Principles to coordinate managed aquifer recharge with natural resource management policies in Australia

John Ward · Peter Dillon

Abstract Managed aquifer recharge (MAR) is a tool available to water-resources managers that assists agencies to secure water supplies and protect aquifers and groundwater-dependent ecosystems in the face of climate change and growing water demand. Yet few natural-resources managers have access to a coordinated set of policies that enable the potential benefits of MAR to be fully realised in urban and rural areas. This paper reviews contemporary Australian water-resource policies and systematically applies a refined set of 'robust separation of rights' principles based on secure entitlements, annual allocations and end-use obligations to guide the coordination of policies specific to each of the four operational processes central to MAR schemes: source water harvesting, aquifer recharge, recovery of stored water and end use. Particular attention is given to the formulation of policies relating to the recovery of water, including the feasibility for market exchange of permanent and temporary rights to recover recharged water, as these have the potential to greatly expand the role of MAR. Aquifer characteristics, existing groundwater extractions and potential third party effects need to be taken into account in determining both recovery entitlements and annual allocations. A transitional pathway to implement novel MAR policies is suggested.

Keywords Groundwater recharge · Water policy · Tradeable rights · Groundwater management · Australia

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J. Ward (✉)
CSIRO Water for a Healthy Country National Research Flagship,
CSIRO Ecosystem Sciences,
Ecoscience Precinct, Boggo Rd, Dutton Park 4102,
Queensland, Australia
e-mail: j.ward@csiro.au

P. Dillon
CSIRO Water for a Healthy Country National Research Flagship,
CSIRO Land and Water PMB2, Glen Osmond, SA 5064, Australia
e-mail: peter.dillon@csiro.au

Introduction

Managed aquifer recharge (MAR) is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit. There are four primary and distinguishable operational processes or elements of water management that are utilised by MAR: the harvesting of source waters, the recharge of water in an aquifer, the recovery of stored water and final end use.

Sources of water, following appropriate treatment, can be recharged, stored within an aquifer and then recovered at a water quality suitable for a specified end use (NRMMC, EPHC, NHMRC 2009). Source waters for aquifer recharge include stormwater, reclaimed water (including water treated to potable standards), desalinated water and natural waters (including surface water and groundwater from other aquifers). MAR is an initiative that assists water-resources managers to secure water supplies and protect aquifers and groundwater-dependent ecosystems, particularly evident when aquifers are under stress through excess demand. MAR can provide a flexible means of contributing to or sustaining both water supplies and aquifer storage when subject to appropriate policies for the recovery of recharged water (Dillon 2005; Pyne 2005). Dillon et al. (2009a) contend that MAR should not be regarded as a substitute for demand management (i.e. managing consumptive use) policies, but it can make these easier to implement and play a complementary role in augmenting traditional water supplies and restoring over-exploited aquifers.

The harvesting, storage and recovery of waters in aquifers has the potential to buffer seasonal water shortages, mitigate the stress of drought, supplement environmental flows and defer the development costs of new water supplies (Pyne 2005; Dillon et al. 2009b). MAR has the capacity to augment domestic and industrial supply by converting urban water waste streams and high flow flood events into more reliable groundwater storage. As a corollary, the resource characteristics of MAR source waters, particularly stormwater, are rapidly changing from one of a waste stream requiring disposal to one of economic and commercial value.

An ad hoc development of stormwater governance and legislation, coupled with the absence of well defined

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entitlements to access stormwater (Brown 2005; Radcliffe 2007) and recycled water (Macdonald and Dyack 2003; AATSE 2004; Radcliffe 2008), is likely to lead to equivocal aquifer storage and extraction, legal dispute and potential detrimental impacts on receiving environments or adjoining groundwater systems (Productivity Commission 2008; Radcliffe 2008; Ward and Dillon 2009). Radcliffe (2007 p. 322) argues that: "If greater remediation and use of recycled water is to occur, …… the same principles of entitlement, allocation and use licensing should be adopted as already apply to suppliers and users of water from surface catchments and groundwater basins".

This paper focuses on coherent and coordinated policies to assign water entitlement and periodic allocations that adequately account for MAR by extending and applying a set of principles to guide MAR policy originally outlined by Dillon et al. (2007). The policy framework is based on the 'robust separation of rights' (Council of Australian Governments 2004; Young and McColl 2003), describing a set of sequenced entitlements, periodic allocations and end-use obligations (Ward et al. 2008; Ward and Dillon 2009).

Combining the principles of the robust separation of rights with each MAR operational element suggests a systematic governance arrangement that allows for the independent and flexible management of MAR. The approach aligns MAR operational components with those natural resource management (NRM) policies central to developing and sustaining water resources.

By focussing on water and NRM policies and their current readiness for MAR, this paper articulates some of the issues in relation to the coordinated design and implementation of urban water policy, accounting for hydrogeological settings; the level of water utilisation in the surface-water catchment supplying source water for MAR; and coordinating entitlements for MAR recovery with existing native groundwater extractions in the proposed storage aquifer. The paper describes the role of MAR in urban and rural water systems, the characteristics of the robust separation of water rights, and recommendations derived by applying robust design principles to the four operational elements of MAR: source-water harvesting, aquifer recharge, the recovery of stored water and final use. The focus is on the Australian experience (see Fig. 1), but context is provided on MAR policies elsewhere in the world.

Current status of international MAR policies

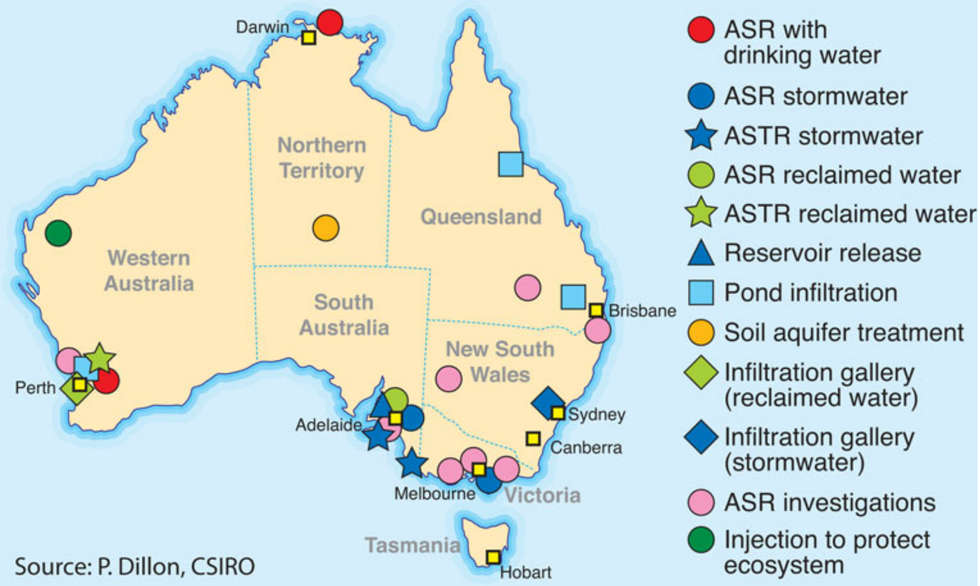
MAR policies exist or are in development for Australia, France and the United States. The Australian National Water Initiative (NWI) is embodied in a 108 clause agreement ratified by the Commonwealth of Australia and the State and Territory Governments. The NWI sets out objectives, outcomes and actions for the ongoing process of Australian water reform, and timelines to achieve this reform. The objective of the 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" (NWI clause 23).

