Water **2014**, *6*, 1500-1514; doi:10.3390/w6061500

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Water Banks: Using Managed Aquifer Recharge to Meet Water Policy Objectives

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Received: 20 February 2014; in revised form: 20 May 2014 / Accepted: 21 May 2014 / Published: 28 May 2014

Abstract: Innovation born of necessity to secure water for the U.S. state of Arizona has yielded a model of water banking that serves as an international prototype for effective use of aquifers for drought and emergency supplies. If understood and adapted to local hydrogeological and water supply and demand conditions, this could provide a highly effective solution for water security elsewhere. Arizona is a semi-arid state in the southwestern United States that has growing water demands, significant groundwater overdraft, and surface water supplies with diminishing reliability. In response, Arizona has developed an institutional and regulatory framework that has allowed large-scale implementation of managed aquifer recharge in the state's deep alluvial groundwater basins. The most ambitious recharge activities involve the storage of Colorado River water that is delivered through the Central Arizona Project (CAP). The CAP system delivers more than 1850 million cubic meters (MCM) per year to Arizona's two largest metropolitan areas, Phoenix and Tucson, along with agricultural users and sovereign Native American Nations, but the CAP supply has junior priority and is subject to reduction during declared shortages on the Colorado River. In the mid-1980s the State of Arizona established a framework for water storage and recovery; and in 1996 the Arizona Water Banking Authority was created to mitigate the impacts of Colorado River shortages; to create water management benefits; and to allow interstate storage. The Banking

Authority has stored more than 4718 MCM of CAP water; including more than 740 MCM for the neighboring state of Nevada. The Nevada storage was made possible through a series of interrelated agreements involving regional water agencies and the federal government. The stored water will be recovered within Arizona; allowing Nevada to divert an equal amount of Colorado River water from Lake Mead; which is upstream of CAP's point of diversion. This paper describes water banking in Arizona from a policy perspective and identifies reasons for its implementation. It goes on to explore conditions under which water banking could successfully be applied to other parts of the world, specifically including Australia.

Keywords: water bank; recharge; water policy; Arizona; Australia

1. Introduction

Since the 1990s, groundwater recharge has been a key policy and water management tool in the state of Arizona and elsewhere in the United States of America (U.S.) [1,2]. In Arizona, recharge is being used in a variety of ways, including soil aquifer treatment to improve water quality, annual storage and recovery to satisfy regulations that require the use of surface water supplies in place of groundwater, and long-term water banking for drought mitigation and future use. In addition, a modest amount of water recharged remains in permanent storage and contributes to Arizona's management goal of reducing groundwater overdraft. The increasingly prominent role of managed aquifer recharge has been facilitated by favorable hydrogeology, the temporary availability of surface water supplies, a well-established regulatory framework, and institutional innovation, including the creation of the Arizona Water Banking Authority (AWBA).

This paper provides analysis of Arizona's large-scale implementation of managed aquifer recharge in the state's deep alluvial groundwater basins, for both intrastate and interstate purposes. The focus is on the sizable recharge activities involving the storage of Colorado River water delivered through the Central Arizona Project (CAP) into the most populated regions of the state. Much of that activity is associated with the AWBA, which is a pioneering example of policy and institutional reform that has elements that could be adapted elsewhere in the world. This paper considers some of those additional opportunities for water banking, including those under less favorable conditions by making use of existing water distribution infrastructure to transfer water between banking locations and water users. In addition to those physical attributes, a precursor for water banking is a robust water entitlement system.

