Hydrological challenges to groundwater trading: lessons from south-west Western Australia

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Abstract

Perth, Western Australia (pop. 1.6m) derives 60% of its public water supply from the Gnangara groundwater system (GGS). Horticulture, domestic self-supply, and municipal parks are other major consumers of GGS groundwater. The system supports important wetlands and groundwater-dependent ecosystems. Underlying approximately 2,200 km^2 of the Swan Coastal Plain, the GGS comprises several aquifer levels with partial interconnectivity. Supplies of GGS groundwater are under unprecedented stress, due to reduced recharge and increases in extraction. Stored reserves in the superficial aquifer fell by 700 GL between 1979 and 2008. Over a similar period, annual extraction for public supply increased by more than 350% from the system overall. Some management areas are over-allocated by as much as 69%.

One potential policy response is a trading scheme for groundwater use. There has been only limited trading between GGS irrigators. Design and implementation of a robust groundwater trading scheme faces hydrological and/or hydro-economic challenges, among others. Groundwater trading involves transfers of the right to extract water. The resulting potential for spatial (and temporal) redistribution of the impacts of extraction requires management. Impacts at the respective selling and buying locations may differ in scale and nature. Negative externalities from groundwater trading may be uncertain as well as not monetarily compensable.

An ideal groundwater trading scheme would ensure that marginal costs from trades do not exceed marginal benefits, incorporating future effects and impacts on third-parties. If this condition could be met, all transactions would result in constant or improved overall welfare. This paper examines issues that could reduce public welfare if groundwater trading is not subject to well-designed governance arrangements that are appropriate to meeting the above condition. It also outlines some opportunities to address key risks within the design of a groundwater trading scheme. We present a number of challenges, focusing on those with hydrological bases and/or information requirements. These include the appropriate hydrological definition of the boundaries of a trading area, the establishment and defining of sustainable yield and consumptive pool, and the estimation of effects of extractions on ecosystems and human users. We suggest several possible design tools. A

combination of sustainable extraction limits, trading rules, management areas, and/or exchange rates may enable a trading scheme to address the above goals.

Keywords

Groundwater trading; water markets; institutions; sustainable yield; externalities; consumptive pool.

1 Introduction

The south-west of Western Australia (WA) has experienced an 11% decline in average annual rainfall since the mid-1970s as compared to the higher-rainfall period between 1914 and 1975 (DoW, 2009a). Figure 3.1 shows total annual rainfall for the period 1905-2008 for a sample site in the area of interest. This decline has been attributed, in part, to climate change resulting from emissions of greenhouse gases (CSIRO and BoM, 2007). Projections of future impacts of climate change for the south-west of WA show increased annual temperatures and decreased annual rainfall (CSIRO and BoM, 2007). The trend towards a warmer and drier climate, coupled with population growth and development, is putting increasing pressure on Western Australia’s diminishing water supplies, and presenting a significant challenge to water resource managers.

Perth is the capital city of the Australian state of Western Australia and has a population of over 1.6 million (ABS, 2010a). Water use in the Perth metropolitan area is around 650 gigalitres (GL) or 527,000 acre-feet (AF) per annum. Of this, around 43% or 286 GL is supplied by the Water Corporation (the water utility supplying the Perth metropolitan area) through the Integrated Water Supply System to domestic customers (Water Corporation, 2009). The remainder, about 57% or 370 GL (Water Corporation, 2009), is privately supplied in Perth and surrounding areas, and is used in agriculture, mining, and public open space, as well as from domestic garden bores for garden watering.

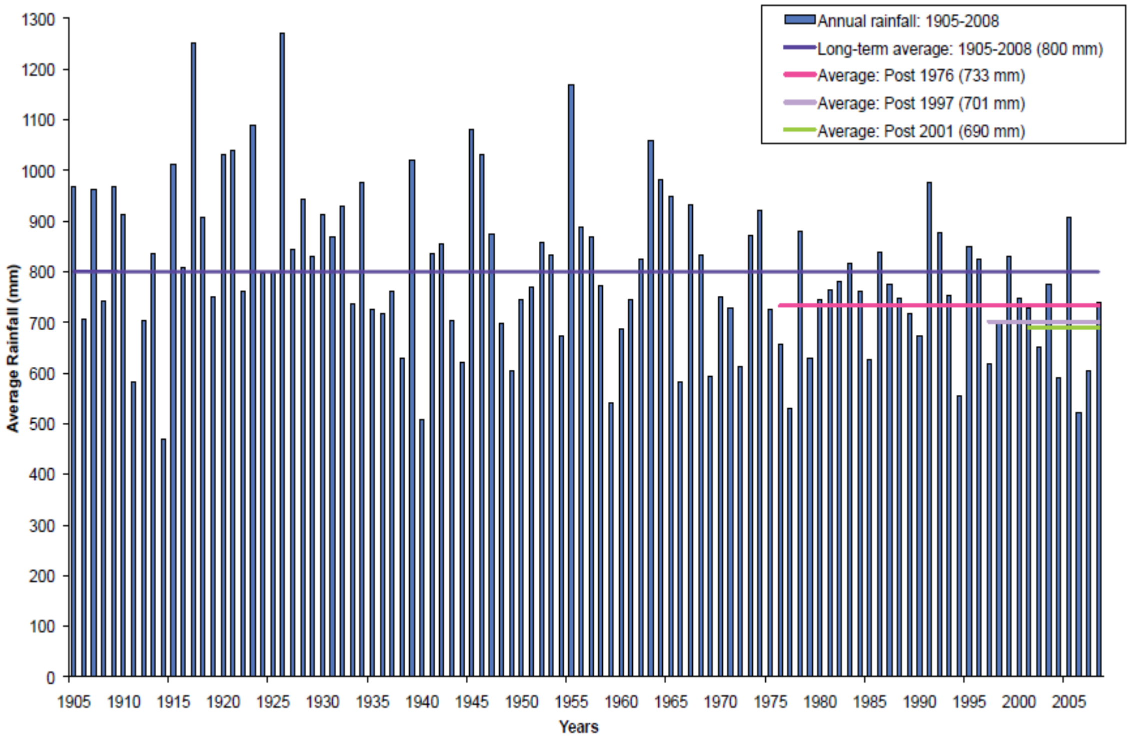

Figure 1.1: Long-term (1905–2008) annual rainfall for Wanneroo site. (Source: DoW, 2009a, p. 9. Reproduced with permission).

Unlike most other state capital cities in Australia, Perth relies heavily on groundwater sources for its public and private water supplies. Storage levels in reservoirs in surrounding catchments, traditionally the mainstay of Perth’s water supplies, have declined significantly over the past 25 years due to reduced rainfall and a 50% decline in stream flows (Water Corporation, 2009). Surface water now accounts for only 20-35% of public water supply. This has led to an increasing reliance on groundwater to meet demand (Water Corporation, 2009). The main source of Perth’s groundwater is the Gnangara groundwater system (GGS), a system of aquifers underlying much of the Perth Metropolitan area. We describe this further in the following section.

The Water Corporation has forecast an increase in demand from 286 GL (232,000 AF) per annum to 515 GL (~418,000 AF) per annum by 2060, based on a projected increase in the population of the Perth metropolitan area to over three million (Water Corporation, 2009). In the nearer term, increasing population is expected to cause an increase in annual demand for potable water alone of 50 GL (~41,000 AF) by 2020 (GSST, 2009). Perth's population increased by over 20% between 2001 and 2009

(ABS, 2010b). The Water Corporation forecasts a potential supply shortfall of 365 GL (296,000 AF) per annum by 2060. Given the projected future decline in rainfall, run-off to dams is expected to continue to diminish, further reducing the contribution of surface water to public supplies. Recharge of groundwater systems, including the Gnangara system, is also expected to diminish further, restricting the availability of groundwater for public supply.

The Water Corporation has identified a portfolio of options to help meet the supply-demand gap (Water Corporation, 2009). Recently, water from Perth's first seawater desalination plant has augmented supplies. A second desalination plant is currently under construction. In addition, recycled water from waste-water treatment plants is increasingly being used for industrial purposes and on parks, gardens, and sports grounds.

One supply augmentation option is rural-urban water trading. Although the Water Corporation has in the past permanently 'traded' surface water with Harvey Water (a south-western irrigation co-operative), rural-urban water trading is currently neither common nor straightforward. There is only a small rural-rural water market, based mainly on trading within the irrigation co-operatives operating in WA

Water trading is increasingly accepted across Australia as an efficient mechanism for managing water resources in fully allocated systems with strong competition for available water (e.g., NWC, 2009; NWC, 2010). Properly functioning water markets can facilitate more efficient use of water, both through making the value of water (i.e., its opportunity cost) transparent and by providing a mechanism for water to 'move' from lower value to higher value uses. In this way markets offer an alternative to the more traditional 'command and control' approaches to water resource management (e.g., Howitt, 1994; Hearne and Easter, 1997).