Stormwater harvesting is the source water for many Australian MAR schemes either planned or in operation (Dillon et al. 2009a). Aquifer storage and recovery (ASR) represents a relatively cost-effective urban-supply alternative compared to other large-scale engineered water-supply options. Dillon et al. (2009a) calculated the mean 2009 levelised costs of seven Australian urban ASR sites within a recharge range of 75–2000 ML/year at A$ 1.12/KL, compared to desalination estimates of A$ 2.45–3.46/kl. The recharge and recovery cost of the Queensland Burdekin rural infiltration scheme in 2009 was A$0.07/kl. Pyne (2005) identifies many locations where the benefits of MAR exceed costs and where the costs of MAR are significantly lower than alternative supplies.

Ward and Dillon (2009) reviewed policy salient to MAR operations of all Australian states, noting that no jurisdictions have MAR-specific policies that are integrated into catchment management strategies, nor take account of the potential for MAR to augment high valued water supplies, and protect aquifers and groundwater-dependent ecosystems. Despite an increasing recognition of the role of MAR in Australian urban water management, few natural resource managers have access to a portfolio of coordinated natural resources management policies that enable MAR in urban and rural areas to achieve the full range of potential benefits (Brown 2005; Ward et al. 2008). Australian MAR schemes are currently subject to an array of discrete policy provisions, at times attempting to comply with competing and un-coordinated policy requirements. In addition to policies prescribing water management and human health, Australian MAR operations are required to comply with policies pertaining to national parks and wildlife, urban development and planning, fisheries and marine environments, environmental planning and assessment, environmental protection, local government acts, native title, road traffic planning, flood mitigation and food acts (Ward and Dillon 2009).

Ward and Dillon (2009, 2011) note that MAR operations are obliged to comply with well-established water-quality guidelines and legislation to ensure human health and environmental integrity, however they contend that:

1. Jurisdictional policies providing for access to Australian urban source water for MAR remain fragmented and poorly defined.
2. There are no Australian examples of fully specified and enforceable rights entitling operators to a secure, non-contentious share of a defined aquifer storage space. To further compound uncertainty, the status of MAR source water is redefined as groundwater when introduced into an aquifer. Without prior consent, it is therefore subject to the licensing and allocation provisions of prescribed or regulated groundwater systems.
3. Current legislation determines that upon aquifer recharge, source water is subject to the extraction and management rules of native groundwater. The right to extract MAR recharged water in a fully allocated and



Source: P. Dillon, CSIRO

Fig. 1 Map of Managed Aquifer Recharge in Australia in 2011. ASR = aquifer storage and recovery (same well for injection and recovery); ASTR = aquifer storage transfer and recovery (different wells for injection and recovery); further definitions of methods in Dillon (2005)

> potentially overdrawn groundwater system remains poorly or informally defined. Tensions will be especially acute during periods of aquifer stress, when groundwater extraction allocations are likely to be severely restricted or prohibited. Periods of water stress are precisely when stored MAR water can best augment restricted urban water supplies. To improve the security of water entitlements for commercial operators, MAR recovery entitlements are likely to require institutional differentiation, operating under differing recovery rules from those governing entitlements to extract native groundwater.

Efforts to issue water entitlements to urban stormwater and wastewater, to access and manage aquifer storage space, and to provide security to operators to recover stored water are only in their infancy (Ward and Dillon 2011). Importantly, methods for transferring entitlements to recover stored water are needed if MAR is to play a major role in sustaining groundwater supplies from aquifers that are heavily exploited or subject to reduced recharge due to climate change (Radcliffe 2007 p.322). Licensing of MAR operators is not yet on the policy horizon, and presumably consistent compliance with Australian guidelines that protect human health and the environment (NRMMC, EPHC, NHMRC 2009) may avert the need for such controls.

In contrast to the Australian endorsement of 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 hydrographic basin. Groundwater management in France is guided by the statutes prescribed in the *Water Law 1964* (revised 1993 and 2007). Elaborating on *Article10*, Dubois (2001, p. 89) summarises French water policy, stating "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. In accord with Dubois, Launay (2003) argues for improved policy coordination concerned with MAR schemes.

The US laws that apply to MAR vary state by state and constitute a new and rapidly changing area of law (Marsh and Saltzman 2009, pp. 56–60). The general position is that if a water user has a right to the water prior to water recharge, then s/he also has a right to recover that water (Pyne 2005). California explicitly protects the rights of those who recharge water to withdraw it. Those who recharge aquifers have rights to exclusively withdraw that groundwater from the aquifer (National Research Council 2008). Arizona requires two permits in order for water to be stored and recovered from an aquifer (Bryner and Purcell 2003, p. 10). The first permit is an underground storage facility permit that allows for the operation of the storage facility (ibid, p. 11). The second permit is a groundwater savings facility permit that requires a contractual agreement with the recipient of the recovered water that for every unit of water received from the MAR, they will reduce their groundwater withdrawals from other sources by one unit.

In Colorado, access to recharge is limited to 30 years and the rights to store water in aquifers depend on the specific rules and regulations for the permitting of that particular aquifer (Bryner and Purcell 2003). Adjacent landowners would only be permitted to withdraw the amount of water their extraction permit allowed, so they are essentially barred from withdrawing any additional water that their neighbour has stored in the aquifer.

Thus, the laws and policies in regards to MAR in the individual states of the USA reflect directly on the abundance of available water resources available and also on the doctrine of groundwater rights followed by the respective state. These laws and policies are not static and will continue to evolve because the ownership of stored water remains an important issue. MAR proponents need to be assured that they have adequate protection of their investments in their facilities and operations (Marsh and Saltzman 2009). Marsh and Saltzman (2009) argue the trend will continue to increasingly protect the legal right to store and use water and to exclude other competing users from withdrawing recharged water.

