Applying robust separation to compare the opportunities for market based policy approaches for Aquifer storage and recovery in Australia and France

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Abstract

Many cities are experiencing mature urban water economies, characterised by limited opportunities for future water impoundments, rising incremental supply and impoundment costs, intensified competition and increased interdependencies between diverse water uses. Aquifer storage and recovery (ASR) is currently promoted as one management approach to augment existing supplies and in many jurisdictions is assuming increasing importance in the portfolio of urban water management strategies. Consistent with trends in international water policy development, Australian water reform has emphasised institutional and governance approaches promoting voluntary transfers of water through market exchange. French water policy relies on regulatory instruments, divested water provision and negotiation. The reform process has made substantial advances in addressing the constraints and tensions associated with mature rural water economies, with limited influence in urban water systems. Transferable water storage and extraction entitlements vested with water bankers warrant exploration due to their potential to induce private investment to secure water supplies and improve catchment water use efficiency. What remains unclear is the degree of alignment of new water management technologies such as ASR operations with explicit water reform directives of market development and the capacity of subsequent urban water legislation to provide consistent and coherent ASR guidelines. The paper describes a systematic approach to align the hydrological characteristics of an aquifer with economic and policy interpretations central to the development and management of ASR. The paper introduces a schema to identify the elements of the urban terrestrial water cycle specific to ASR, the development of a typology to characterise the aquifer potential for ASR, and determine the nature of property rights for each system element according to the principles of robust separation of water rights. We implement the schema to ascertain the opportunities for market based approaches in ASR subject to French and Australian water policy.

Introduction

Internationally, cities are subject to increasingly variable rainfall patterns and increasing populations. As a corollary they are experiencing mature urban water economies, characterised by limited opportunities for future water impoundments, rising incremental supply and impoundment costs, intensified competition between diverse users and increased interdependencies amongst water uses (Randall 1981, Watson and Rose 1980). Substantial advances have been made in the scientific understanding and technologies associated with aquifer storage and recovery (ASR) and is currently promoted as a cost effective management approach to augment existing supplies and in many jurisdictions is assuming increasing importance in the portfolio of urban water management strategies (Pavelic *et al*. 2006a,b; Dillon 2006, SA EPA 2004). The harvesting, storage and recovery of urban stormwater and reclaimed water in sub-surface aquifers buffers seasonal shortages and more recently in Australia, partially remedies inter-drought water stresses.

ASR and variants such as aquifer storage transport and recovery (Rinck-Pfeiffer *et al*. 2005) involves the storage of water in subsurface aquifers when water is plentiful and extracted (or recovered) during times of peak demand or water stress (Pyne 1995). Peak stormwater flows and waste water streams can be harvested, treated passively (e.g. constructed wetlands) or actively (e.g. dissolved air flotation/filtration) and injected into confined aquifers for subsequent recovery for non-potable purposes (Pyne 1995, Pavelic *et al*. 2006a, Swierc *et al*. 2005). Advocates contend that ASR has the capacity to augment domestic and industrial supply by converting urban water waste streams and high flow flood events into groundwater base flow. Future extractions of stored water are able to cost effectively satisfy diverse water demands through water quality differentiation; *viz*. supplying users requiring non-potable water, characterised by lower treatment costs.

Pavelic *et al*. (2006) and SAEPA (2006) highlight additional benefits of ASR, including:

- A reliable storage preventing evaporation, algal growth and mosquito breeding;
- A continuity to water supplies during periods of prolonged drought and substantial reductions in water supply;
- Potential for contaminant and pathogen attenuation during storage

- Freshening zones in brackish aquifers that otherwise would have limited beneficial use (contingent on aquifer characteristics);
- Potential for reduced pumping costs, amelioration of salt intrusion, restoration of groundwater levels, and surface subsidence (through increased hydraulic pressures)
- The detention element associated with ASR has capacity to mitigate peak flows in flood events

Australian water reform (NWC 2007, CoAG 2004) has emphasised institutional and governance approaches promoting voluntary transfers of water entitlements through market exchange. The reform process has made substantial progress in addressing the constraints and tensions associated with mature rural water economies, however the reforms have had limited influence in urban water systems (NWC 2007). Transferable water storage and extraction entitlements vested with ASR bankers warrant exploration due to their potential to induce private investment to secure water supplies and improve catchment water use efficiency. A simple ASR system that complies with reform objectives might be typified by:

- Durable, non-diffuse source waters and retention ponds associated with minimal or science based environmental flows that resolves the tension in consumptive and no-consumptive use;
- Source waters managed by an independent agency both willing and able to comply with statutory obligations;
- Non-controversial and cost effective treatment of aquifer injectant;
- Comparable water quality characteristics of injectant and receiving waters;
- An aquifer environment that is not subject to localised increases in hydrologic pressures and capacity constraints;
- ASR externalities are of low marginal value or are managed;
- An adaptive and mutually agreed governance regime, where risk is clearly and unequivocally defined.

These conditions are rarely if ever present in praxis and what remains unclear is the degree of alignment of new water management technologies such as ASR operations with explicit water reform directives and the capacity of urban water legislation to provide consistent and coherent ASR guidelines.

The advances in the development of rural water markets provide guidance to policy design in a mature urban water market. However, the advances are relatively recent and mainly confined to surface waters, limiting opportunities for urban policy makers to gain experience and expertise in ASR market design, testing and field implementation. Appraisals of the relative importance of market based approaches in urban policy portfolios have also been informal and arbitrary (Hatton MacDonald and Dyack 2003). As a corollary, simple rules and evaluation protocols to identify *a priori* the relative advantages over other policy instruments to resolve specific re-allocation and coordination dilemmas have not yet emerged.