In this paper, we present some of the background, challenges, and possible approaches to designing an economically and environmentally robust groundwater trading scheme. An objective of the paper is to inform and promote inter-disciplinary discussion on the topic. Using as a case-study a major Western Australian aquifer system, we orient groundwater trading within the Australian water reform agenda. We then present some of the economic conceptual context for groundwater trading, and introduce key issues such as third-party (including environmental) impacts. This foundation is then used to address a number of the primary hydrological challenges to the design of an effective groundwater trading scheme. Finally, we present a selection of possible approaches to mitigating some of the issues discussed.

2 Gnangara case overview

The GGS covers an area of approximately 2,200 square kilometres (DoW, 2009a), extending roughly 90 kilometres north from the Swan River, and east for around 40 kilometres from the coast (see Figure 3.2). The system comprises multiple aquifers at varying depths: uppermost is the unconfined superficial aquifer or 'Gnangara Mound'; the Mirrabooka aquifer is semi-confined; the deeper, 'confined' aquifers are the Leederville and the Yarragadee.

Perth, the fourth-largest city in Australia (ABS, 2010b), is dependent on the Gnangara system for a majority of its public water supply. As well as municipal supply, water from the GGS supports a range of activities, assets, and values, from the economic to the social and ecological. Residential, commercial, and industrial land uses rely on GGS water, as do public parks and extensive peri-urban horticulture. The groundwater system supports wetlands, native flora and fauna, and the associated diverse nature conservation values of its overlying region.

Estimated total annual withdrawal from the system was 321 GL (260,000 AF) in 2009 (DoW, 2009a) with abstraction averaging 298 GL per annum from 2004 to 2007 (De Silva, 2009). There are currently more than 5,000 licences to 'take' (i.e., extract) groundwater across the system (DoW, 2009a). About 60% of total groundwater abstracted is for self-supply use, including irrigated agriculture and domestic gardens. The remaining 40% is used in urban water supply (De Silva, 2009). The superficial aquifer contributes around 70% of total groundwater used (DoW, 2009a).

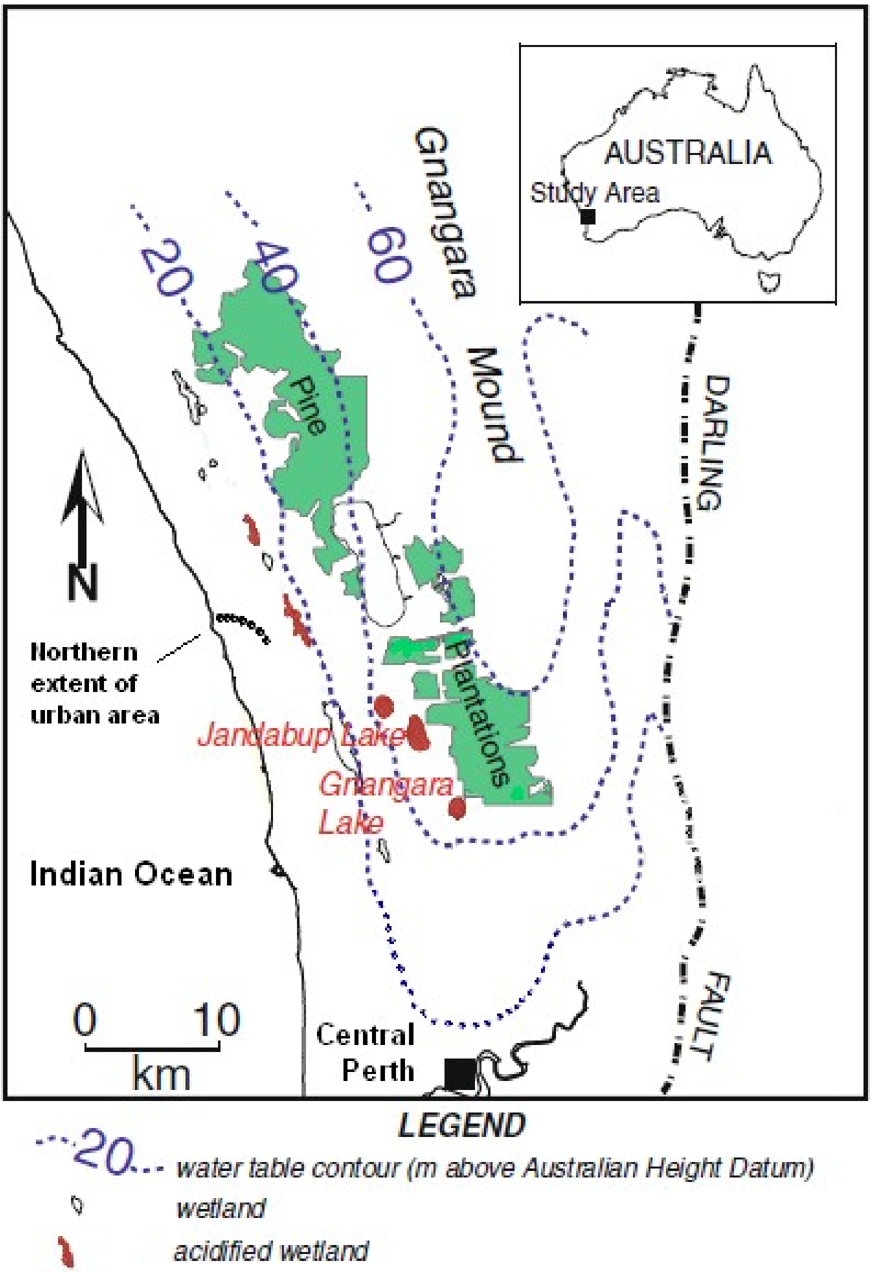

Figure 2.1: Location of the Gnangara groundwater system. (Source: Appleyard and Cook, 2009. Reproduced with permission).

The increasing abstraction from the Gnangara system has contributed to declining groundwater levels. Other contributing factors have included reduced aquifer recharge due to the drying climate, maturation of pine plantations over large parts of the overlying area, and less frequent burning of native woodlands (GCC, 2009). The

Western Australian Department of Environment estimated a rate of decline in water levels around the central area of the Gnangara mound on the order of 0.2 metres per annum since 1997 (Vogwill, 2004). This translates into an average annual storage depletion of around 60 GL (~48,000 AF). The overall volume of groundwater stored in the system declined by approximately 700 GL (~567,000 AF) between 1979 and 2008 (DoW, 2009a). Areas of the superficial aquifer have suffered water-table drops in excess of 4 metres (GSST, 2009).

The drop in water level across the system is not uniform; the areas of greatest decline are associated with public water supply bore-fields and with pine plantations (Yesertener, 2002). The Water Corporation's groundwater use increased from approximately 18 GL (~15,000 AF) in 1976 to approximately 142 GL (~115,000 AF) in 2008 (GCC, 2009, p. 23). The cone of depression caused by extraction from the Yarragadee aquifer for public water supply in the Perth area can be seen in the artesian monitoring bores 60 km (37 miles) to the south. In addition to reducing water available for consumptive use, the continued drop in water levels is adversely affecting the ecological function of surrounding water-dependent ecosystems such as lakes and wetlands, especially where the water-table is within a few metres of the surface (Xu, 2008). Despite increasing recognition of the role of groundwater in maintaining ecosystem health across Australia (Froend *et al.*, 2004), Malcolm notes "ongoing failure to comply with wetland management objectives" in the Gnangara case (2004, p. 2).

The superficial aquifer has closest links with surface ecosystems, is subject to a larger range of competing uses than the deeper aquifers, and is therefore of "prime concern" (Malcolm, 2004, p. 1). There is, however, some hydrological connection between the superficial and confined aquifers in certain locations (DoW, 2008; Pigois *et al.*, 2010); the deeper aquifers cannot, therefore, be considered truly confined. Surface ecosystems, and human users of water from the superficial aquifer, are thus not isolated from the effects of extensive pumping from the deeper aquifers, predominantly by the Water Corporation for public supply.[1] The Water Corporation

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[1] Indeed, Pigois *et al.* (2010) confirm the existence of areas of direct connection between the superficial and the deeper 'confined' aquifers in the Gnangara case, and note that describing aquifer interconnection is "critically important for the sustainable management of the Gnangara Mound..." (Pigois *et al.*, 2010, p. 1).

operates approximately 180 bores, across all aquifers; since 1998, roughly 40 bores have been decommissioned as a result of environmental concerns (GSST, 2009).

The primary body in Western Australian water regulation is the state's Department of Water (the Department) which manages licensing and allocation. Groundwater consumption by agricultural licensees has not historically been measured, although this issue is being addressed by a metering program begun in 2005. While agriculture accounts for only around 18% of total GGS water use (GSST, 2009), use by individual agricultural licensees can be significant, and much agricultural use remains unmetered. In an important cluster of 10 intensively-farmed groundwater areas – including the one in which metering began – as many as 60% of licences remain unmetered (DoW, 2010a). Private garden bores, common in WA for garden watering, are also unmetered; an estimated 72,500 unlicensed garden bores withdraw an estimated 58 GL (~47,000 AF) per year from the superficial aquifer, or 18% of total use from the GGS (DoW, 2009a).