An integrated framework for the governance of MAR

This paper presents a synthesis of an initial framework proposed by Ward and Dillon (2009) and refinements gained from a series of workshops attended by 54 decision makers and analysts of State and Commonwealth agencies and industries concerned with the management of MAR. Participants were invited to critically review the MAR policy and governance arrangements proposed by Ward and Dillon, and suggest revisions sharpened through the lens of operational and implementation challenges specific to each jurisdiction (Dillon et al. 2010b).

In establishing new MAR projects, the management of water resources needs to be addressed in concert with local health and environmental protection. The left hand side of Table 1 shows the surface water and groundwater-quantity attributes considered in formation of Australian policies relevant to MAR that are the subject of this paper. The right hand side of Table 1 shows the water-quality aspects of MAR operations addressed by various Australian guidelines notably the MAR guidelines (NRMMC-EPHC-NHMRC 2009) and are reported elsewhere (e.g. Dillon et al. 2010a and Page et al. 2010).

When evaluating a new MAR project, the guidelines require that the first step is to determine that there is sufficient demand for recovered water; that there is an entitlement to surface water available for recharge, and that there is a suitable aquifer in which the available source water volume can be stored and recovered. The guidelines say nothing about the process of assigning access and management rights to water interests because this is the domain of water-resources management policies at the level of state jurisdictions. However, in most states, these policies are nascent and still emerging. Table 1 summarises the key surface water and groundwater-quantity and water-quality attributes that need to be considered in integrated policy frameworks to facilitate MAR operations.

Aligning MAR with robust water allocation policy

The National Water Initiative (Council of Australian Governments 2004) describes separately managed policy instruments, drawing on the principles of the robust separation of the rights of water interests (Young and McColl 2003). The separation of rights requires a three-tiered system of instruments to distribute and allocate volumes of water efficiently over time. A water plan embodies community values and science-based guidelines to appraise the state of a water or aquifer storage system, to negotiate the agreed level of system modification and to prescribe the rules to determine the environmental and consumptive "pools". The three policy instruments are termed:

- Entitlement: which defines the characteristics and number of unit shares of the defined consumptive pool, subject to periodic allocations and the distribution of shares to individual interests
- Allocation: which defines the process to periodically allocate the volume of water/aquifer storage space to each share, and accounts for a variable water supply or aquifer storage capacity

Table 1 Integrated natural resource management, health and environmental issues to be addressed for effective governance of MAR (adapted from NRMMC-EPHC-NHMRC 2009)

	Quantity Water source and storage entitlements and allocation	Quality Human health and environment protection
Surface water	Environmental flow requirements (including urban stormwater and sewage effluent) Water allocation plans and surface water entitlements Inter-jurisdictional agreements.	Catchment pollution control plan Water-quality requirements for intended uses of recovered water (Aust Guidelines for Water Recycling (AGWR) phases 1,2 (NRMMC–EPHC–AHMC 2006; NRMMC–EPHC–NHMRC 2008) Risk management plan for water-quality assurance (AGWR phases 1,2)
Groundwater	Groundwater allocation plan and groundwater entitlements Resource assessment accounting for groundwater-dependent ecosystems Demand (consumptive use) management Allocatable capacity and entitlement for additional storage in the aquifer Transfer of entitlements from MAR operations Inter-jurisdictional agreements	Groundwater-quality protection plan for recharged aquifer in accordance with Groundwater Protection Guidelines (ANZECC-ARMCANZ 1995) Water-quality requirements for intended uses of groundwater (Water Quality Guidelines for Fresh and Marine Waters, 2000, AGWR phase 1 2006 or Augmentation of Drinking Water Supplies, AGWR phase 2A 2008) Risk management plan for water-quality assurance beyond attenuation zone, accounting for aquifer biogeochemical processes

- Use obligations: which prescribes or proscribes the obligations of water use and takes into account existing water users and third party effects

Table 2 combines the four operational elements of MAR (harvesting, recharge, recovery and end use) with the principles of the robust separation of water rights (entitlements, allocations and use conditions) into a unified framework (Ward and Dillon 2009). The framework suggests a systematic governance arrangement that allows for the coordinated, independent and flexible management of MAR operational elements. The systematic approach reveals opportunities to align MAR operational components with natural resource management and economic policies central to the NWI and to the development and management of MAR.

Most urban jurisdictions in Australia lack water-quantity policies that enable the full realisation of MAR benefits and are capable of resolving the tension and conflicts of competing individual interests. In contrast, the National Water Quality Management Strategy now contains Guidelines for Managed Aquifer Recharge within the second phase of the Australian Guidelines for Water Recycling to ensure that human health and the environment are protected at MAR operations (NRMMC-EPHC-NHMRC 2009). Effective urban water management requires an approach that coordinates water-quality standards to ensure public and environmental health with NWI consistent policies to manage volumetric supplies and consumption of urban water. However policies concerned with property rights of water quantity have received limited attention and are not yet established for all elements of MAR operations in Australian and international jurisdictions (Ward and Dillon 2009; Ward et al. 2008).

Source water harvesting

In *rural catchments* described by a water plan, water from streams and lakes intended for aquifer recharge in a MAR operation should be treated exactly the same as for any other water diversion under the NWI. A water plan establishes the maximum annual limit on aggregate water extractions, regardless of whether consumption is for immediate use or storage. MAR source waters derived from water resources described by the water plan are likely to be one of several competing consumptive uses. MAR operations are therefore required to hold an entitlement granting access to a defined share of source waters and subject to the same set of accounting conventions and obligations as other entitlement holders. Using the robust framework, no additional policies are required for harvesting of surface waters in rural catchments.

In *urban stormwater* catchments, the management of stormwater has been rarely subject to a regime of entitlements, allocations and use obligations described by a water plan. The imperviousness of urban catchments has typically increased urban runoff coefficients to an order of magnitude higher than pre-European settlement. As a result considerable harvesting of stormwater could occur without impinging on natural environmental flows. It is suggested that a system of stormwater entitlements to the environment and to private and public interests within the catchment (including householders and organisations that invest in stormwater harvesting infrastructure) be established. The assignment of entitlements could be an adaptation of existing rural catchment water entitlements requiring water register conventions. A water register, similar to that used for rural surface water systems, represents an accounting convention that tallies the stormwater credits and debits for each entitlement holder. The net effect of urban development including impact on total flows, especially in inland cities, needs to be considered when determining the level of water diversion and consumption in Water Plans.