Colby (1995) and Bromley (1991), and specific to the Australian context, Paterson (1987) and Tisdell *et al.* (2003) contend that the evolution of urban and rural water policy represents the historical accretion of partial remedies and hard engineering approaches, often typified by the absence of both rigorous economic analysis and a systemic or integrated policy approach. AATSE (2004) and Hatton McDonald and Dyack (2003) and ACIL Tasman (2005) have noted the absence of well defined entitlements to access stormwater, recycled water, and aquifer storage. They contend there are consequent impediments to the development of ASR, leading to equivocal aquifer extraction, future legal wrangle and potential detrimental impacts on receiving environments or adjoining groundwater systems. Jimenez (2007) describes an *ad hoc* development of stormwater governance and legislation in Victoria, pointing to limited integration between jurisdictions, institutions and managing agencies. The Australian Natural Resource Policies and Programs Committee (2007) contend there are strong possibilities that existing legislation, policy and institutions may not be readily adapted to market innovations in natural resource management (including water) or subject to instrument failure, with an attendant social cost. The rapid development of regional ASR is likely to exacerbate this disjunction.

In contrast, the success of the Angus Bremer prescribed wells, a South Australian rural ASR scheme for irrigators gazetted in 1980 and subject to the *Water Resources Act 1997*, provides some guidance to resolve the challenges ASR technologies present to existing urban water policy approaches.

In response to these potential impediments and sources of conflict, the paper describes a systematic approach to align the more complex characteristics of source waters, aquifer storage, recovery and final use with economic and policy interpretations central to the development and management of ASR. The paper introduces background information on Australian and French water policy and the concept of Young and McColl's (2003a) robust separation of property rights as applied to ASR. We contend that the robust separation framework is a suitable antecedent for the coordination of collective action through either market or negotiated approaches. We describe a schema to identify the elements of the urban terrestrial water cycle specific to ASR, the nature of property rights for each system element according to the principles of the robust separation of water rights (Young and McColl 2003) and finally the development of an aquifer typology to aid in establishing potential tradeable rights as one example of an ASR policy instrument.

Robust Separation

Bromley (1991) states that negotiable water entitlements must be specified in terms of secure, enforceable rights, the duties of the right holder, the obligations of those excluded from the right and the duties and obligations of the managing authority[i]. The Australian National Water Initiative (CoAG 2004, s.37, s.28) recommends that water access entitlements be specified as unit shares of a defined consumptive pool, and periodic water supply (allocations) and the impacts of use be managed independently.

Young and McColl (2003a) and Young (2007) propose a three tiered "unbundled" or separated system of instruments to distribute and allocate volumes of water (or other natural resources) efficiently over time. A Water Plan establishes the rules and science based guidelines to appraise the state of a water system and subsequent to that appraisal, prescribes the rules to determine the environmental and consumptive "pools". When more than one person has an interest in the water system or "pool" the first instrument defines the unit shares of the pool and the distribution of shares to individual interests. The second instrument defines an independently managed process to periodically allocate the amount of water to each share. The third instrument prescribes the obligations of water use. A robust system of water management will: i) resolve the resource allocation tension between consumptive use and the environment, and amongst consumptive users, issues related to distribution and use; ii) provide secure, economically efficient and low cost trading and administration; iii) clarify the assignment of risk and circumstances of compensation; vi) and address the management of externalities. A robust system also must pass the conventional tests of efficiency and fairness in a changing world. Young and McColl (2003a) contend that these objectives are best achieved through the robust separation of water interests and recommend:

1. **water entitlements** specified as secured long term unit shares of a variable pool of consumptive water, subject to periodic allocation;
2. an agreed process for **the allocation** of water when it becomes available, typically on an event, season or annual basis contingent on science and the state of the resource, managed independently of entitlements;
3. a process to assign risk defining unequivocally where responsibility lies, under what circumstances compensation is due, and the processes for obtaining redress with non-controversial settlement;
4. conditions and **obligations specified in a separate water use licence**, cognisant of third parties;
5. the introduction of debit and credit accounting systems, water exchange rates and associated formal transaction mechanisms;
6. the guaranteed recording of financial and other formal interests on a register, formal settlement procedures, and irreversibility of market transactions;
7. In an extension of Tinbergen (1950), robust systems are characterised by the use of separate instruments for each distinguishable or discrete component of the water cycle and water use system.

The system proposed by Young and McColl (2003a) is now being implemented across Australia and is required of all States and Territories as part of the National Water Initiative. Young (2005) has recently applied the notions of robust design to resolve enduring tensions of over allocated water and excess irrigation drawdown from a ground water system in the south east of South Australia. We have adapted this line of reasoning as a guiding reference for the robust design for ASR market based policies. The main difference between the system proposed by Young (2005) and that needed for ASR is that ASR provides an additional source of water.

Background to water and ASR management

Water can be classified as a common pool resource, partially characterised by enforceable, exclusive, excludable and transferable rights to utilise a defined amount from the total available water. A substantial component of available water confers a mutually shared, environmental benefit to the owners of those extractive rights, which is both costly to exclude beneficiaries (a characteristic shared with public goods) and subject to rival or subtractable consumption (a characteristic shared with private goods). When joint outcomes depend on multiple actors contributing inputs or actions that are costly and difficult to quantify and policy instruments are deficient in restricting usage, incentives exist for individuals to act opportunistically, often appropriating to a level where aggregate overuse and reduced benefits occur. A social dilemma occurs when individuals are tempted by short term gains to over appropriate the common pool resource, thereby imposing group shared costs on the common pool community (Ostrom 1998). Individual over appropriation will eventually lead to reduced benefits for all.