An additional complication in the Gnangara case is that plantations of maritime pine (*Pinus pinaster*) intercept rainfall that would otherwise have contributed to aquifer recharge (DoW, 2009b). While not a traditionally-measurable use of groundwater, this interception has substantial effects on the availability of the water resource for other uses. Not being easily amenable to objective quantification, interception could be a source of controversy in efforts to adjudicate limited groundwater resources.

3 Water reform in Australia

The Australian Government’s recent water reform agenda commenced with the 1994 Council of Australian Governments' (COAG) Water Reform Framework. This aimed to achieve efficient and sustainable water use by establishing an integrated and consistent approach to water resources management throughout Australia. COAG set out a framework for the encouragement of water trading, elements of which included:

- a comprehensive system of water allocations or entitlements, including separation of water property rights from land title, and a clear specification of the right or entitlement;

- provision that trading arrangements for water be introduced where they did not exist; and
- deliberate allocation of water towards environmental requirements, to be determined based on the best scientific information available and with regard to maintaining the health and viability of river systems and aquifers (COAG, 1994).

In general, considerable progress on the COAG water reforms was made over the decade following their commencement, although this varied between the states. In much of Australia, however, drought conditions and growing demand during this period exacerbated the parlous state of water supplies, with widespread stress on both the environment and consumptive water users.

In 2004 COAG reinvigorated and extended its 1994 water reform agenda with the signing of the Intergovernmental Agreement on a National Water Initiative (NWI) (NWC, 2008).[2] The over-arching objective of the NWI is to achieve "… a nationally-compatible, market, regulatory and planning based system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes …" (NWI, 2004, clause 23).

A key element of the NWI was the establishment and enhancement of water markets and water trading, whilst recognising and protecting third-party interests and the needs of the environment. The NWI reflected the improved understanding of the management needs of both surface and groundwater systems, and the requirements for effective and efficient water markets. To this end the NWI required that the states:

- "facilitate the operation of efficient water markets and the opportunities for trading, within and between States and Territories, where water systems are physically shared or hydrologic connections and water supply considerations will permit water trading;
- minimise transaction costs on water trades, including through good information flows in the market and compatible entitlement, registry, regulatory and other arrangements across jurisdictions;

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[2] Western Australia did not sign the NWI until April 2006. Its plan for implementing the NWI reform agenda is embodied in its Implementation Plan for the NWI (Government of WA, 2007).

- enable the appropriate mix of water products to develop based on access entitlements which can be traded either in whole or in part, and either temporarily or permanently, or through lease arrangements or other trading options that may evolve over time;
- recognise and protect the needs of the environment; and
- provide appropriate protection of third-party interests" (NWI, 2004, p. 10-11).

For water trading to be successful requires clearly specified and secure water rights or entitlements. These entitlements should reflect the hydrological realities of the surface or groundwater system in question (Young and McColl, 2009). The operating rules of the market, intended to deal with hydrological and other constraints, should not unduly restrict trade and lead to market inefficiencies (Howe, 1997). Finally, the metering of consumptive use of groundwater, and the monitoring of aquifers are essential for successful and sustainable groundwater trading (NRMSC, 2002).

3.1 A new form of water right

Dudley and Musgrave (1988, p. 1) described a water usage right that related to "a share of the capacity (not contents) of river storage reservoirs and their inflows". In 1997, Vaughan and Emerson observed that "... it would be folly to assign rights to a fixed quantity of an inherently variable resource" and suggested instead a system in which "... a fixed share but a variable quantity for each irrigation season would be set according to water availability" (1997, p. 179). This principle – constant proportional shares of the annually available water – is often referred to in Australia as 'consumptive pool'.

The concept of a water access entitlement as a perpetual or open-ended share of a consumptive pool (rather than as a volumetric entitlement as currently the case in Western Australia) is the centrepiece of the NWI water rights and trading regime. A consumptive pool is the amount of a "specified water resource" that can be made available for consumptive use, as determined in a relevant statutory water allocation plan (NWI, 2004, p. 6). Water allocated to environmental requirements typically falls outside the consumptive pool, although not necessarily so.

Such water access entitlements enable adaptive management of water resources under fluctuating water availability. They allow the allocation among users, in proportion to their share of the consumptive pool, of the total water available in a given year. The NWI also proposes an approach to allocating the risk arising from changes in water availability, depending on the cause of the change.[3] The clear assignment of risk arising from potential future changes in the consumptive pool, and the payment of compensation if appropriate, are aimed at further strengthening the security of title embodied in water access entitlements.

Unlike the existing water allocation licences in WA, water access entitlements are separate from land title and are ‘unbundled’ or separated from land use and infrastructure construction approvals. Separate approvals are required to construct and operate bores and wells, for example, and to extract and use water. The separation of land and water title, and the unbundling of the approvals process, mean that water access entitlements are a more secure and tradeable water right than currently exists under the licensing regime in WA.[4]

States are required under the NWI to move towards converting existing entitlements into fully tradeable water access entitlements and to facilitate the development of markets for those rights. This requires the development of appropriate conversion factors and transitional arrangements. Where water resources are over-allocated, existing volumetric entitlements should be returned to sustainable levels before converting them into water access entitlements (NWI, 2004).[5] This typically involves a water resource manager reclaiming entitlements that have been allocated but never used (‘sleepers’) or which have ceased to be used (‘dozers’).[6] The introduction of trade gives the owners of previously unused or under-used entitlements an incentive to sell them, effectively increasing the level of water allocation (Bell and Quiggin, 2008).

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3 See NWI 2004, Clauses 46-51 for details of the NWI Risk Assignment Framework.

4 Licensing is currently based on the *Rights in Water and Irrigation Act 1914* (RiWI Act).

5 One of the NWI objectives was to "complete the return of all currently overallocated or overused systems to environmentally-sustainable levels of extraction" (NWI, 2004, p. 4).

6 In Western Australia the RiWI Act gives water resource managers the power to reclaim unused allocations.

A requirement of the NWI is that water access entitlements be issued in accordance with a statutory water allocation plan (NWI, 2004, clause 36). Such plans should provide for "secure ecological outcomes" and "resource security outcomes" (NWI, 2004, p. 7). Water planning is a significant reform under the NWI, in the recognition that "best available science, socio-economic analysis and community input" are important in resolving competing demands for water (NWI, 2004, p. 7). Being statutory, the plans are legally binding on both the state and water users.

3.2 Groundwater management

In recognition of the importance of groundwater in Australia’s natural resource base, COAG, as part of its 1994 water reform agenda, requested that the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) investigate groundwater management arrangements (COAG, 1994). The resulting 1996 ARMCANZ paper concluded that groundwater trading could expand, and that it offered potential to solve difficult management issues as demand for water use increases. ARMCANZ also identified a number of groundwater reforms relating to the COAG agenda, including:

- "achievement of efficient sustainable use of groundwater in accordance with a nationally agreed approach to sustainability;
- public identification of the sustainable yield, allocation and use of aquifers, with allocations limited to sustainable levels where appropriate";
- "establishment of systems to support transferability of groundwater entitlements"; and
- "provision of adequate funding for groundwater investigation in high priority areas" (ARMCANZ, 1996, p. 5).

A subsequent paper on groundwater trading was produced in 2002 by the Natural Resource Management Standing Committee (NRMSC). This paper also identified benefits of groundwater trading, but noted difficulties in introducing effective trading regimes resulting from technical, social, and political impediments. A recent unpublished government study recognised the potential for groundwater trading in Western Australia, while pointing out a number of uncertainties and/or constraints which could limit the feasibility of trading in the region. The heterogeneous nature of many groundwater systems means that information and knowledge of the resource is an important pre-condition for trade in these systems (Hamilton and Smithson, 2010; Brozovic *et al.*, 2010).

4 Groundwater trading

"The concept [of groundwater trading] has been developed for some time, but has not been applied to anywhere near the same extent as with surface water, apart from in a small number of local areas" (NRMSC, 2002, p. 1).

Water trading is prominent on the Australian national policy agenda; groundwater trading in particular may be an appropriate policy response to water scarcity in the Perth region and elsewhere, if challenges and impediments can satisfactorily be addressed. Two main justifications present themselves, for the use of trading as a policy response to scarcity:

- trading can aid in the adjustment of groundwater users to new, lower, entitlements (e.g., NRMSC, 2002); and
- as the resource becomes more scarce, users are inclined to seek higher-value uses of it; trading allows water to 'move' to higher-value uses (e.g., Vaux and Howitt, 1984; Haddad, 1996; Grafton *et al.*, 2010; NWC, 2010).