Stormwater flows in an urban catchment usually occur intermittently and in short durations. Consequently, environmental flows, the consumptive pool and flow sharing arrangements are more problematic than in

Table 2 Natural resource management for MAR based on the robust separation of rights

MAR governance instrument:	Source water harvesting	Recharge	Recovery	End use
Entitlement	Unit share in surface water, stormwater or effluent consumptive pool, (i.e. excess to environmental flows)	Unit share of aquifer's finite additional storage capacity	(Tradeable) extraction share which is a function of managed recharge.	NA
Periodic allocation	Periodic (usually annual) allocation rules. Potential for additional stormwater or treated effluent subject to high flows or development offsets	Annual right to raise the water table or piezometric head subject to natural recharge and total abstraction	Extraction volume contingent on ambient conditions, natural recharge and spatial constraints	NA
Obligations and condition	Third party rights of access to infrastructure for stormwater and sewage	Requirement not to interfere with entitlements of other water users and water bankers	Existing licence may need to be converted to compatible entitlement to extract (unit share)	Water use licence subject to regional obligations and conditions, for use and disposal

NA not applicable

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systems characterised by a stronger more predictable base-flow component such as rural catchments.

Assigning stormwater entitlements to individual water interests may be possible but initially impractical because of the high transaction costs of managing unpredictable flow volumes and frequencies. The variability of stormwater quality, the typically small detention capacity in relation to total flow volumes and the need to mitigate high flows that cause flood damage add complexity to the exercise.

Hence, it is unlikely that the volume of the consumptive-use pool of stormwater will be known at the time when a harvester must decide whether to divert water and how much. Generally stormwater infrastructure is managed by a local council authority; although the sovereign status of the water itself varies across jurisdictions (SA NRMC 2007; Ward et al. 2008; Ward and Dillon 2009). For illustrative purposes, it is assumed that a catchment includes the stormwater infrastructure managed by a single local government authority.

Ward and Dillon (2009) suggest a sequenced approach, commencing with storm water harvesting licenses and evolving towards competitive entitlement tenders as stormwater demand matures. One initial solution would involve the issuing of volumetric licenses by a local council to all storm water MAR harvesting operations within the same catchment. To increase cost effectiveness through economies of scale and promote operator cooperation, license holders could rely on a single harvesting operator acting on behalf of all harvesting licenses. In this example, the infrastructure would be publicly owned and over time, the harvesting operation within the catchment could be contracted through a competitive tender process, thus promoting innovation and maximising aggregate economic benefit. As the MAR operation matures and certainty improves, licences could be converted to tradeable entitlements and additional public or private harvesting infrastructure constructed.

Applying the aforementioned arrangement to all catchments in a coordinated manner avoids the problem of downstream-upstream externalities. The default alternative, that the upstream MAR location has priority over locations downstream, could deny or reduce access to existing operators, diminishing security of supply for downstream operations. Sharing arrangements for Queensland overland flows provide a policy template for coordinating downstream-upstream stormwater conflicts (Queensland Department of Natural Resources 2007; Young and McColl 2009). In unregulated Queensland water-supply systems, significant amounts of water can periodically be obtained by capturing overland flows, especially in extremely episodic systems like those found in Australia’s Darling River system. Harvesting of overland flows is prohibited when the flow rate is low. As the flow rate increases and exceeds defined thresholds, progressively more and more licence/entitlement holders are allowed to commence water-harvesting operations. To prevent over-harvesting, flow-rate threshold announcements are usually made on a daily basis and, for each threshold, entitlements specify a maximum daily volume that may be diverted or taken while flows remain above that rate. Stormwater access entitlements could be articulated according to similar flow rate thresholds.

There have been limited reuse opportunities for *sewage* by third parties in urban areas (see Marsden Jacobs 2005, Productivity Commission 2008 for an example in Sydney). Systems of entitlements, allocations and obligations to sewage are warranted to facilitate highest valued recycling. Entitlements and allocations are warranted to protect the security of environmental flows, third-party obligations for discharge of treated sewage effluent and to avoid increases in sewer chokes due to deposition of solids at low flows. Harvesting obligations should ensure that any changes in effluent quality would neither adversely compromise the uses of water discharged from the sewage treatment plant, nor the discharge loads of contaminants and nutrients. Where additional treatment costs are incurred by harvesting operators to achieve these obligations, these would be reflected in the price of water to the end user.

Aquifer recharge

The assignment of recharge entitlements assumes at the outset that there exists an aquifer-management plan that defines the ambient environmental “pool” expressed as a range of allowable water table depths (or piezometric heads), or aquifer storage capacity and prescribes the management of native groundwater in the aquifer. The first three MAR elements of Table 2 require the discrete specification of a unit share entitlement of a defined consumptive pool and independently managed rules to establish periodic allocation and the conditions of use. The second of these is an entitlement to access aquifer storage space for recharged water. Net aquifer storage capacity accounts for a finite storage space by prescribing a cap on the water-table elevation (or piezometric head). The cap establishes the consumptive “storage pool”. A recharge entitlement represents a unit share or quantum of the net aquifer storage capacity. A recharge entitlement therefore defines the right to actively store additional water or the right to raise the water table/piezometric head.

Aquifer recharge entitlements in general will not be an issue in over-exploited aquifers, as there will be adequate aquifer storage capacity for multiple MAR operations, and generally MAR will be welcomed as a means of attempting to restore hydrological equilibrium. MAR therefore may provide an alternative to reductions in extraction entitlements and allocations.

In aquifers which are in existing long-term balance or where piezometric levels are trending upwards over a number of years, recharge capacity is finite. Excessive recharge could cause water tables to rise, potentially causing either flooding of basements, water logging, differential expansion of clays and damage to building structures, dryland salinity, unintended discharge of groundwater, or causing wells to become artesian. The MAR guidelines require that these risks are examined and addressed (NRMMC-EPHC-NHMRC 2009). To allow for multiple recharge operations, there needs to be an equitable and transparent way of distributing available recharge capacity between MAR operators. If water-resource managers do not take this into account, increasing and uncoordinated competition for the available aquifer storage capacity can potentially lead to litigation due to interference effects between sites. Such effects may include increased pumping costs, which compound adverse environmental impacts, and reduced recovery efficiency in brackish aquifers.

Close coordination of operations would be required to minimise the adverse effects on groundwater hydraulic pressure (resulting in increasing energy costs for injection and recovery) and salinity of recovered water. Hence it is suggested that the recharge entitlement include spatial specifications for ASR well location to ensure buffering between operators and minimise operator conflict. As an initial step, a number of individual recharge entitlement holders may choose to contract a single recharge operator.