Common (1995) and Randall (1981) contend that managing water is complex and likely to require a combination of economic or market instruments in concert with community involvement to coordinate aggregate extraction strategies. When consumers can abstract water from a common source without impinging or diminishing the perceived needs of other consumers, there is no need or incentive for the voluntary exchange in water or defined rights to water. In the absence of water scarcity (both actual or perceived), there is little pressure for the clear distribution of entitlements to water resources as all demands can be adequately met with current supplies, precluding the need for a coordinated social solution (Demsetz 1967). As the level of relative scarcity increases, as in mature water economies, an escalation in tension arises between competing uses, necessitating some form of adjudication to establish an equitable, judicious balance between users. Markets, regulatory instruments and social compacts are water policy approaches implemented to resolve those tensions.

Markets are attractive because of their ability to coordinate and truthfully reveal private information. They are effective economisers of information, expressed as precise price signals (Smith 2002). Bowles and Gintis (2004 p. 385) posit that when comprehensive and coherent contracts can be drawn and enforced at low cost, markets are superior to other governance structures. Where residual claimancy and control rights can be aligned, market competition provides a decentralised and difficult to corrupt mechanism that punishes the inept and rewards high performers. In contrast, the state is relatively well suited for handling particular classes of problems where it alone has the power to make and enforce the rules that govern the interaction of private agents: e.g. if participating is mandatory (public health and education and defence).

Ostrom (1998) articulates an alternative arrangement, proposing that common pool resources can be effectively managed if there are information, communication and sanctioning options available to those using the resource. Communities can resolve common pool dilemmas that states and markets are not well equipped to manage, especially where the nature of social interactions or the goods being transacted makes contracting, exclusion or enforcement highly incomplete or costly. Adjudication relies on the revelation of dispersed private information unavailable to the state in concert with formal institutions to apply rewards and punishment to members according to their conformity with or deviation from social norms. Communication promotes conditional reciprocity; sanctions reinforce the social compact through reputation. Social compacts are reinforced by self monitoring, strong reciprocity or conditional cooperation, (facilitated through mediums of communication) and a series of escalating, credible sanctions.

If ASR is commercially viable for one operator, then it is also likely to be viable for a number of operators in the same aquifer or with the same water source. In the absence of coordination or cooperation, each operator potentially impinges on the access to water for recharge of others, on the total available aquifer storage volume, and in confined aquifers, on the groundwater pressures at the sites of other proximal operators. In brackish confined aquifers the operations of one MAR site are also likely to influence the shape of the plume of fresh injectant in the aquifer at neighbouring sites, and hence influence the recovery efficiency (proportion of injected fresh water that can be recovered at a salinity that meets requirements of uses) of other operations (Dillon *et al*. 2007).

The design of ASR entitlements, allocations and end use licenses therefore need to account for aquifer characteristics, which directly constrain or make possible the market exchange of ASR water. Aquifer characteristics and regulatory instruments that govern aquifer management will influence for example; the transfer distance of recovered waters (a function of transmissivity and native groundwater salinity), water quality changes at the well head will effect the number and spatial configuration of injection wells; the magnitude of pathogen or disinfectant attenuation will effect the range of uses, demand levels and price; and changes in hydraulic pressures will effect independent 3rd parties via pumping costs, sea level intrusions and surface subsidence.

Australian and French Water policy

Consistent with trends in international water policy development (Easter *et al*. 1998 Dinar *et al*. 1997), Australian water reform, emphasising voluntary transfers of water through market exchange, has made substantial advances in addressing water re-allocation and resolving the tensions associated with increasing scarcity of mature water economies. A cornerstone directive of Australian water reform and the National Water Initiative (NWI) is the development of: "…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" (CoAG NWI clause 23).*

By ratifying the NWI, the States have agreed to (NWI clause 58): i) facilitate the operation of efficient water markets, ii) minimise transaction costs on water trades, iii) enable the appropriate mix of water products to develop, based on fungible access rights, entitlements or allocations, vi) recognise and protect the needs of the environment; and v) provide appropriate protection of third-party interests. The National Water Commission (2007) has proposed that NWI (clause 92 iv) articulate similar water management priorities specific to urban water cycle management. As policy praxis, a competent and willing regulatory framework is antecedent to effective markets, to ensure the coherent specification and enforcement of fully articulated property regimes and the entrained rights to the benefits of property access (Quiggin 1998, Bromley 1991, Randall 1981, Young and McColl 2003a,b).

Reform procedures and directives emphasising the exchange of tradeable independent water rights, have been extensively implemented in rural water systems compared to urban counterparts (COAG 2004). What remains unclear in the Australian context is the degree of alignment of new water management technologies, such as ASR operations, with explicit water reform directives of market development and the capacity of subsequent urban water legislation to provide consistent and coherent ASR guidelines.

In contrast to the Australian endorsement of market exchange transferable water rights vested in the individual, French water policy relies on regulatory and planning instruments. Water management is subject to compliance with three tiers or jurisdictions of water policy: the European Union, the National level and at the level of the hydro-graphic basin.

European Union directives on drinking water and waste water treatment increased the demand for water quality and treatment and were subsequently incorporated into French law in 1992 (and guided by the statutes of the French *Water Act 1964*, establishing six jurisdictions based primarily on hydro-graphic catchments managed by an Agence de l'Eau" (water agency) as the operational executive). The 2003 European Union Water Framework Directive (WFD) introduced the statutory basis for the conjunctive management of groundwater and surface water. The key aims of the Directive (incorporated into French law in 2004) seek to expand the scope of water protection to all waters, surface waters and groundwater at the scale of river basins; to achieve an approved water use status for all waters by specified dates; to combine emission limits and quality standards; to establish pricing based on full cost accounting; to employ participatory approaches and to deploy protocols to expedite the formulation of new legislation and policy implementation.