On the first point, users facing adjustment to reduced water allocations will value flexibility. Fixed annual volumetric allocations (such as are in place in the case-study area, for example) have the advantage of providing some certainty to users. Reductions in these fixed allocations, however, present water users with new production decisions. Users' transitions from old to new water allocation levels are unlikely to be instantaneous. Rather, users would likely benefit from the ability to purchase additional water – for example to maintain current practices while new techniques or infrastructure are adopted. Conversely, trading allows other users to gain the economic benefit of selling their allocation in cases where it may be too low to continue past practices profitably. These simple examples demonstrate that, while valuable to some extent at all times, the flexibility provided by a market in water rights may be of particular benefit during transitions in use levels required by new, or newly-apparent, levels of scarcity. Indeed, it is this factor that gives rise to the 'trade' in 'cap-and-trade' arrangements. When policy-makers administratively impose scarcity on the right to emit carbon dioxide, for example, they simultaneously establish the means by which newly-constrained polluters may exchange these rights (in the form of permits), helping them manage their adaptation to the new conditions.

The second main justification for trading as a response to scarcity relates to heterogeneity. Emitters of CO_2, for example, have different private costs of emissions abatement, with the result that they place different values on a given emissions permit or allowance. The same is true in the water trading case; groundwater users have differing private costs of reducing their water use. In other words, they place different values on the marginal unit of water. Brewer *et al.* (2007) provide several dramatic illustrations of the inter-sectoral range of valuations for water. An example: “[g]roundwater for farming near Marana, Pima County, Arizona costs approximately $27 per acre-foot, whereas the same water supplied by Tucson Water ... will cost customers from $479 to $3,267 per acre foot" (Brewer *et al.*, 2007 p. 2). It is these differing private valuations which allow water consumption / extraction (or CO_2 emission) to 'move' to higher-value uses under trading. Users who can relatively cheaply use less water may do so (including exercising the options to cease production or change operations). Users whose 'abatement' costs are higher (i.e., to whom marginal water is worth more) may purchase a water access entitlement (or emissions permit). In this way, economic efficiency is enhanced, and the allocation of the traded resource moves closer to an economically optimal state. Among other requirements, an effective groundwater trading scheme requires:

- that water use be capped or limited, thus imposing the impetus to trade;
- that usage volumes be measured;
- secure and tradeable water use entitlements, unbundled from other approvals; and
- that third-party effects be managed.

One of the requirements for effective and efficient water markets is the minimisation of transaction costs - the various, often administrative, barriers to a given transaction that are a common feature of water transfers (e.g., Haddad, 1996; Brewer *et al.*, 2007). Transaction costs - both financial and otherwise - can arise from legal and regulatory sources, and depend on the institutional context – including the cultural environment – of the prospective transactions or market.

Groundwater trading, unlike some markets in surface water, does not usually involve the physical exchange of water itself. Instead, it is the right to extract water that is exchanged. Hydrologically and environmentally, alterations in the site of extraction of a given quantity of groundwater may give rise to different impacts from pumping at the respective selling and buying locations. In highly transmissive aquifers, pumping impacts may be transmitted widely and thus spatially equalised over a short time. Otherwise, however, groundwater trading is, from a management perspective, more usefully thought of as transferring the impacts of groundwater pumping. This is the foundation for much of our discussion; we consider the potential for addressing alterations in the level and distributions of impacts from groundwater extraction.

The impacts of groundwater pumping can range from relatively simple and compensable third-party financial effects (such as a neighbour's altered pumping costs as a result of a nearby pumping transfer) to much more complex, spatially- and temporally-distributed impacts.[7] The most direct of these impacts are Howe's "contemporary pumping externalities": costs imposed on current neighbouring groundwater users in the form of increased pumping costs (Howe, 2002, p. 627). Less direct are the surface impacts of otherwise unseen groundwater pumping which can be dramatic. Environmental effects of excessive groundwater extraction include the drying of wetlands and springs, streamflow reduction and declining lake levels, and the loss of vegetation and groundwater-dependent ecosystems (GDEs) (Zektser *et al.*, 2005). Such impacts have occurred in many cases, including Tampa Bay in Florida (see Glennon, 2002), the Edwards Aquifer in Texas (see McCarl *et al.*, 1999), and in the Gnangara system in Western Australia (see Malcolm, 2004). A high-profile example in the case-study area is that of the many caves in Yanchep National Park. Several of these support between 30 and 40 invertebrate species, which rely on groundwater streams or pools (Froend, 2004). These ecosystems are "critically endangered" and are classified as threatened by the Department of Environment and Conservation (DoW, 2009a, p. 25). In some cases, land subsidence – the sinking of ground surfaces – is another dramatic effect of groundwater withdrawal. This has occurred in California's San Joaquin Valley, and "land surfaces in parts of central Arizona have fallen 9 meters in the last 20 years" (Howe, 2002, p. 627). Seawater intrusion is an additional risk to coastal aquifers, potentially causing irreversible

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[7] We do not imply that spatial considerations are moot with respect to the financial pumping cost externality. Brozovic *et al.* (2010) note that this externality "is spatially variable and depends on the location of wells relative to each other" (p. 162).

damage. The distinction between financially compensable impacts and those of a non-monetary nature is an important one. The distinction between “physical” and “pecuniary” externalities is also made by Howe (1997).[8,9]

A limitation exists on the extent to which the optimisation of resource allocation can be expected to function in the marketplace; not all values are represented in the market. Market transactions fail, by definition, to include 'external' costs, which fall instead on parties who are neither buyer nor seller (e.g., increased pumping costs for other water users). Environmental damage is a third-party impact in which the third party is not an individual, and may not be monetarily compensable.[10] This common type of market failure is of general concern in resource management, and is one of the economic corollaries to the hydrological challenges we present.

Analyses of groundwater trading or transfers, with the explicit intent of addressing the range of potential impacts, have been relatively rare. A number of studies approach specific aspects of this or related problems. Knapp *et al.* (2003), for example, evaluate the interaction between surface water transfers and groundwater management, and discuss the impacts of out-of-basin surface water sales on groundwater extraction. In assessing the impacts of groundwater use, however, their analysis includes only the pumping cost externality, and excludes “[o]ther phenomena such as land subsidence, water quality, seawater intrusion, natural habitats, or equity considerations...”. Similarly, Brozovic *et al.* (2010) confine themselves exclusively to the pumping cost externality and do not address any environmental effects of groundwater extraction. Heaney *et al.* (2006) identify several potential third-party effects of water trading in the surface water context of Australia's southern Murray-Darling Basin; they attribute these effects to the failure of unbundled water access

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[8] Impacts – positive or negative – that are borne by the parties involved in the transaction (i.e., the buyer and seller) are referred to as 'private' costs or benefits. Other costs or benefits than those borne by the transacting parties are known as 'external' costs or benefits, or simply as externalities.

[9] There may be cases where external effects from pumping are exclusively financial, and thus straightforwardly compensable. In such cases, it would be feasible to make direct trade-offs between economic values – for example from increased economic benefit due to concentration of groundwater extraction for a high-value use, versus increased pumping costs for neighbours. Where feasible, such direct economic trade-offs could be permitted within the design of a trading scheme; hence our focus on the distinction between financially compensable and non-monetary impacts.

[10] For example, damages suffered by non-humans are not amenable to monetary compensation.

entitlements to take into account “the spatial characteristics of water supply, demand and use” that were incorporated in the earlier joint land/water right (p. 291). The specific impacts they discuss, however, are largely particular to surface water transfers and not to the impacts of groundwater extraction either pre- or post-transfer. Heaney *et al.* (2006) suggest that their described water market is incomplete with regard to storage and delivery infrastructure, capacity constraints, congestion and the third-party effects from these due to trading. We describe third-party effects of the redistribution of groundwater use that likewise arise from market incompleteness, but along different dimensions. We give particular attention to environmental impacts of pumping, and the potential for their spatial redistribution, concentration, and qualitative transformation under trading. Qureshi points out that “trade does not always result in gains, especially when negative externalities are considered” (2009, p. 1644).

The design of a sound groundwater trading scheme needs to meet the challenge of addressing unvalued, or un-valuable, impacts. Transfers of groundwater extraction due to trading may impose external costs that are both uncertain and difficult to quantify. In attempting to develop an efficient management regime, it would be convenient if it were possible to express all impacts in monetary terms, to allow the assessment of the merits of particular trades. In reality, however, some of these negative externalities are non-monetary in nature and may include damages that are theoretically and/or practically difficult to 'monetise'. With respect to environmental impacts in particular, monetisation, even if assumed possible, may represent a substantial additional source of uncertainty. One reason is that even the best non-market valuation studies may be methodologically unable to incorporate the full range of non-market values. Policy systems need to be designed in recognition of this difficulty.

