setting, an adaptive management scheme has been chosen by the regulators. Trigger levels for maximum drawdown of 5 m (in confined aquifers) and 2 m (in unconfined aquifers) as well as 0.2 m at springs were defined set to define acceptable impact(Cox 2011). These trigger levels are not the result of a modelling process but set with respect to an expectation of what would be accepted by the community.The current large scale cumulative impact assessment model being developed by QWC will identify areas likely to be impacted within the next 3 years and initiate immediate negotiations of ‘make good agreements’ between the industry and the affected landholders even prior to the physical manifestation of the impact. With current knowledge it is not possible to provide an estimate of sustainable yield for the targeted Walloon coal measures.

The currently preferred option to dispose of the produced brackish waters is to desalinate via reverse osmosis and to inject into overlying and underlying aquifers to mitigate the impacts of CSG development.

CONCLUSION

Sustainable yield estimations have moved from simple estimates of groundwater recharge to the estimates which preserve agreed ecological services. This has resulted in a growing number of integrated surface-groundwater model applications in Australia. With increasing water scarcity, the incentives to invest in better quantifications of transient groundwater availability increases. There is growing recognition of the uncertainty in sustainable yield estimation and the limits in long term forecasting of groundwater level evolution due to uncertainties in distributed hydrogeological characteristics, climate variability and most of all future demand patterns.Fixed groundwater allocation systems therefore need to be replaced by variable allocations depending on a set of agreed operational rules which are activated in response to monitored groundwater and streamflow quantity and quality data. A growing number of hydro-economic models is now capable of simulating the impacts of different sets of operational rules on (i) the frequency of not achieving the environmental goals and (ii) the economic returns in a water limited industry. The example of the Lockyer Valley shows the complexity of augmenting a natural system with a higher value imported water resource.This is demonstrated alongside a methodology to estimate the demand and costs for water imports under different target groundwater levels. Adaptive management approaches have become an accepted approach to deal with uncertainty in groundwater modelling. As an example for a very uncertain system, the adaptive regulations for groundwater impact of the coal seam gas industry in Queensland are described. Recent conflicts with innovations in water allocation plans in Australia demonstrated that a high level of trust in the science is required when allocations need to be reduced and lifestyle is affected. A combination of predictive uncertainty assessment in models, adaptive management strategies based on publicly available monitoring data and transparent communication of assumptions in hydro-economic models are seen as valuable exercises to earn this trust. A risk assessment approach is appropriate, where the level of investigations is matched against the possible consequences of use. The challenge is to ensure that additional investigations
and regulations keep pace with growing use.

LITERATURE


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