In synthesizing the intent and obligations of the various echelons that influence French Water policy, management is defined by the State in partnership with local communities and users. Water policy is administered at three jurisdictional levels conditioned by directives of the European Union: the national, water basin and local water commission levels. National policies are required to simultaneously consider consumptive water use requirements and the non-consumptive needs of aquatic ecosystems, surface and groundwater quantity and quality. The through processes participation and cooperation. Masterplans for Water Development and Management (Schéma Directeur d'aménagement et de gestion des eaux SDAGE) and Local Water Development and Management Plans (Schémas d'aménagement et de gestion des eaux SAGE) guide both the coordination of diverse and competing water users and operational implementation. Both seek to establish partnerships and to coordinate the actions of Public Authorities and private developers (see Piegay *et al*. 2002 for a review on the implementations of these plans). Economic incentives are restricted to mobilizing specific financial resources and accounting conventions in accord with the "polluter pays" principle. Water in France is considered as a "national common heritage" and managed according to a regime of either State or Common property rights and as a corollary is characterized as a common good, non-tradable resource. Sovereign rights to water remain with the State whilst local needs and resource parameters determine the details of access exclusion and use, expressed as a mosaic of common pool and regulatory property right regimes.

The organization of water provisioning and services is based on a tripartite relation between the community, water users and the service provider (the provider can be either a public or private entity). The local community retains sovereign authority for the organization of water provision through elected representation and assured delivery through association with advisory commissions and regulatory agencies. When service management is delegated to a private provider, the community retains overarching responsibility and infrastructure ownership remains with the community. The supplier-user relationship is ratified via contractual water service and provisioning arrangements. In summarising French water policy, Dubois (2001, p.89) states, “*There is no strict water resource management today in France, but an ensemble of management actions which converge in a more or less coherent and efficient way.*”[1]. In accord with Dubois, Launay (2003) argues for the need of improved coordination (p.35).

Current management and governance of ASR

To conform with NWI prescriptions (CoAG 2004), the management of urban water systems, including ASR is required to introduce markets and market incentives, where hydrologic connections and water supply considerations permit the exchange of either tradeable water entitlements or allocations.

South Australia has developed small scale ASR operations, associated with extensive hydrological and water quality research (inter alia Pavelic *et al*. 2006a,b), affording an opportunity to assess the concomitant development of ASR and policy. A review of the South Australian legislation and ASR guidelines indicates ASR relevant policies manage separately and independently source water capture and harvesting, aquifer injection, groundwater characteristics and end use (State *NRM Act 2004*, made operational by the State *NRM Plan 2006*, *EPA (Water Quality) Policy 2003*). The *EPA Code of Practice for Aquifer Storage and Recovery (2004)* sets out a non-binding set of guidelines for ASR in South Australia. The primary objective of extant policy is to maintain or improve groundwater quality and the integrity of receiving aquifers.

Literature based insights indicate that the management of four French ASR sites at Flins Aubergenville, Croissy, Dunkerque and Dijon has been delegated to a private company. They are also two sites that are managed directly by communities: in Lyon (Crepieux Charmy) and near the River Garonne (several small sites). Sites at the river Durance and La Reunion are also under consideration.

The European directive *Eaux Résiduaires Urbaines 1991*, transcribed into the French water law of 1992 is the legislative basis for stormwater management. According to French Water law, declaration and authorisation are two regimes which determine the harvesting and use of stormwater. For example declaration is less constrained than authorization, invoked when the total harvesting surface area (“superficie totale desservie”) is > 1Ha and < 20Ha and approved with completed documentation. The granting of an Authorisation (>20Ha) is conditional on the results of preliminary studies and assessments complying with prescribed water condition standards[ii]. Table 1 summarises the specifications that determine a scheme to be administered as one of declaration or authorization.

ASR element	Declaration	Authorization	Nomenclature [1]
Capture or retention of stormwater in surface water or in infiltration pounds	total surface concerned (“superficie totale desservie”) of more than 1ha but less than 20ha	Total surface concerned of more than 20ha	5.3.0
Re-injecting (in the same aquifer) water which was taken for geothermic use, mining or building	Re-injected for a total capacity of more than 8 m3/h but less than 80m3/h	Total capacity of re-injection of more than 80 m3/h	1.3.1 5.1.1.0
Injection into an aquifer subject to permanent quantitative restrictions	Capacity under 8 m3/h	Capacity of 8 m3/h or more	1.3.1.0
Other types of release in the soil or sub-soil		yes	1.2.0
Installations allowing an extraction in an aquifer	total flow-rate of more than 8 m3/h but less than 80m3/h	Total flow-rate of more than 80 m3/h	1.1.0

[1] Elaborated from the « Décret n°93-743 du 29 mars 1993 relatif à la nomenclature des opérations soumises à autorisation ou à déclaration en application de l'article 10 de la loi n° 92-3 du 3 janvier 1992 sur l'eau » (revised in March 2007).

Table 2 Characterisation, monitoring and typology of entitlements and allocations of ASR water cycle elements