4.1 Socially beneficial transfers

Groundwater pumping can have varied and diffuse effects, imposing costs on other groundwater users, on society, and on surrounding ecosystems. Without trading – that is, under known distributions of groundwater extraction – these impacts need to be managed. This can be done by limiting use at particular locations and/or overall. Under trading, however, the potential spatial redistribution of these impacts requires additional management. An economically and environmentally robust groundwater trading scheme would ensure that trading results in transactions that do not reduce overall (i.e., 'social') welfare. That is, from a given trade, the following should hold:

$$MPB + MEB \geq MPC + MEC \qquad \text{(Equation 1)}$$

where:

- MPB is the marginal private benefit generated by the trade (i.e., to the transacting parties – e.g., increased productivity);
- MEB is the marginal external benefit from the trade (i.e., positive externalities – e.g., higher water-table levels for neighbours of the purchaser, improved water levels for GDEs);
- MPC is the marginal private cost of the trade (i.e., costs borne by the transacting parties – e.g., opportunity cost of foregone water use); and
- MEC is the marginal external cost caused by the trade (i.e., negative externalities – e.g., increased pumping costs, drying of wetland due to reduced water-table levels, loss of migratory bird habitat).

A newly-established trading scheme could redistribute groundwater extraction such that concentration and overall impacts are either increased or decreased relative to the pre-trading condition. In meeting Equation 1, net losses are prevented and the economic efficiency of the consumption of available water is improved.

The quantitative estimation of financial welfare effects from implementing these tools and approaches in a trading scheme is not the intent of this paper. Other studies have made some tangentially related estimates. In a study of potential improvements to private net farm income for the Nile River basin , Gohar and Ward (2010) estimated the marginal value of allowing intra-regional trade as $US 0.5 billion per annum, and of allowing inter-regional trading as a further $US 0.12 billion per year. (They note their use of “numerous simplifying assumptions” and that “[a]griculture is the only water use analyzed” (Gohar and Ward, 2010, p. 2544). Qureshi *et al.* (2009) offer a basin-wide estimate ($17 million annually) of the opportunity cost of a basket of restrictions to water markets in the Murray-Darling Basin (as compared with an unrestricted trading scenario). For the southern Murray-Darling Basin, Heaney *et al.* (2006) suggest that trade in permanent entitlements would increase by roughly 600 GL (~486,000 AF) were administrative barriers removed. There is clearly scope for further work to address potential welfare gains from the implementation of tools and approaches such as are suggested here, particularly in the context of groundwater trading, and particularly giving attention to the incorporation of both financial and non-monetary impacts.

4.2 Trading in the Gnangara case

There is currently very limited trading in the Gnangara system. Despite pro-trading policy statements dating back to 2001, significant changes to the legal and policy environment in the GGS case are needed to facilitate the development of a market in groundwater rights. Skurray *et al.* (2011) analyse the legal and policy environments affecting groundwater transfers in the Gnangara case, describe a number of what Colby (1990) calls “policy-induced transaction costs” (p. 1184), and identify institutional impediments to the development of effective trading in groundwater usage rights. The rights to the use and flow, and to the control of GGS groundwater legally rest with the Crown, except as provided for in the RiWI Act. Use is permitted through a licensing system; water rights thus take the form of licences ‘to take’ water. Licences are bundled with land use and infrastructure approvals. Lengthy and often complex assessments can be required before approval is given for a trade to take place, imposing substantial transaction costs on potential sellers and buyers. The consumptive pool regime discussed earlier would help to overcome some of these limitations.

One of the primary goals of a trading scheme is to make use of the range of valuations held by market participants for the traded asset. In the Gnangara case this is notably attenuated by the nature of the current management area boundaries. The Department of Water divides the GGS into a number of management areas. At the superficial aquifer level, there are 51 separate management areas, several of which are at some points as little as one kilometre across (DoW, 2009a). Transfers or leases (short-term exchanges) are generally permitted only within the boundaries of a given management area. Because of the large number and small size of many of these areas, such requirements mean that transfer opportunities are greatly limited, reducing the feasibility of establishing markets in groundwater. This issue is compounded by the fact that licences are based on a stated land use and that the management area boundaries partly coincide with land use divisions. The current GGS groundwater areas were established primarily on "cadastral" boundaries (DoW, 2008, p. 2); they were not intended to align with hydrological realities, nor to facilitate economically and environmentally beneficial trades. This causes an artificial attenuation of the range of trading possibilities, particularly reducing the opportunities for trade between uses. It is possible that a new statutory water allocation plan, under new legislation, may address the re-design of the current 51 GGS management areas, improving their hydrological appropriateness and suitability for trading (DoW, 2008).

5 Hydrological challenges to establishing trade

In this section we describe a number of the requirements for effective implementation of a groundwater trading scheme, focussing on requirements that have a hydrological basis and/or that require hydrological information regarding the groundwater resource. As Ostrom notes with regard to the appropriation of common-pool resources such as groundwater, "[a] major source of uncertainty is lack of knowledge. The exact structure of the resource system itself – its boundary and internal characteristics – must be established" (1990, p. 33). As we discuss below, these internal characteristics may be several, and are important to the design of an effective trading scheme.

Uncertainty and delay in the environmental and social impacts of groundwater use require management regimes that are flexible and adaptable, rather than rigid policies based on inadequate hydrological information, or that fail to incorporate the relevant hydrology. We propose that groundwater trading schemes should be designed and managed with sensitivity to hydrological conditions, as well as to our evolving understanding and knowledge of those conditions.

5.1 Establishing boundaries

Figure 3.3 illustrates a highly simplified aquifer system with multiple extraction points. In this simplest case we consider a highly transmissive aquifer, in which the impacts of spatially uneven pumping are equalised rapidly. The first hydrological challenge, then, is to define the boundaries of the aquifer system at the ground-surface level. This is a fundamental input to the design of any trading program; without an understanding of these boundaries, resource managers cannot know which users' groundwater extraction is drawing from the same resource, and therefore which users should be subject to the same cap on resource use and should have shares in a given consumptive pool.

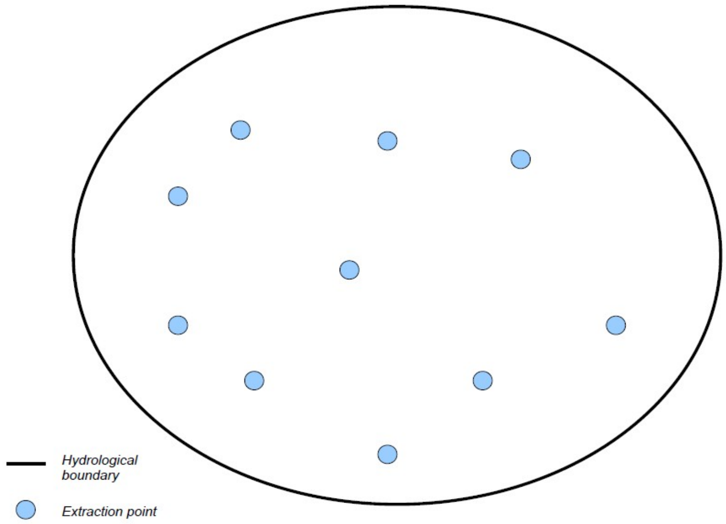

Figure 5.1: Conceptual outline of high-transmissivity aquifer with extraction points. (Source: author).

The physical boundaries of the area for which a consumptive pool is defined are based on those of the groundwater system (both horizontally and vertically). Hydrogeological connectedness, groundwater flow and other properties of the system, as well as groundwater quality, can influence the definition of the area for which a consumptive pool is defined. Hamilton and Smithson (2010) note that sources of complexity in the management of groundwater trading include “the three-dimensional nature of groundwater systems, [and] uncertainties around water source boundaries” (p. 2). We propose that all aspects of a trading scheme should be designed so as to facilitate the incorporation of new or changed information – hydrological and otherwise – as it becomes available.

Given the assumed highly transmissive nature of this example aquifer, there is no need to consider the spatial distribution of pumping impacts. These are, effectively, spread evenly across the system quickly enough such that spatially explicit aspects of their distribution with respect to their points of origin are of little concern. What is important in this case, apart from establishing the system's boundaries, is establishing the sustainable yield.

5.2 Sustainable yield

The second hydrological challenge we consider is what overall volume of water use should be permitted. As discussed previously, one of the key NWI water trading provisions was the concept of a consumptive pool – the quantity of water from a specified resource that can be made available for consumptive use (NWI, 2004). Once established, shares in the consumptive pool can be issued as perpetual and secure water access entitlements which are separate from land ownership and use, from other water use approvals, and which can readily be traded.

The size of the consumptive pool in terms of the volume of water available, is generally based on some estimate of the annual sustainable yield of a system.[11] One possible approach is to define the consumptive pool as the available net recharge of the aquifer.[12] This could be defined as the gross recharge, less any outflow to the ocean and leakage to other aquifers, with a volumetric allocation reserved for environmental needs. The sustainable yield may have to be calculated annually, taking into account previous rainfall recharge and water level responses. Under the consumptive pool model, an allocation announcement is made at the beginning of each year, based on an estimate of the size of the consumptive pool for that year. This announcement sets the volumetric entitlement available to each water access entitlement holder for the coming year, based on the number of entitlements held. In the case of groundwater, the net recharge is unknown at the beginning of the year, although can be estimated. A response to this source of uncertainty would be to use the calculated net recharge volume from the preceding year. We suggest that the allocation announcement be based on a rolling average of net recharge volumes from the preceding five years.[13]

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[11] Sustainable yield is also referred to as the ‘sustainable diversion limit’ or the ‘sustainable extraction limit’. The National Water Initiative defined the “environmentally sustainable level of extraction [as] the level of water extraction from a particular system which, if exceeded would compromise key environmental assets, or ecosystem functions and the productive base of the resource” (NWI, 2004, p. 29).