Recharge capacity is unlikely to be exceeded for the first MAR projects operating in any aquifer. If adequate source water is available and competition for the storage capacity increases, the rights of existing and new recharge operations will require protection. The specification of buffer zones in the recharge entitlement, which would prevent proximate MAR operations, is one approach to protect existing operations and it can be easily monitored. In order to minimise the potential for litigation and reduce operational costs it is also possible to issue recharge entitlements to a single operator for multiple recharge sites within a defined aquifer zone. Recharge entitlements, subject to constraints reflective of local aquifer conditions, could be transferable when an aquifer is approaching full recharge assignment.

Recovery of recharged and stored water

The volume of water that may be recovered is generally a function of the volume of water recharged into the aquifer. Fit for purpose uses of recovered water may include drinking-water supplies, irrigation, industrial supplies, toilet flushing, etc. In addition ecosystems can be sustained or existing groundwater users protected by raising piezometric heads to support base flows, maintain lakes or groundwater dependent vegetation and by protecting against saline intrusion. This section discusses policy implications that account for hydrogeological characteristics, aquifer equilibrium, native water quality and mixing of recharge water.

Security of recovery entitlements for MAR operators is an important consideration for investment, and these need to link to the volume actually recharged with the rules declared at the outset of operations. In line with rural water plans, review after 5–10 years should be a part of the groundwater allocation planning cycle. Hence, metering of recharge and recovery will be essential to support claims of entitlement. Monitoring of groundwater levels and salinity will assist in evaluating the public benefits of aquifer restoration of the MAR operator in relation to their private benefit. A cogent argument could be mounted to shield the credits earned by MAR operators from any reductions in annual native groundwater allocations. Dimensions to consider in determining recovery entitlements include:

1. The proportion of recharged volume that may be recovered
2. The time period over which recharge credits may be recovered
3. Linkages between the volume that may be recovered and the time period of storage in the aquifer (e.g. a depletion rate)
4. The maximum annual recovery
5. The transfer of entitlements and allocations to recover water to other groundwater users; and the rules governing such transfers conditioned by proximity, gradient, direction, aquifer pressure, water quality and quantity of the transferee with respect to the recharger

These considerations are discussed in depth in Ward and Dillon (2011) and summarised in the following sections.

Proportion of water recovered

In the case of over-exploited aquifers, where groundwater levels are in long-term decline and aggregate extractions of native groundwater have not been reduced to sustainable volumes, recovery from MAR operations could be limited to a specified percentage of recharge volume. The un-recovered balance represents a net contribution towards restoring aquifer hydrological equilibrium. For the Australian case, an entitlement to recover 90 % of recharge is considered reasonable (Dillon et al. 2010b). This would return the system to a less stressed state and provides a windfall net benefit to other groundwater users in return for use of otherwise unused aquifer storage capacity. A 10 % margin on profitability would be within the contingency of robust viable operations, and projects where proponents claim this threatens viability are possibly not feasible.

Recovery from ASR in over-exploited and brackish aquifers in South Australia has been limited to 80 % of recharge volume for locally pragmatic reasons. When recovery approximated 80 % of recharge, the salinity of the recovered water reached the limits for its intended beneficial use (AMLRNRMB 2008). Limitations on recovery volumes relative to the volume of MAR recharge impose additional costs on MAR operators, while producing benefits for other groundwater users in the same aquifer (such as reduced pumping costs or reduced salinity concentrations). Methods that account for the net costs and benefits to all parties as a result of MAR operations would provide an incentive for MAR where surface-water allocations are available. It is suggested that a recovery entitlement of 100 % of the volume of MAR recharge water be ordinarily provided in aquifers that are not over-allocated. Whether the salinity of recovered water constrains the proportion of recovery compared to recharge would be determined by the operator from a salinity meter on the recovery main, but should not be set as an arbitrary default constraint by the regulator.

State regulators responsible for policy pertaining to MAR schemes and participating in the 2010 MAR workshop were in consensus in each state jurisdiction that in over-allocated aquifers entitlements to recover recharged water (recovery credits) should be endowed with a higher level of security than entitlements to native groundwater (Dillon et al. 2010b). That is the recovery credit should be retained (Table 3) and not reduced with native groundwater allocations if groundwater levels were to decline. This recognises the effort of the MAR operator in creating the credit, and in already having contributed a net social benefit to others drawing from the aquifer. Table 3 describes the proposed recovery entitlements for different aquifer characteristics.

In locations where it is necessary to reduce groundwater extraction, the cost of recharge may be less than the cost of reducing demand from the aquifer. In such locations, and particularly if MAR schemes are to be constructed to provide increased security to existing users of groundwater, up to 100 % of the recovery entitlement could be transferred or traded to existing users in return for surrendering part of their equivalent entitlement of native groundwater. The percentage of groundwater entitlement forfeited could be based on the degree of over-allocation of the resource and the extent to which this is offset by MAR operations. In this way all beneficiaries contribute to the costs of MAR operations and the recharge operator is not penalised for providing a public benefit. Communities of groundwater users could combine (e.g. groundwater users associations) to undertake MAR with entitlement transfers to their own wells, subject to aquifer characteristics and compliance with NRM provisions. Alternatively, publically funded operations could be established and paid for through fees associated with groundwater entitlements, to cover the costs of MAR operations to sustain aquifer volumes. It is expected that cohesion developed among groundwater users in non-competitive collegiate groundwater management via MAR will assist in implementing demand management where it is identified that the incremental cost of expanding MAR exceeds the costs of forgoing supplies.

There is no need to limit the percentage of recovery to less than 100 % of the volume injected in groundwater systems in long-term hydrologic equilibrium. One hundred percent recovery would be the long-term goal of effective groundwater management, based on native groundwater extractions and recharge enhancement. For some brackish aquifers in hydrological equilibrium, the MAR operation may make more water recoverable at an acceptable salinity concentration than the volume of water recharged. Given that recovery entitlements carry greater security than native groundwater, it is proposed that in such cases the MAR operator could apply for an entitlement to native groundwater to the volume exceeding the original recovery entitlement.