Water cycle element	Urban water system: harvesting and treatment		Storage		Aquifer extraction	Final water use
	Source waters	Treatment **Hazard and critical control point**	Aquifer characteristics Modified from LWA (2001.p104), Pavelic *et al* (2006b), BRS (2007)EPA (2004)	Aquifer infiltration **Hazard and critical control point**	Extraction	End use licence **Hazard and Critical control point**
Evaluation criteria	Surface waters Other Groundwater Stormwater Recycled water Effluent	Sieves/screens Settling ponds Retention ponds/ wetlands (subject to residence and dwell times) Secondary treatment DAFF	Sensitivity of aquifer dependent ecosystems (volume and water quality) Vulnerability of confining layers to pressure changes Mineral dissolution Aquifer thickness Porosity Potential Injection rates Vertical and horizontal hydraulic gradient Landform/ topography Groundwater salinity Vulnerability of other groundwater users to pressure changes Pathogen/contaminant fate and attenuation	Spreading ponds In stream Channels Direct injection	Declining or rising aquifer Independence of injection and extraction well or Consortium of well heads managed collectively	Demand for potable non-potable Industrial commercial or agricultural Consumptive non-consumptive Change in water quality through use Potential for salt or metal mobilisation in receiving zone Depth of receiving water table Hydraulic conductivity
Monitoring	Monitor injectant to EPA standards eg turbidity (NTU) for stormwater correlated with nutrient and heavy metal loads or salinity (Cl) for GW or rural surface waters. Right to store contingent on compliance with jurisdiction specific standards eg SA EPA (Water Quality) 2004 viz. Quality injectant > aquifer		Multi criteria index of storage potential Monitor ambient GW water quality, state of confining layers	Monitor injected volume to comply with cap on water table rise Monitor natural infiltration rates Double entry register of inflows and extractions	Monitor volume and quality of extracted water Comply with demand requirements and EPA standards	Monitor quality and volume Monitor water disposal of consumptive uses Comply with water use licence conditions
Property rights	**Entitlement**: unit share in stormwater consumptive pool, excess to minimal environmental flows Periodic **allocation** rules, risk assigned to entitlement holder Potential for additional stormwater or effluent offsets			**Entitlement**: unit share of aquifer consumptive pool i.e. additional net storage capacity Annual **allocation** to raise the water table subject to ambient rainfall and total abstraction	(Tradeable) extraction volume a function of injection **entitlement** unit share, extraction **allocation** level contingent on ambient conditions and spatial constraints. Existing licence may be converted to entitlement to extract	**Water use licence** subject to regional obligations and conditions, for use and disposal

Applying the principles of Robust Separation to ASR

In an attempt to align the hydrological, economic and policy interpretations of ASR, we firstly describe a schema to identify the elements of the urban terrestrial water cycle specific to ASR, point to hazard and critical control points, the development of aquifer characterisation to help identify the potential of ASR, and finally determine the nature of property rights for each system element consistent with the principles of robust separation of water rights expressed in the NWI (Young and McColl 2003a,b). Those system elements are source water capture, aquifer storage and water extraction. Final water use is subject to licence conditions and obligations independent of ASR property rights. We then apply the evaluation schema to a specific aquifer case study in metropolitan Adelaide. Finally the paper points to the jurisdictional and legislative framework specific to the Adelaide case study, identifying likely policy alignments, divergences and failings of ASR policy when subject to compliance with NWI water reforms.

ASR process characterisation

Table 2 summarises key elements of the urban water cycle with specific relevance to ASR. The elements are: i) source waters, harvesting and retention ii) aquifer infiltration and active injection iii) extraction of stored water and vi) the use of extracted water. Each ASR element is subject to a set of evaluation criteria and a process of hazard based critical control, managed through regulated compliance with either volume or water quality specifications (Swierc *et al*. 2005). For the purposes of illustration, we assume that non-compliance with any critical control point invokes a regulatory veto and until rectified, precludes further participation in ASR. For example, Table 1 describes a vector of aquifer characteristics, compromising in broad terms; potential aquifer storage capacity, infiltration rates, dwell times, injectant mobility and transmission, and ambient aquifer water quality. The suitability of an aquifer for ASR can be established according to a multiple criteria index, weighted with reference to scientific understanding and of the relative importance placed on criterion by the community, users and the agency managing the aquifer.

The monitoring section of the table details auditing protocols to assess compliance with the hazard based critical control points. Monitoring is a necessary precursor for the enforcement of property rights (an un-enforced right is no right at all). The final section of the table describes governance regimes and suggests entitlements, allocations and use obligations for each element of the terrestrial ASR urban water cycle. The purpose of the table is to illustrate a rule based decision framework to enable the alignment of regional biophysical and hydrologic variables, monitoring regimes antecedent to compliance and enforcement and where appropriate the necessary property right conditions to facilitate market exchange.

Defining and articulating interests in ASR

Consistent with the NWI directives and the principles of robust separation of water interests, source water harvesting, aquifer storage, and extraction are distinguishable urban water cycle elements. Each element requires the discrete specification of a unit share entitlement of a defined pool, and independently managed rules to establish periodic allocation and the conditions of use. Final water application of extracted ASR water is subject to end use licence conditions, cognisant of third parties including the environment. The following section describes a framework to establish entitlements as unit shares, allocations and use conditions for each of the ASR urban water cycle elements.

For illustrative purposes, from Table 1 we select the characteristics of the South Australian ASR described by Pavelic *et al*. (2006a, b). They are a stormwater ASR source, a brackish aquifer of low transmissivity, localised freshening zones of 100-200 m, pathogen and contaminate attenuation, a community of current extracting end users of brackish water, and potential non-potable industrial and agricultural end use. We assume compliance with regulatory water quality standards at each of the critical control points.

Harvesting stormwater

The proposed South Australian *Local Government (Stormwater management) Amendment Bill 2006* redefines a stormwater system as a prescribed water resource, requiring a local council stormwater management plan subject to approval by a regional Natural Resource Management Board. In accordance with the *Natural Resources Management Act 2004*, a water plan specifies the minimum flow to sustain ecosystems dependent on stormwater, although the *Act* does not explicitly state this is a science based determination. For the purposes of this discussion, we assume that the regional NRM board will have determined the relative annual contributions of both stormwater and natural catchments to dependent ecosystems for each stormwater plan and as a corollary, the residual consumptive pool. Establishing the environmental pool represents a quantifiable antecedent to establishing the consumptive stormwater pool and subsequent harvesting entitlements.