[12] Other possible approaches to determining sustainable yields have also been proposed (e.g., as described in Evans, 2007) but are not discussed here.

[13] While five years is a somewhat arbitrary timeframe, using such a multi-year period would reduce the influence of anomalous rainfall years, and would more usefully reflect trends in recharge volumes.

In the case of a multi-level system of aquifers, such as the Gnangara system, it may be preferable to define a separate consumptive pool for each aquifer. Depending on the structure of the system, water users might potentially have shares in a number of consumptive pools.

Development of the consumptive pool model using sustainable yield presents a number of hydrological information and monitoring requirements, including:

- knowledge of the hydrogeology of the groundwater system and the interconnectedness of aquifers;
- knowledge of the water balance to allow an estimate of net recharge, sustainable yield, and consumptive pool volumes; and
- an understanding of the third-party impacts of abstraction levels, and the likely spatial relationships between impacts and points of extraction.

We use the concept of sustainable yield throughout the paper on the premise that, by definition, this is the amount of water that can be used sustainably over time.[14] We suggest that the consumptive pool volume be based on aquifer sustainable yield, and that therefore the definition of sustainable yield is a foundation for a trading scheme.

Clarification of the hydrological boundaries and of the sustainable yield of an aquifer are, we suggest, the two primary hydrological challenges in establishment of a trading scheme for groundwater use; they are necessary regardless of the nature (transmissivity, internal structure) of the groundwater system.

In highly transmissive systems, impacts are due to the reduction of overall water-table levels. This makes them simpler to manage than cases – including the Gnangara case – in which transmissivity is lower and impacts from pumping are more localised.[15] We first discuss the simpler, high-transmissivity case.

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[14] We acknowledge that limiting extractions to a sustainable level does not mean that there will be no impact on environmental conditions, relative to conditions without human use.

[15] The distinction between highly-transmissive and less-transmissive aquifers is necessarily an over-simplification. In nature, aquifer properties do not conform to such a simple dichotomy but can range across a continuum. We use the distinction as a means of clarification, and primarily to introduce the spatial and temporal distribution of impacts.

5.2.1 Impacts management via sustainable yield

The management of impacts caused by groundwater pumping generally translates directly or indirectly to the management of groundwater levels. Because impacts are transmitted relatively rapidly throughout highly-transmissive systems, increases in pumping costs, for example, are equalised across the aquifer and therefore borne by all users. The main factor affecting an individual's pumping costs in such cases, then, is overall extraction from the system, rather than any one neighbour's use.[16]

Similarly, in more transmissive aquifers, the potential for environmental impacts is largely a function of overall extraction, rather than of localised use. In the case of Figure 3.3, there were no sensitive ecosystems in the system; in Figure 3.4, we introduce a wetland into our illustrative hypothetical groundwater system, as a proxy for any GDE.

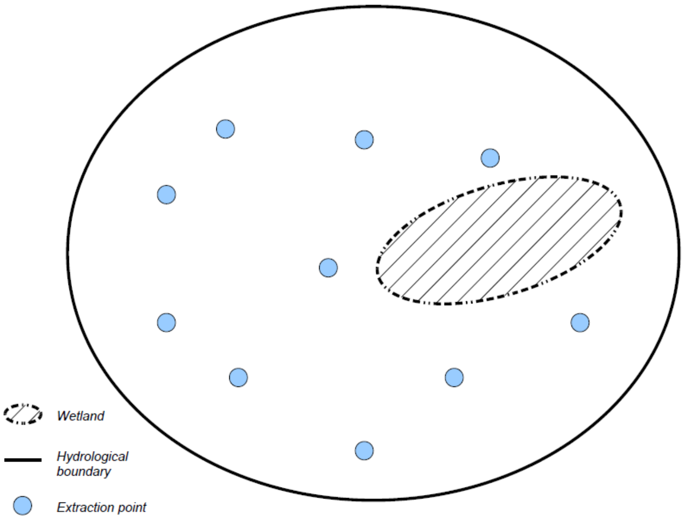

Figure 5.2: Conceptual outline of high-transmissivity aquifer with extraction points and wetland. (Source: author).

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[16] In contrast to the GGS, the Edwards Aquifer in Texas, for example, is a highly transmissive, single-stratum formation (Kaiser and Phillips, 1998). As a result, water-level changes due to drought, pumping, and rainfall, are transmitted quickly across the aquifer (Howe, 2002), reducing the potential for concentration of impacts. The equalisation of impacts does not mean that individual users' contributions to water-table levels are equal.

A fundamental difference between meeting environmental water requirements in surface water systems and doing so in groundwater systems is that 'environmental water' requirements for GDEs usually relate to a water-table level, rather than to a volume of water. In surface water management, leaving a certain volume of water in a river may provide 'environmental flows'. The same approach used in groundwater systems, however, may leave a water-table at too great a depth to be of use to surface GDEs.

As long as the condition of high transmissivity is maintained in our example aquifer, the only additional hydrological challenge to establishing an environmentally and economically robust trading scheme in the Figure 3.4 case is that of ensuring that the annual (or periodical) extraction limit maintains ecosystem health. This can be considered part of the comprehensive definition of sustainable yield for the given aquifer case, rather than as a separate piece of information. It may be prudent to use shorter consumptive pool announcement periods in this case (than in the Figure 3.3 case) to limit the potential damage from overestimation of sustainable yield.

The NRMSC noted that exceeding sustainable yield is “highly undesirable” because of the “direct and immediate social and economic” impacts of the necessary reductions in use. Combined with the uncertainties in determining sustainable yield figures, the committee suggested that these impacts may warrant the precautionary approach of limiting allocations to levels lower than sustainable yield in some cases (NRMSC, 2002, p. 4).

No special management, then, would be required in this (high transmissivity) case once the acceptable overall usage level is established. Once overall use is properly capped – at a sustainable level – groundwater extractors could trade amongst themselves without the need for management intervention, or case-by-case review for the purposes of environmental protection or the limitation of other impacts on third parties.

Most groundwater systems are not so transmissive that the spatial distribution of extraction does not matter. While managing environmental and other impacts under lower-transmissivity conditions is also a matter of water-table management, it is at a more localised level. We now discuss the third hydrological challenge – understanding the spatial distribution of impacts with pumping.

5.3 Impacts and extraction – clarifying the relationships

Under lower transmissivity conditions, groundwater trading presents the possibility of spatial redistribution of the impacts from groundwater extraction, as well as the potential for their locational concentration. Whereas the impacts of CO_2 emissions, for example, are diffuse and the location of emission largely immaterial, the impacts from groundwater pumping may be likened to a form of point-source pollution: impacts vary with the location of groundwater extraction.

In Figure 3.5 the example aquifer is, like the GGS case-study, of lower transmissivity. Our examples thus far have demonstrated the need, as inputs to the design of a trading scheme, for fundamental hydrological information about groundwater systems as whole units: their boundaries and extractable recharge volumes. Once the simplifying factor of very high transmissivity is removed, it becomes more important to address Ostrom's "internal characteristics" requirement.

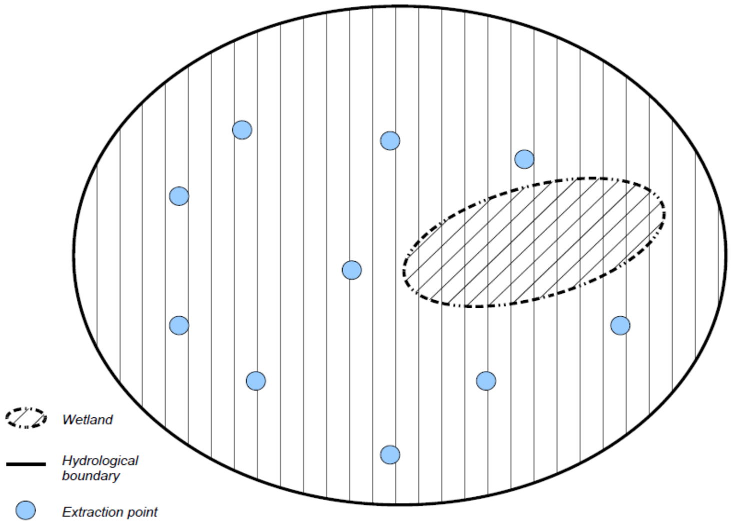

Figure 5.3: Conceptual outline of lower-transmissivity aquifer with extraction points and wetland. (Source: author).