Time period over which water may be recovered

Major fresh groundwater systems with extensive storage capacity and long residence times will have minimal additional 'natural' discharge as a result of MAR and the full recharge volume should be available for recovery over long time periods. In these aquifers, the rules governing the time period for recovery will be balanced by administrative practicality and the need to provide incentives to conserve water for the future. In Arizona, for example, a moving 30-year recovery entitlement to the accumulated net recharge (i.e. recharge minus recovery) is allowed (Arizona *Underground Water Storage, Savings, and Replenishment Act 1994*, Colby and Jacobs 2007). MAR recharge is institutionally differentiated from native groundwater rights, whereby the volume of recharge that may be recovered by a MAR operator in any year is the amount up to the accumulated recharge less abstraction over the preceding 30 years. This provides both an incentive to retain water in storage in case there is a

Table 3 Recovery entitlement descriptions for different aquifer characteristics

	Over-exploited aquifer		Aquifer in equilibrium	
	Long hydraulic retention time T [a] (T>30 years)	Short hydraulic retention time T (T<30 years)	Long hydraulic retention time T (T>30 years)	Short hydraulic retention time T (T<30 years)
Maximum cumulative % recovered [c]	90 % (S)	90 % (S)	100 % (S)[d]	100 % (S)[d]
Time period for recovery (years)	30	T[b]	30	T[b]
Depletion rate for stored water (%)[c]	0 (S)	100/T (S)	0 (S)	100/T (S)
Maximum recovery in any year	<Max annual recharge	<Max annual recharge	–	–
Transfers permitted	Yes	Yes	Yes	Yes

[a] T represents the hydraulic retention time (years) of recharged water (ratio of storage volume to aquifer discharge)

[b] Value of T ranges from 1 to 29 years

[c] Maximum percent recovered in a brackish aquifer is constrained by the salinity (*S*) of the recovered water needed to meet end-use requirements. Recovery ceases when water reaches this salinity threshold or the percentage constraint whichever occurs first

[d] In some brackish aquifers the salinity constraint may not be reached until recovery significantly exceeds 100 % recharge. In such cases the MAR operator could apply for entitlement to native groundwater for the amount in excess of their recovery credit (100 % recharge volume)

serious drought ahead (i.e. the right to recover in times of drought remains with the recovery entitlement holder), while allowing considerable flexibility to meet present needs. Periods shorter than 15–20 years are likely to result in MAR operators favouring present consumption rather than longer-term water conservation. The potential losses of entitled water at the end of the moving average accounting period and deferred investment returns are potential factors affecting the timing of recovered water.

In contrast, thin coastal aquifers with steep lateral hydraulic gradients are examples of aquifers with high rates of turnover (that is short hydraulic retention time (expressed as T years) in Table 3, determined as the ratio of storage volume to aggregate groundwater discharge including abstraction). The total volume of recharge will not persist as additional storage within the aquifer so the time period to recover recharge credits should be shortened to T years (where $T < 30$ years). As currently expressed it is overly precise (and reduces credibility) for a hydrogeological document, to reflect the reduced hydraulic retention time. Table 3 summarises recovery entitlement descriptions.

Depletion rate for stored water

In aquifers with short residence times, the volume of recharge accessible for recovery declines with time due to natural discharge. That is, the residual storage is depleted and is fully expended over the hydraulic residence time in the aquifer. The process of recharging the aquifer may also increase the rate of natural discharge. The estimated hydraulic retention time used to determine the depletion rate for stored water needs to account for changes in natural discharges in aquifers where MAR contributes a significant fraction of natural groundwater flow. Hence establishing fully disclosed recovery rules that are a function of the mean aquifer hydraulic residence time is recommended to reflect the natural regime.

Where hydraulic residence time exceeds 30 years there is no need to determine a depletion rate as the specified time period over which water may be recovered (30 years) already avoids the carryover of non-recoverable entitlements. In brackish aquifers the proportion of less saline recharge volume that can be recovered at a quality suitable for the intended use (defined as the recovery efficiency) is expected to increase over successive recharge seasons. Monitoring of electrical conductivity of recovered water indicates when to cease recovery operations. However, the proportion of unrecovered water that remains accessible at a suitable quality will decline with time. Declining water quality in these circumstances, analogous to a volumetric depletion rate, applies in all brackish aquifers and is accentuated where hydraulic residence times are short.

It should not be necessary to set depletion rates because of salinity concentrations for two reasons. First, it is difficult to predict salinity attenuation. Second, the Australian MAR Guidelines (NRMMC, EPHC, NHMRC 2009) require operators to follow a risk-management plan that delivers water quality fit for purpose. However, operators will need to be aware of guideline obligations as their water-supply agreements to third parties would define the extent of their responsibility for water quantity, continuity and quality of supply.

Maximum recovery in any year

Although the maximum cumulative percentage recovered is specified, it is possible to conceive of situations where a MAR operator has accumulated a recovery credit over a number of years and aims to recoup that credit within a single year. As a consequence, recovery rates are much higher than normal recharge or recovery rates and could cause a significant cone of depression with adverse short-term impacts on third party groundwater users (particularly in confined aquifers) or on groundwater dependent ecosystems (particularly in unconfined aquifers).

A suggested approach is to limit the annual extraction volume in over-exploited aquifers to be no greater than the maximum annual recharge. In reality, the constraint acts as a surrogate to avoid excessive reduction in pressure in neighbouring wells or ecosystems, which should be an operating condition under the MAR guidelines. However the ability to prove this would be difficult and litigious in an aquifer with multiple pumping wells and with variable recharge. Equating the extraction limit to the maximum recharge achieved in any year in part links recovery with the aquifer's capacity to transmit water. The recovery constraint also acts as an inducement to recharge water, so as to maximise the ability of recovery entitlement holders to draw on reserves in drought years. It also provides a protection against multi-year droughts so that not all reserves are drawn down in the first year of a drought.

Transfer of entitlements to recover water

Allowing the transfer of recovery entitlements and allocations complies with the NWI objectives of facilitating markets where appropriate, and allocating water to higher value purposes. Market exchange and transfers provide a means of compensating MAR operators for recharge that contributes to benefits shared by the aquifer community such as restoration of over-allocated aquifers and maintenance of hydrologic equilibrium. Importantly market exchange of either recovered water or recovery entitlements can substantially reduce public expenditure on aquifer restoration. Transfers of recovery entitlements or allocations provide a means for groundwater-user cooperatives to invest in recharge as an alternative to, or in combination with, strategies to reduce consumption. Entitlement transfer enables MAR schemes to combine recharge and recovery measures to restore equilibrium in previously over-exploited aquifers.

Rules governing the transfer of entitlements and allocations will be necessary to prevent adverse consequences for the aquifer, the environment, and other groundwater users. For example in South Australia, groundwater entitlements cannot be traded down-gradient in a stressed groundwater system, consistent with the position of the Natural Resources Management Standing Committee (2002). This very simple rule stops transfers of entitlements and allocations into existing cones of depression where groundwater is locally over-exploited. It is recommended that this approach be applied broadly to MAR operating in groundwater systems that are over-allocated, avoiding increased energy costs of pumping and salinisation of the aquifer due to increased drawdown. Considerations in determining the transfer of entitlements to prevent perverse outcomes include the direction of groundwater gradient, the ambient groundwater salinity gradient and inter-aquifer transfers.