Consider a connected stormwater network as an administratively feasible, hydrological and spatial unit for a stormwater management plan, characterised by a common, low cost and accurate monitoring point of minimum environmental flow. The *Stormwater Act* indicates a local council network as the most likely unit, although aggregations of connected council stormwater networks may provide more cost effective administration and shared monitoring costs. Common pool aggregations introduce the potential of inter-jurisdictional cooperatives as a means of cost effective stormwater management (see Ostrom 1998, Bromley 2000). The prescribed environmental pool sets the lower boundary condition of the consumptive stormwater "pool", the upper bound constrained by infrastructure capacity. The primary function of stormwater management is flood mitigation, avoiding intermittent peak flow events breeching diversion capacity. Defining the consumptive pool offers additional stormwater management strategies that utilise markets to increase economic efficiencies (ie the net benefit of water use). For effective stormwater markets, the consumptive pool is the basis of entitling each legally defined unit share of a stormwater management plan, equal access to stormwater harvesting. We briefly discuss two alternative governance strategies.

South Australian Metropolitan councils are responsible for the maintenance of a stormwater network, and as stormwater assumes an economic value, have an incentive to retain all consumptive unit shares and act as sole stormwater harvesters. Contingent on compliance with water quality and treatment standards, council harvested stormwater may be either used for direct municipal use, or to convert peak flows to a more reliable base flow, diverted to retention ponds or constructed wetlands for storage and biological treatment. As an alternative or augmentation to surface storage, councils may also operate as aquifer injectors when faced with prohibitive costs of wetland construction, surplus peak flow volumes or excessive evaporation losses. A variant of the sole unit share scheme is the granting of fee paying stormwater harvesting licences or negotiating contractual harvesting arrangements with commercial interests, with potential for administrative feasibility, minimised transaction costs and maximised net benefits. Harvesting may be direct off-takes in the stormwater infrastructure or alternately in retention ponds.

If transaction costs of markets are low relative to benefits or they are likely to generate persistent stormwater management innovations, councils have an option of distributing unit harvesting shares to multiple commercial interests. The potential for additional net benefits gained by combining stormwater offsets and harvesting markets is one example. Tietenburg (1998) appraises the merits of alternative the entitlement distribution mechanisms of auctions or grandfathering.

Young and McColl (2007) propose stormwater offsets as an approach to reduce the need to construct additional stormwater infrastructure to prevent peak flooding. Offsets can operate as an incentive for developers and land owners to maximise runoff retention before entering the stormwater system, reducing stormwater volumes. Stormwater harvesters however seek to maximise stormwater flow for eventual treatment, storage and resale. If such a scheme were in operation, the strategic placement of stormwater harvesting off takes, preventing peak flood events exceeding infrastructure capacity, can also generate additional revenue opportunities for harvesters through the production of stormwater offsets. Cost effective offsets can be traded with developers, to meet their stormwater reduction obligations. Combined with ASR, the offset scheme outlined by Young and McColl (2007) illustrates a comprehensive market approach to stormwater management, providing incentives to both reduce infrastructure demands and augment water supplies.

Harvesting by non-council interests is contingent on a stormwater unit share entitlement. Hilmer (1993) recommended that control of infrastructure cannot be used to restrict access by independent commercial entities. Under the Commonwealth *Trade Practices Act,* (1974) third parties can apply for access to a capacity constrained monopoly infrastructure under reasonable rights and conditions, with a right to binding arbitration if agreement cannot be reached (ACIL Tasman 2005). If there are additional benefits to be gained by extended private access, councils breech the *Trade Practices Act* if they were to attempt to monopolise stormwater infrastructure.

Young (2006) proposes a 5 year moving average of rainfall as one example of a transparent reference for the announcement of annual harvest allocations for share holders in a groundwater extraction system. Accounting for unpredictable, peak stormwater events creates additional challenges, however, the 5 year allocation proposal provides a basis for stormwater harvesters to plan for seasonal and climatic variability. Allocations should be managed by an agency independent of access entitlements, possibly by the Stormwater Authority. Section s*56* of the *NSW Water Management Act 2000* provides a template for the allocation announcement, which states a defined share entitles the holder to take water at a specified rate, time, circumstance or location and may be expressed as a specified volume or proportion, of available water, of a storage structure or a storage inflow.

Harvesting stormwater is necessarily opportunistic, and the risk of intermittent, variable harvest allocations should be assigned wholly to the unit shareholders, precluding the right to seek redress or compensation, avoiding controversial settlement. Harvesters also assume the risk of system leakage, although with the economic value of stormwater established, there is an ongoing incentive to minimise leakage. As an example of entitlement obligation, continued harvesting rights would be conditional on the regulated disposal of concentrated retention pond contaminates and waste.

Aquifer storage and recovery

From Table 1, we consider the possible arrangements for storage entitlements as unit shares, periodically determined allocations and use conditions for a brackish aquifer, with low transmissivity, localised freshening zones of 100-200 m, pathogen and contaminate attenuation and a community of existing water extractors and end users. From the *NRM Act 2004*, it is unclear whether brackish aquifers are defined as a prescribed water resource and subject to a water plan. An aquifer water plan defines the ambient environmental pool expressed as the range of allowable water table heights, or aquifer storage capacity. For expository purposes, we assume the aquifer management is described by a water plan. The estimated net aquifer storage capacity prescribes a cap on water table height, and establishes the consumptive “storage pool” and the unit share represents the storage or aquifer warehousing entitlement, defined as a quantum of the net storage capacity. The entitlement therefore defines the right to actively store additional water or the right to raise the water table. We assume that injected water complies with the critical control point water quality standards. The clear separation of source water harvesting and aquifer storage rights provides increased flexibility in system operation. Injectors with storage entitlements may either own a unit share in stormwater harvesting or may choose to procure via market exchange stormwater or alternate injectant sources for storage and future extraction. Alternatively, storage entitlement holders may choose to trade the right to store stormwater to those needing cost effective stormwater offsets.

To monitor net storage capacity, volumes of aquifer injection by individual interests must be monitored and entered in a central, double entry register or accounting system, maintained and administered by the agency responsible for aquifer health.