One hydrological challenge is to clarify the influence of aquifer internal characteristics on the spatial distribution of impacts from a given extraction point. Some such hydrogeological attributes relate to the interconnections and interactions between different aquifers within a given system (such as the multiple aquifer levels within the Gnangara system), and between groundwater and surface water. Groundwater management policy – including the fundamentals of a trading scheme – should of course take into account these interactions, rather than treating, for example, surface and groundwater as entirely separate (e.g., Young and McColl, 2009) or partially confined aquifers as wholly confined. In addition, internal aquifer characteristics influence the distribution of impacts, even in the absence of interconnections or interactions. Tumlinson *et al.* (2006) describe the "spatially distributed heterogeneities" that can occur within given cones of depression, influencing its expansion (p. 22).

An example in the Gnangara case is the current reduced rainfall regime; diminished surface water supplies have increased reliance on groundwater for municipal and other uses. This compounds the effect of lowered groundwater recharge from rainfall. Grafton *et al.* (2010) note that recently increased groundwater extraction in the Murray-Darling Basin has reduced surface water streamflow by around 300 megalitres per year. Knapp *et al.* (2003) observe that reduced surface water availability due to transfers increases the value of groundwater (and therefore the value of groundwater management). The interaction between surface and groundwater is a particular management challenge in many areas (e.g., Young and McColl, 2009). For example, between a river and connected aquifer, the appropriate management area boundary may not necessarily be the river bank.

Limiting overall extraction to the sustainable yield does not necessarily eliminate environmental and third-party impacts from groundwater extraction, especially in less transmissive systems. Depending on transmission rates, cones of depression may extend outward from an extraction point to lower the water-table across an area. Nor does reducing extraction to sustainable levels ameliorate the effect on water-tables of a history of extraction exceeding net recharge levels, for example.

The localisation of impacts around extraction points is the source of two significant challenges in developing a hydrologically sound trading scheme. Because of spatial heterogeneity in assets, uses, and ecosystems affected, impacts from extraction at the new location of use may be quite different in scale, nature, and value from those occurring from extraction at the original place of use. Additionally, a trading scheme has the potential to concentrate consumption spatially, thus potentially concentrating – and compounding – the external impacts.

The potential for localised impacts is a major management issue and leads to the need to manage water-table levels at the sub-aquifer scale. Another hydrological challenge is to estimate the effects of extractions on proximal ecosystems and on human users. Depending on aquifer transmissivity, and on the location and water needs of dependent ecosystems and other potential sites of impact, differing spatial distributions of water use will have differing total costs. Design of a robust trading scheme should be informed by the potential range of these total costs. It should perform at least two main functions: it should allow for the economic incorporation of external costs, and it should have design elements (e.g., market rules) that limit the scope and/or direction of trades such that Equation 1 is not violated.

Due to the natural range of aquifer transmissivity values, there may be cases in which it is appropriate to manage the spatial distribution of impacts in aquifers of relatively high transmissivity, and conversely where relatively lower-transmissivity aquifers can safely be managed simply by sustainable yield. This may depend on the nature and potential compensability of the potential impacts in the respective cases.

5.3.1 Inter-temporal effects

Many of the external costs of groundwater use can also occur inter-temporally. The time lags between cause and effect depend on the transmissivity of the particular aquifer, among other hydrological factors, and their prediction is thus not straightforward. Future groundwater stocks can be depleted by present-day over-use, environmental impacts can be delayed, and irreversible reductions in future aquifer storage capacities can also occur. Especially in very large groundwater systems, or in those with very low transmissivity, there may be third-party impacts that occur at times significantly distant in the future. Where the economic valuation of future impacts involves the use of discount rates (e.g., in determining whether Equation 1 holds in an inter-temporal sense) potentially dramatic yet temporally distant outcomes may be too undervalued to influence present-day decisions, depending, of course, on the discount rate chosen.

Inter-temporal effects can be limited by restricting overall consumption to sustainable levels. This way, impacts can gradually be equalised and dissipated by recharge and/or sub-surface flows. Under this type of regime, new impacts that take more than a small number of years to become apparent could generally be considered negligible. Where there is reason to believe that impacts would not be negligible, extraction limits (including the spatial distribution of extraction) could be adjusted appropriately.

6 Potential tools / approaches

Potential third-party impacts could be limited by the implementation of market rules, embedded in the relevant management policies (such as the water allocation plan and/or the water use approval system). Such tools may function best in combination (subject to the avoidance of excessive complexity and resultant transaction costs).

State-wide policy in WA is that trades must not result in "unacceptable" environmental or social impacts, "either through direct impacts or through the concentration of water abstraction within a small area" (DoW, 2010b, p. 7). While this policy goal is appropriate, the case-by-case review process to which proposed trades are currently subjected in the Gnangara case is cumbersome and a major impediment to efficient trading. One of our research goals is to identify ways in which such administrative transaction costs could be reduced by designing a trading scheme to incorporate, as far as practicable, hydrological, environmental, and social requirements. We offer brief comments on a number of these potential policy design options.

6.1 Trading limits

One means of limiting the potential for concentration of use is to impose a limit on the water available for trade, as a proportion of the total water extracted within a management area over a given period. Limiting tradeable water use to, for example, 50% of the overall allocation limit of a management area, would restrict the potential scale of associated impacts. This seems a rather 'brute force' approach to limiting potential impacts from groundwater exchanges, but has simplicity in its favour.

A similar approach has been used in Australia to limit inter-regional trading of surface water, as a way of limiting socio-economic external effects. Very low percentage limits were in place at times during the decade 1998–99 to 2008–09. Victoria and New South Wales had 4% annual limits on "the volume of water entitlement that may be traded out of an irrigation [district or area]" (NWC, 2010, p. 34). In many cases these very low limits were reached earlier than half-way through the water-trading year, and were found to "create uncertainty and [to be] costly to buyers and sellers" (NWC, 2010, p. 35). This reflects the fact that creating such barriers to trading can create costs for market participants, as well as potentially providing external benefits.

Previous work has also noted examples of the use of trading limits, in Australian surface water management, as a tool for limiting inter-area transfers. A 2% limit on the permanent transfer of water entitlements out of its jurisdiction has been imposed by the Central Irrigation Trust in South Australia, “to protect regional interests” (Qureshi *et al.*, 2009, p. 1644). Victorian state water authorities can limit permanent net inter-area transfers to 4% of the selling area's allocation annually (Qureshi *et al.*, 2009). Heaney *et al.* (2006) suggest that inter-regional trading may remain at low levels partly due to trading limits imposed by irrigation managers. We suggest the potential usefulness of trading limits in groundwater management, as means of limiting the concentration of impacts within a given management area.

Where two hydrologically connected areas share a common border, it would be theoretically possible for the full volume of tradeable extraction in each respective area to be concentrated closely together, effectively at nearly a single point. Using trading limits alone to address this potential could result in otherwise unnecessarily restrictive limitations. Implementing trading limits low enough to prevent even unlikely outcomes would be restrictive ; it would be preferable to use trading limits in combination with one or more other management strategies.

Another possibility is to use concentration limits according to location. These could be used instead of or in combination with buffer zones. Trading rules would limit the potential for concentration of use at certain distances from a sensitive area. Similarly, concentration could be limited according to proximity to the management area border (thus addressing the problem of cross-boundary concentration). Such concentration limits would effectively be spatially-varying limits on purchases.

6.2 Management areas

The National Water Initiative is explicit regarding the importance of management areas (or “trading zones”) as management tools. It notes that the establishment of trading zones may facilitate the management of trading, by “setting out the known supply source or management arrangements and the physical realities of relevant supply systems within the zone” (NWI, 2004, p. 30). It also specifies a benefit of appropriately defined management areas: that “trade can occur within and between zones without first having to investigate and establish the details and rules of the system in each zone” (NWI, 2004, p. 30). The NWI recommends that both surface water and groundwater trading areas be “defined in terms of the ability to change the point of extraction ... from one place to another, and protection of the environment” (NWI, 2004, p. 38).

In the Goulburn-Murray Water system in Victoria, management area-based trading rules are used to prohibit surface water trading between particular districts and sub-districts. One goal of these rules is to manage salinity impacts and to “encourage water to move from areas of high salinity impact to those of lower salinity impact” (Qureshi *et al.,* 2009, p. 1644). In New South Wales groundwater management, area boundaries have been used to manage trading in both the Lower Namoi and Lower Murrumbidgee groundwater source regions . In the former, three areas were defined, and rules established to control the direction of water transfers “in order to prevent additional drawdown impacts in the more heavily impacted areas” (Hamilton and Smithson, 2010, p. 3). Trades from areas of lower impact to higher impact are prohibited.

The larger the management area, the greater the theoretical potential for the concentration of impacts due to spatial redistribution under trading. This is one reason to limit trading to within sub-aquifer-level management areas. Establishing a single trading area incorporating all hydrologically connected points across the Gnangara system's 2,000 km^2 area, for example, would allow the potential for unacceptable impacts due to excessive concentration of pumping. It may also increase the range of potential transformations between different types of impacts, and the scope over which these could take effect.