Direction of groundwater gradient

The transfer of recovery entitlements and allocations depends on distances between the transacting parties, gradient, direction, aquifer pressure, water quality, and transfer quantity with respect to the recharge entitlement holder. MAR recharge and recovery periods will generally be in wet and dry seasons respectively. As a general principle, the permissible location of traded recovery entitlements is guided by the requirement to minimise impact on other users, the aquifer and the environment.

The cones of impression and depression around injection and recovery wells in confined aquifer systems can be extensive and may represent a serious constraint to entitlement and allocation transfers. In contrast, unconfined systems, typified by more localised hydraulic impacts of recharge and extraction, restrictions on transfer locations are likely to be of less consequence. For salinity-intrusion barriers, transfers of entitlements or allocations well away from the coastal margin will help sustain groundwater levels at the barrier where water is injected.

In large or transmissive aquifer systems, it is unlikely that the increased groundwater volumes can be reliably differentiated as either recharge or native groundwater. Generally, it is not necessary to demonstrate that the water recovered is the recharged water, or that the hydrostatic pressure at the point of recovery has been directly affected by recharge. Recovery entitlements should not be traded down-gradient into cones of depression. Subject to these conditions, transfers of MAR recovery entitlements between groundwater management units would be subject to the same constraints as trading of native groundwater.

Ambient groundwater salinity gradient

At the location of the MAR site, health and environmental approval under the Australian MAR Guidelines (NRMMC, EPHC, NHMRC 2009) requires no degradation of local groundwater beneficial uses (beyond a small and temporary attenuation zone). Hence, the salinity of recharge water will generally be equivalent or less than native groundwater at the recharge site. In an aquifer that has a lateral salinity gradient it is therefore possible to recharge water of a higher salinity than occurs in other parts of the same aquifer. There may be local considerations to favour this for example in protecting beneficial uses by averting the potential ingress of very saline or polluted water.

As a general rule, it is desirable to transfer the recovery entitlement from sites where low salinity water is recharged to sites of higher native groundwater salinity in order to achieve a net freshening effect on the aquifer (i.e. improving the aquifer salt balance). There will be occasions to transfer or trade the recovery entitlement from a site where more brackish water is recharged (at a salinity less than local native groundwater) to a well with a lower salinity concentration in native groundwater. To reduce the risk of diminished water quality over time in aquifers characterised by a lateral salinity gradient, it is suggested that recovery entitlements or allocations traded from relatively brackish recharge wells to recovery wells where groundwater is fresher be proportionally reduced using a ‘salinity exchange rate’. The salinity exchange rate in part addresses low salinity native groundwater being replaced by higher salinity recharge water. There would be no exchange rate applied for transfers to wells where groundwater has the same or higher salinity than the recharge water.

For simplicity, it is proposed that the ‘salinity exchange rate’ is calculated as the ratio of the salinity of groundwater at the point of recovery to the average salinity of recharged water. For example if the average salinity of recharged water is 1,000 μS/cm at the source recharge well and ambient groundwater at the point where the recovery entitlement has been transferred is 800 μS/cm then the salinity exchange rate is 80 % and the transferred volumetric allocation to the purchaser would equate to 80 % of the volumetric recovery allocation sold by the recharger. The proposed exchange rate requires ongoing monitoring of the salinity concentrations of native groundwater, recharge and recovered water. The concept aims to encourage a MAR operator to recharge lower salinity water (assuming a variable salinity source), conferring competitive advantage by avoiding the penalty of proportional reductions of tradeable recovery volumes.

Inter-aquifer transfers

The question as to whether recharge in one aquifer can result in recovery credits in another is not simple. A regulator could potentially justify preventing the transfer of recovery rights if two aquifers are not hydraulically connected. However circumstances can occur where a recovery credit produced by recharge into a fresh aquifer could be transferred to a more saline aquifer, enabling abstraction of that water associated with environmental benefits for one or both aquifers. As an example, the recovery entitlements assigned to a municipality in South Australia for its stormwater recharge in an over-allocated aquifer system that is a source of irrigation supplies, are instead claimed from a separate saline aquifer to top-up an urban lake with considerable amenity value (SA NRMC 2007). As a principle, it is suggested that compliance with the NWI (Council of Australian Governments 2004), committing agencies to establish the environmental, social and economic benefits and costs for all stakeholders, should guide determinations of inter-aquifer transfer of MAR recovery entitlements and allocations.

The Australian Guidelines for MAR require that operators meter and record annual recharge and recovered volumes as part of verifying protection of health and the environment at MAR operations. In most operations additional parameters such as salinity will also be recorded and these data should be available to monitor compliance with NRM requirements and human health regulations.

End use

As a requirement of the entry level assessment of new MAR projects under the Australian Guidelines for MAR, the end uses for recovered water are required to conform to existing and proposed catchment and groundwater management plans. End users of recovered MAR recharge may also be required to demonstrate that the use and disposal of water complies with existing urban planning, environmental impact and health policies.

Groundwater management plans have not been prepared for some urban areas. It is noted that stock and domestic wells in urban areas can cause over-abstraction of shallow aquifers and that this class of wells are currently excluded from groundwater allocation plans. Failure to account for domestic wells may mean management plans are incapable of protecting aquifers and connected ecosystems. An effective means of managing these systems may need to rely on regulatory provisions at the whole of aquifer scale rather than individual well interventions.

Transitional policies to facilitate MAR development

Ward and Dillon (2009, 2011) argue that most Australian jurisdictions are a long way from an NWI consistent MAR entitlement and allocation system. However all have in place existing water-affecting regulations and bore construction permit-based systems to allow a limited number of individual MAR projects to proceed. Further clarity and a synthesis of science and community attitudes is required to enable water-sharing arrangements and consumptive pool entitlements to be unambiguously defined in urban areas. Ward and Dillon (2011) suggest a transitional pathway is needed to progress from each jurisdiction's current position towards intended NWI-conforming governance arrangements and propose detailed transitional pathways for policies relating to source water harvesting, recharge, recovery and end use. The proposed transitional pathway is intended to guide inclusive, ongoing and constructive discussion in urban jurisdictions.