Holding a storage entitlement does not automatically confer the right to inject water in the aquifer. An allowable annual volume of stormwater injection, equally apportioned to all unit access entitlements and contingent on the height of the water table, is calculated as the net product of non-ASR ambient infiltration and total existing extractions. The 5 year moving average of past rainfall provides an initial equitable basis for determining the annual storage allocation, with scope for planning by storage interests for climate variance and future demand. The risk that the annual allocation will vary is borne by the unit share holder, not the aquifer manager. Independently determined allocations may vary from zero in flood years (high levels of ambient infiltration and low extraction volumes) to greater than 100% for extended dry periods or drought. Depending on aquifer residual storage capacity, flood years potentially pose a storage dilemma: they represent the periods when stormwater is most available for harvesting and extractions are likely to be minimal. Pre-injection retention ponds or a series of constructed wetlands subject to increased dwell times may provide a partial solution for harvested stormwater in excess of aquifer storage capacity.

Defined entitlements to aquifer storage introduce the potential for inter period water banking, debit and credit accounting systems and water quality exchange rates. The banking system proposed for groundwater extraction by Young (2005) acts as a template for water banking, mindful that the ASR “bank” accounts refer to additional storage capacity, not resident groundwater. Injectors are able to store long term water deposits, but are subject to a temporal decay function for future extractions that reflects aquifer diffusion and transmissivity rates. Recent proposals for an expanded water banking scheme specific for the low transmissitivity aquifers characteristic of Adelaide, advance the notion of conjoint access rights to the dam storage and reticulation infrastructure for ASR derived water transport (Dillon pers comm. 2008)

Aquifer injection of water of a higher quality than ambient groundwater may confer considerable benefits to existing or contiguous groundwater users. Reduced pumping costs, improved water quality (dependant on the dimensions of the freshening zone), pathogen attenuation, amelioration of salt intrusion and reduced surface subsidence may all reduce the costs incurred by existing users. Potentially a future market could be developed that provides a means for injectors to be compensated for the introduced cost reductions, mindful that the effectiveness and adoption of a market approach is highly dependent on the magnitude of transaction costs relative to benefits associated with formal exchange mechanisms. Informal, voluntary, cooperative approaches, such as compacts between ground water user groups outlined by Ostrom (1998) and Bromley (2000), are likely to provide pragmatic, cost effective and acceptable solutions, whereby injectors simply contribute a public benefit to the common pool community.

Low transmissivity is likely to act as a potent determinant of well location with consideration of potential non-linear effects of proximate injection consortiums, (viz. increased freshening zones and pathogen attenuation or adversely, increased hydraulic pressures on vulnerable aquitards) or spatially dispersed well heads. The conditions of the entitlement can specify well location and characteristics in accord with spatial and temporal differentiation of storage capacity. In times of high ambient infiltration, a possible condition of the storage entitlement may require injectors to either cease injection or pump excess water from the aquifer, regardless of end use demand, to maintain aquifer integrity and comply with prescribed water table heights.

Existing water reform institutions are concerned primarily with water extractions, pertaining to both surface and groundwater, with limited reference to storage rights. Dudley and Musgrave (1988) and recently revised by Brennan (2007), were one of the first to propose a capacity share; a single water interest representing an amalgam of water storage and extraction entitlements. Cognisant of transaction costs and the encouragement of scheme adoption, Dudley and Musgrave (1988) and Young and McColl (2003a) recommend parsimony in institutional design and care in the temporal sequencing of instruments. With the likelihood of a limited number of aquifer water bankers (thin markets) and to maintain consistency with current administration processes, an existing ASR storage entitlement would confer rights to extraction, expressed as a proportional relationship of injection and accumulated aquifer storage. South Australian guidelines nominate extraction as 75%-80% of aggregate storage. As the numbers of water bankers increases, expertise in ASR and trading improves and the relative cost of transactions decreases, the potential of further efficiency gains and innovation may warrant the unbundling of extraction and storage entitlements.

Transmissivity combined with brackish receiving waters assumes a key causal role when establishing spatial opportunities for exchange of extraction entitlements or allocations. We assume as in surface water transactions, entitlement exchange implies a permanent transfer whereas allocation transactions are temporary. High transmissivity rates confer extensive spatial dispersion of exchange opportunities in extraction entitlements: *viz.* the high water quality injectant is available to distant pumping interests within the allocation accounting period (e.g. 12 months), without depressing water tables or affecting other distant aquifer interests. Adelaide metropolitan aquifers are characterised by low transmissivity, restricting injectant mobility to approximately 100-200 m freshening zones per well within the annual accounting period. Without additional piping and pumping costs, trade in higher quality recovered water is likely to be constrained to pumping interests within the injection zone.

Discussion

In this paper we have been primarily concerned with market based institutions and policy approaches to improve the governance of ASR. We have attempted to introduce a systematic and structured approach to align the hydrological characteristics of an aquifer with economic and policy interpretations central to ASR development and management. The paper has described a schema to identify the elements of the urban terrestrial water cycle specific to ASR, the development of a typology to characterise the potential of ASR and finally we have described the nature of property rights for each system element according to the principles of the robust separation of water rights.

For expository purposes the paper has limited discussion to a case study of ASR in South Australia. Assuming that urban water systems are to be compliant with the market directives of the Australian National Water Initiative, we have described the characteristics of potential interests in source water capture harvesting, aquifer storage, and extraction as distinguishable urban water cycle elements. The South Australian ASR are typified by a stormwater source, a brackish aquifer of low transmissivity, localised freshening zones of 100-200 m, pathogen and contaminate attenuation, a community of current extractors of brackish water, and potential industrial and agricultural end use. We assume compliance with regulatory water quality standards at each of the critical control points. Changes in these system characteristics are likely to correlate with changes to the nature of the access (capture, storage or extraction) entitlements, the rules regarding annual allocations and the obligations attached to access.