A related reason to use multiple management areas within a single aquifer system is to allow for localised allocation limits – for example where there are difficulties in establishing the sustainable yield of a larger area. There may be limited information on whether recharge is evenly distributed across a large system, or on how quickly that recharge and the sub-surface flow will equalise impacts from pumping. Management area boundaries should be designed with consideration to aquifer internal characteristics and their influence on the distribution of impacts.

Whether or not groundwater-dependent ecosystems exist within a management area is an important consideration. If not, third-party effects of concentration might be limited to compensable increases in pumping costs. Where GDEs exist within a management area, trading limits and/or concentration limits could be used to limit the concentration of impacts near those locations. Directional trading rules could be used to create 'sell-only' buffer zones around sensitive areas.

Trading area boundaries could also be designed to exclude environmentally sensitive areas. Within areas of this type, pumping could be highly concentrated at the centre, with decreasing concentration levels permitted closer to the management area boundary. The sensitive ecosystem in this case is therefore outside the management area, with a protective buffer around it created by the radial limitations on concentration in the surrounding management areas.

6.2.1 Inter-area transfers

The 'trading in impacts' aspect of groundwater trading suggests the idea that trading should occur only between hydrologically connected locations. One rationale for this perhaps arises from the fact that hydrological connection between trading partners allows recharge (if applicable) and/or sub-surface flow to equalise or smooth, over time, the impacts of an exchange between two points. Another is that the impacts (costs) of increased pumping at the buying location are at least partly hydrologically offset by benefits of reduced pumping at the selling location (although benefits may not fully offset costs, for a number of reasons). An example is the altered pumping costs of neighbours of buyers or sellers; these may not offset each other where the relationship between pumping costs and groundwater depth is non-linear. The hydrological connections of prime importance in the context of groundwater trading, however, are those between the respective extraction points and their surrounding areas, GDEs, etc. The effects of interest are the impacts or benefits propagating from points of altered extraction volumes as a result of trade.

In terms of designing a cap-and-trade style program, the overriding consideration regarding hydrological connection would be that hydrologically separate extraction points should not be included under the same cap. Each hydrologically distinct area has its own sustainable yield. Overall caps on use should apply to hydrologically relevant units/areas and not straddle or partition them. The policy question under consideration is how best to define management areas to reduce the total net impacts from transfers. Out-of-area transfers are not ruled out, and could be reviewed individually.

Until recently in the Gnangara case, a form of trading rule existed: inter-area trades were permitted only where the trade would reduce stress on the source area, and where consumption in the receiving area remained within the sustainable yield (WRC, 2001). Trades were not permitted to increase allocation (i.e., use) in an already fully-allocated management area. This policy was replaced in 2010; the current stipulation is simply that "[a] water entitlement transaction must remain within a water resource management unit (WRMU) (i.e. same surface water subarea or groundwater subarea and aquifer)" (DoW, 2010b, p. 6).

6.3 Exchange rates

Exchange rates are a potential means of limiting the concentration and transformation of impacts due to trading. Exchange rates are defined in the National Water Initiative: “the rate of conversion calculated and agreed to be applied to water to be traded from one trading zone and/or jurisdiction to another” (NWI, 2004, p. 29). Exchange rates are noted in previous work as potential tools for managing conveyance losses and differences in entitlement yield (Beare *et al.*, 2005, in Heaney *et al.*, 2006); third-party impacts between states (Qureshi *et al.,* 2009); and increases in external costs, such as downstream salinity impacts in surface water (Heaney *et al.*, 2006). In interstate impacts from surface water trading, Qureshi *et al.* (2009) note that the Murray-Darling Basin Commission allows trades in the downstream direction to transfer the full entitlement (i.e., an exchange rate of 1). Transfers in the upstream direction, however, are subject to an exchange rate of 0.9, such that only 90% of an entitlement's volume is transferred. These implementations account for characteristics of surface water transfers such as volume (including delivery losses) and reliability.

Heaney *et al.* (2006) observe that exchange rates could be useful in dealing with third-party impacts such as downstream salinity increases (by requiring that a purchase incorporate additional water for dilution). In the surface water context, Heaney *et al.* also note that a levy could be imposed on traded water use; “[t]he levy revenue could be used to provide an incentive to trade water from regions with high external costs to regions with lower external costs” (Heaney *et al.*, 2006, p. 290). Such a levy would perform a related function to our suggested use of exchange rates in the groundwater context.

The Department of Water implies the use of exchange rates or similar mechanisms when it notes that “[w]ater allocation management plans ... in over-allocated areas [may] stipulate that a transaction may only be approved if a certain percentage of the water entitlement is surrendered to the department” (DoW, 2010b, p. 9).

While exchange rates are described elsewhere, our particular suggested use of them in the groundwater trading context has not been extensively discussed. In a management system that precludes unacceptable impacts (by barring transfers with certain attributes) not all allowable transfers will be equally beneficial to overall welfare. Exchange rates could be used in a number of ways to promote the satisfaction of Equation 1. Exchange rates would alter the proportion of the unadjusted volumetric entitlement which would be exchanged in a given case, thus effectively imposing price premiums or discounts on groundwater transfers having particular attributes. For a transfer of groundwater use to a purchaser who is located further away from a sensitive GDE than the current owner, an applicable exchange rate might exceed 100% in order to encourage the environmentally beneficial sale. This means that the buyer is permitted to extract more water than the seller gives up, and so is willing to pay more, thus encouraging the seller to sell. Those transfers which buyers and sellers choose to make would be those that create sufficient private value (due to gains from trade) to surmount the imposed exchange rate, thus broadly accounting for environmental impacts or benefits .

The development of a system of exchange rates would rely on information regarding the hydrological relationships between extraction, water-table levels, and environmental damage. It would be important, for example, to know the respective sensitivities to impacts at the buying and selling locations.

An alternative model could use inter-area exchange rates; management areas could be smaller in this case, and could be defined as the area in which 1:1 exchanges were permissible. Trades between neighbouring areas could involve lower exchange rates; that is, buyers involved in cross-boundary transfers would received less than 100% of the pumping volume foregone by the seller.

Exchange rates were used in the surface water context, as part of the Pilot Interstate Water Trading Project in the Murray-Darling Basin, to account for "increased negative externalities arising when water use is transferred upstream" (Quiggin, 2001, p. 90). Groundwater flow in the superficial aquifer of the Gnangara system is generally from the crest of the water-table 'mound' – shown by the contour lines in Figure 3.2 – westward toward the coast (DoW, 2008). Exchange rates could potentially be used in the management of 'upstream' and 'downstream' groundwater transfers, and their potential external costs.

7 Conclusion

In groundwater-dependent regions, the implementation of groundwater trading based on sustainable extraction volumes is one potential policy response to water scarcity. Western Australia's major metropolitan area exhibits growing demand for groundwater, while facing conditions of diminishing supply. Groundwater-dependent ecosystems are under increasing pressure due to the extraction of groundwater for a range of human uses. Implementation of groundwater trading would be consistent with the principles of Australia's National Water Initiative.

Groundwater trading can be thought of as transferring, and thus potentially transforming, the impacts of groundwater extraction. These impacts can be varied and diffuse, ranging from financial third-party effects to more complex environmental impacts including the drying of wetlands, springs, and lakes , and can be distributed over time as well as over distance. The nature and extent of these impacts may be difficult to forecast. Further, negative environmental impacts, in particular, may not be amenable to 'monetisation'. The result is that negative externalities from groundwater trading may be uncertain as well as not monetarily compensable.

In less transmissive systems, the potential for spatial (and temporal) redistribution, locational concentration, and qualitative transformation of impacts represents a major management challenge. Impacts at a new location of extraction may differ in scale and nature from those at the original place of extraction. Differing spatial distributions of water use will have differing total impacts and therefore costs. A hydrological challenge is to estimate the effects of extractions on ecosystems and on human users.

An economically and environmentally robust trading scheme for groundwater use would ensure that all transactions leave overall welfare constant or improved, incorporating impacts on third- parties, and addressing non-market impacts as well as future effects. The avoidance of welfare-reducing trades would be built into the system. We have presented a number of challenges to approaching such a design, focusing on those with a hydrological basis or hydrological information requirements.

Appropriate hydrological definition of the boundaries of an aquifer system is a fundamental input to the design of any trading scheme as well as to establishment of the appropriate consumptive pool. Definition of sustainable yield – the overall volume of water use that should be permitted periodically – is another primary hydrological challenge in trading scheme design.

We suggest several possible design tools that could be useful in achieving the above goals. Using a combination of sustainable extraction limits, trading rules, management areas, and/or exchange rates, it may be possible to establish a system in which external impacts are largely limited to those amenable to monetary compensation, and in which those costs of compensation are borne by users of the trading scheme.

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