The trigger points at which aquifer management would transition from a permit-based system to an entitlement system for MAR in a given catchment or groundwater basin are illustrated in Fig. 2. The transitional arrangements from resource development to resource management are based on the "open-closed" typology of Falkenmark and Molden (2008), applied to groundwater resources in northern Australia by Ward et al. (2009). The example of a northern Australian groundwater basin best represents the current early stage of stormwater harvesting, sewage recycling and MAR development in Australia. The terminology used in Fig. 2 is as follows: *Replenishment* (R) describes system inflows, inclusive of MAR recharge, *Base flow* represents the negotiated and sustainable water table or piezometric head and the volume of storage available for MAR recharge prescribed in the water plan, *Available for consumptive use* (In) represents the harvestable volume related to infrastructure constructed over the years and *Actual consumptive use* (C) represents the volume of diverted water or aquifer extraction. The waved lines are indicative of inflow variation and are a graphic representation of highly episodic and ephemeral water resources, with similarities to stormwater flows and aquifer recharge.

Falkenmark and Molden (2008) define an open basin as one able to satisfy the full suite of domestic, industrial, agricultural or environmental water commitments for the whole of the year. Open basins also have surplus water entitlements and are able to meet additional water demands. In contrast, closed basins are characterised by over-assigned entitlements and are unable to satisfy the full suite of domestic, industrial, agricultural or environmental water commitments for part of the year. A closed and sustainable basin has all water entitlements assigned, and is able to fulfil the full suite of water commitments for all of the year.

Figure 2 is a graphic representation of potential northern Australia water management arrangements which provides a template for institutional triggers relevant to MAR operations. The figure shows a potential time sequence of water-resources development and the various instruments to determine the attributes and assignment of rights.

1. Water planning is introduced early in the development pathway. The open phase is of sufficient duration for the equitable and efficient assignment of entitlements if required. Knowledge can be updated to reduce uncertainty about environmental response to water harvesting, recharge or recovery. For MAR operations that move into a development/modification phase following feasibility evaluation and the activation of water demand factors, a negotiated water plan is required.
2. A precautionary reserve pool is proposed, in addition to the extractive-consumptive pool (C in Fig. 2) and environmental flow (base flow) specified in the water plan. The reserve pool reduces over time as a function of increasing levels of certainty concerning the consumptive pool of source water or aquifer storage capacity, based on monitoring and demonstration projects. The reserve pool also provides an opportunity to test compliance and sanctioning actions without compromising base flow.

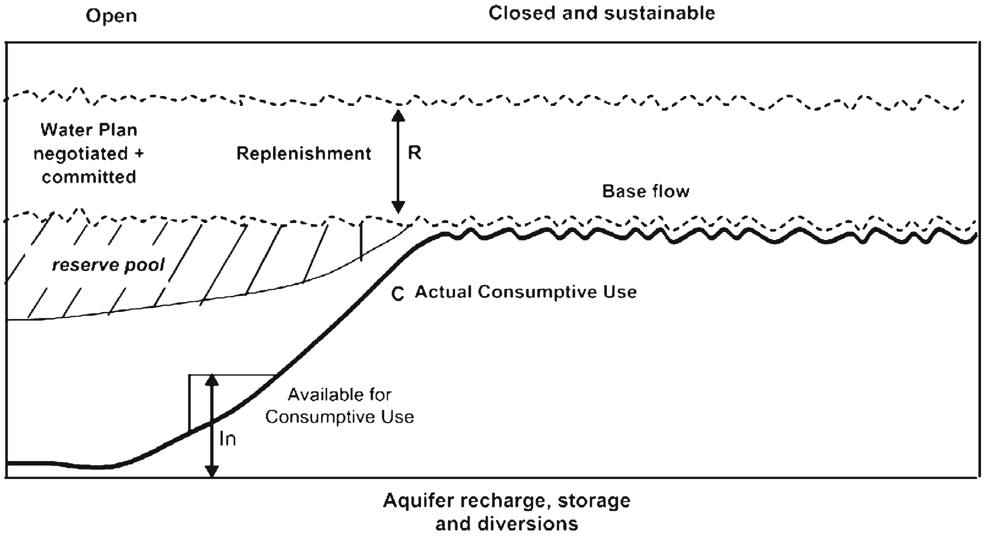

Fig. 2 Open to closed development pathways of northern Australian groundwater basins, inclusive of potential MAR operations

3. As a corollary, the number of available entitlements is initially restricted, with additional entitlements potentially made available as the reserve pool is reduced in volume. Importantly, an alternate permit system may be the simplest, most cost effective and feasible approach when the reserve pool volume is proportionately high. At the commencement of reserve pool reduction, permits can be transferred to entitlements according to the water-planning specifications. Restricting the number or proximity of MAR operations also averts localised interference effects among MAR operators before such effects can be predicted.
4. Water markets that can efficiently re-allocate recharge and recovery entitlements and allocations are unlikely to play a substantial role until the reserve pool is exhausted (i.e. all entitlements have been assigned to various interests).

The sequencing of planning and resource allocation instruments illustrated in Fig. 2 minimises exposure to the adverse outcomes of a poorly planned development phase, including failure to recognise the consequences of uncoordinated extraction, political interference and development that is not economically viable. The transitional pathway avoids the substantial social, political, economic and environmental costs of a closed and unsustainable phase. The sequenced institutional transition described here is intended to stimulate thinking and provide policy design principles that maximise the benefits of currently under-utilised resources, improve urban water management, and are sustained in spite of climate variability and changes in population and land use.

Conclusions

The absence of well-defined entitlements to access stormwater, recycled water, and aquifer storage is likely to result in uncertain aquifer recharge and extraction, future legal disputes, potential detrimental impacts on receiving environments and failure of MAR to achieve its full potential value in water-resources management.

Contingent on limited demand for aquifer storage, the assignment of entitlements to recharge is not a pressing need but is likely to become so as MAR develops. In the first instance, the Australian MAR Guidelines, which take into account localised effects on groundwater levels, pressures and discharges, should suffice. As future multiple MAR operators compete for storage space, groundwater-management plans implemented in each Australian jurisdiction could be invoked to prevent over-recharging of aquifers while protecting recharge entitlements of existing MAR operators. A single operator transitional policy within an area of aquifer and provision for buffer distances between operators can be used to manage negative interactions. Existing legislation and policies will require careful effort to adapt to market innovations in urban water management to ensure the benefits of MAR are free of unacceptable consequences.

Provisions are needed to address the complications in stormwater catchments and a simple transitional solution allowing a single harvesting operator per urban catchment is proposed. Recovery entitlements, including the right to transfer, are vital to the uptake of MAR as a groundwater management tool, and could be adopted into existing groundwater allocation policies. Adoption has already begun in South Australia. Recovery entitlements should be differentiated from entitlements to native groundwater. The principles suggested account for a range of widely encountered hydrogeological situations. Further discussion on these is warranted to determine well-articulated, equitable, efficient and transferable policies.

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