Consistent with the principles of robust design, we have proposed discrete specifications for a unit share entitlement of a defined pool, and independently managed rules to establish periodic allocation and the conditions of use. The final water application of extracted ASR water is subject to end use licence conditions, cognisant of third parties including the environment. Robust design for ASR introduces a systematic approach to i) resolve the resource allocation tension between consumptive use and the environment and amongst consumptive users, ii) provide secure, economically efficient and low cost trading and administration; iii) clarify the assignment of risk and circumstances of compensation; vi) and address the management of externalities.

Jimenez (2007) *inter alia* contends Victorian stormwater legislation is typified by *ad hoc* historical accretion of partial remedies and hard engineering approaches, limited integration between jurisdictions, institutions and managing agencies and often typified by the absence of both rigorous economic analysis and a systemic or integrated policy approach. The South Australian *Local Government (Stormwater management) Amendment Bill 2006* aims to rectify a similar policy trajectory, redefining stormwater as a prescribed water body subject to water planning and regulation at the scale of by local councils. Consistent with Australian Water Law, the *Bill* also prescribes the final management and harvesting rights to the Stormwater Authority under conditions of non-compliance, assigning the right to revoke and resume local council stormwater management and storage including ASR. Although the *Bill* does not articulate or specify the nature of entitlements and allocations, the interpretation of water plans may be sufficiently flexible to allow amendments that encompass robust design principles.

French water legislation articulates statutory prescriptions and proscriptions at the EU, national and local basin level for inclusive of the harvesting, aquifer storage and extraction applicable to ASR. Both the European Union WFD and the French incorporation of the directive, seek to establish science based rules to define the consumptive and non-consumptive “pools” for water management, partially fulfilling the first instrument of robust separation. The *Water Act 1964* and pursuant legislation, prescribes water quality standards that represent the hazard control points necessary for reliable ASR. Volumetric determinations are however at the whole of basin scale, and based on the proposed separation of the urban water cycle, do not articulate sufficient precision for non-contentious share entitlements for a localised ASR operation. The minima and maxima that trigger declaration or authorisation standards do not account for regional heterogeneity for stormwater or aquifer characteristics. Similarly the legislation does not provide instruments to define an independently managed process to periodically allocate the amount of water to each share. Without clear specification, the assignment of risk and circumstances of compensation remain poorly defined. The detection protocols and efficacy of corrective instruments to manage non-water quality externalities (e.g. subsidence, increased pumping costs) also remain obscure. It has been difficult to determine the capacity of French water policy to fulfil the third instrument of robust separation; stipulating the obligations of final water use.

Robust separation in the Australian context, articulates a property right regime that facilitates secure, economically efficient and low cost trading and administration. We propose that regardless of a market based or a negotiated, regulatory ensemble of instruments to coordinate water use, adherence to the principles of robust separation applied to ASR will resolve the resource allocation tension between consumptive use and the environment, and amongst consumptive users, in concert with issues related to distribution and use.

We acknowledge the limited extent of the concepts expounded in the paper and acknowledge there are many other areas of enquiry involving ASR institutions and governance that warrant research and analysis. Radcliffe in AATSE (2004, pp-183-186) summarises some principal conclusions regarding the governance and management of recycled water; many are relevant to the improved governance of ASR. For example Hatton MacDonald (2003) and AATSE (2004) argue for a more rigorous estimate of urban water prices that supersedes the widely endorsed convention restricting prices to distribution or treatment costs only. They contend that water prices (including recycled water) need to account for a more comprehensive economic value of water, inclusive of externalities and resource rents. AATSE (2004) argues for the necessity of a recycled water demand analysis prior to ASR operations. Tietenburg (1998) describes the procedural justice and equity arising from the distribution of entitlements either through auction process or grandfathering.

Colby (1995) argues for a cautious approach to developing water markets, arguing that the cardinal nature of water and the heterogeneous demands placed on it makes standardised, immediate and anonymous market transactions undesirable and improbable. The detrimental aspects ascribed to a systemic price-making market for water demands are compounded and complicated when measures of water quality are included in the transaction protocols. The systematic application of the robust separation of rights in ASR market based policy design, integrated with aquifer hydrology, will assist to circumscribe and address some of these potential hazards.

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[i] (Randall 1981 p. 202) contends that water rights (for irrigation) need to be resolved and articulated in terms of:

1. the time-span of the entitlement and provisions for rental rights to deliveries in the event that long term entitlements are specified;
2. the method of accommodating the stochastic nature of water availability. Possibilities include individual rights to some specified small fraction of deliverable water available, and the specification of different entitlement classes in terms of reliability that is, the probability of water delivery;
3. the time and place of delivery;
4. the ownership of tail waters and return flows and the attendant obligations upon the owner.
5. the conditions under which entitlements could be transferred, with special reference to transfers which would change the time and /or location of water demand.

[ii] Directive 80/68/CEE du Conseil du 17 décembre 1979 concernant la protection des eaux souterraines contre la pollution causée par certaines substances dangereuses (pollution)

Directive 200/60/CE du 23 octobre 2000 établissant un cadre pour une politique communautaire dans le domaine de l'eau (promotion of an integrated water management)

Circulaire DE/SDGE/BRGE-DCH/04 n˚7 du 16 mars 2004 relative a la gestion quantitative de la ressource en eau et a l'instruction des demandes d'autorisation ou de déclaration des prélèvements d'eau et des forages. (extraction)

Décret n°2006-881 du 17 juillet 2006 modifiant le décret n°93-743 du 29 mars 1993 relatif a la nomenclature des opérations soumises a autorisation ou a déclaration en application de la loi n°92-3 du 3 janvier 1992 sur l'eau et le décret n°94-354 du 29 avril 1994 relatif aux zones de répartition des eaux (all actions dealing with water