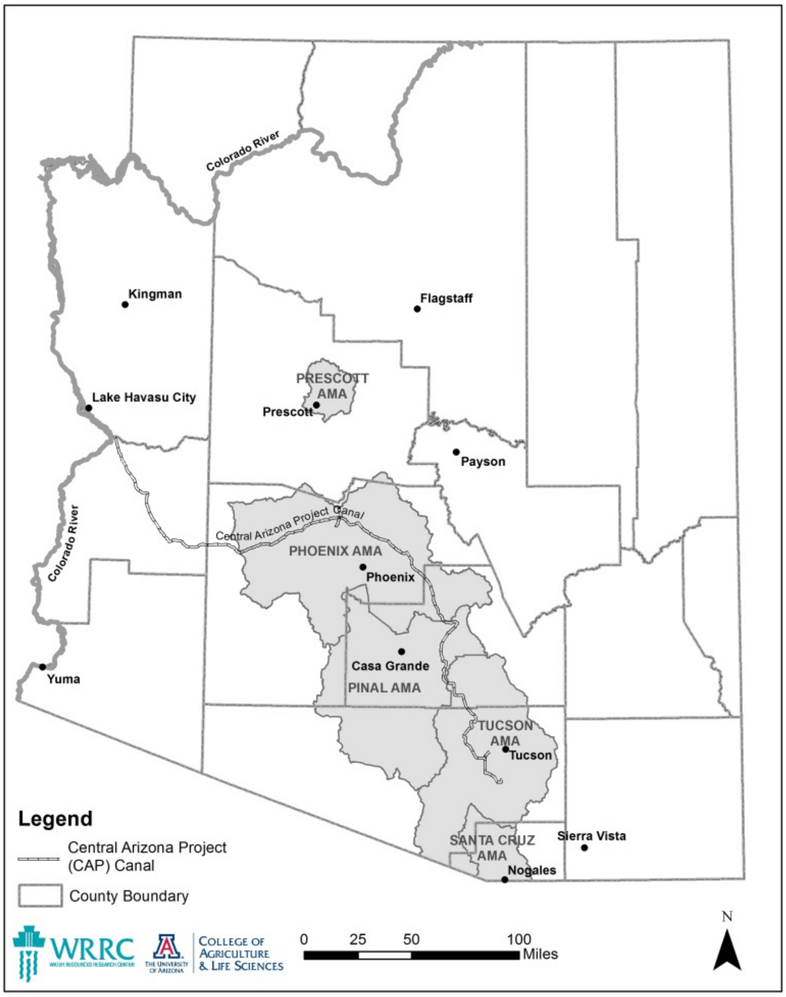
2. The Arizona Physical Setting

More than three-quarters of Arizona's population lives in the central part and south-central part of the state, with more than half of the state's 6.5 million people living in the Phoenix metropolitan area [3]. A sizable share of Arizona's irrigated agriculture is also located in this semi-arid region, which is characterized by low precipitation rates and surface water resources available in limited areas [4]. However, groundwater is a relatively plentiful and widely dispersed resource. Natural recharge rates are low, but storage volumes are large in the deep and productive alluvial aquifers of the basin and range region. Post World War II population growth and improved pumping technology led to increased pumping of these deep aquifers. By the late 1970s, the issue of overdraft reached a political crisis point, and resulted in fundamental changes in Arizona water management [5]. Extensive new groundwater regulations were established, which in turn helped ensure Federal funding for the Central Arizona Project (CAP).

2.1. Groundwater Regulation in Arizona

In 1980, the Arizona legislature passed the Groundwater Management Act (GMA), which established an extensive regulatory regime, and created the Arizona Department of Water Resources (ADWR) to administer it [6]. Water use is particularly intensively regulated in Arizona's Active Management Areas (AMAs), which are delineated on the basis of groundwater basins. Figure 1 depicts Arizona's five AMAs. Within these AMAs, groundwater rights were created and quantified, long-term management goals were established, mandatory conservation programs were implemented, and a moratorium on new irrigated agricultural land was imposed. Use of water by the mining industry was made subject to conservation regulations but otherwise not limited quantitatively [7,8].

Figure 1. Map of Arizona showing the Active Management Areas (AMAs) and county boundaries. Source: Water Resources Research Center, The University of Arizona [1].



The existence of quantified rights and associated regulatory and administrative framework created the necessary preconditions for a number of additional responsibilities and programs overseen by ADWR, including the Underground Storage and Recovery Program, which has helped put Colorado River water delivered through the Central Arizona Project water to use [1].

2.2. The Central Arizona Project

Adoption of the GMA, which included provisions requiring new municipal growth to depend on renewable water supplies and not mined groundwater, helped ensure federal funding for the Central Arizona Project. The CAP is a large-scale water importation project that lifts and transports Colorado River water to the central and southern part of the state by means of pumps, canals, tunnels and siphons. The 542 km (336 mile) CAP system is capable of delivering more than 1850 million cubic meters (MCM) per year of Arizona's 3454 MCM (2.8 million acre-foot (MAF)) Colorado River entitlement to Arizona's two largest metropolitan areas, Phoenix and Tucson, along with agricultural users and sovereign Native American Nations. The CAP is governed by a 15-person elected board of directors, with representation from each of the three counties in the CAP service area. The CAP canal and county boundaries, although not county names, are depicted on Figure 1.

The long-anticipated completion of the CAP altered Arizona's water resource portfolio, but political considerations at the federal level resulted in the CAP's Colorado River water allocation having junior priority on the Colorado River and thus is subject to significant reduction during declared shortages. Despite drought conditions on the Colorado River that have extended into their second decade, a Colorado River shortage has yet to be declared according to regulations established by the Secretary of the U.S. Department of the Interior, the Master of the Colorado River [9]. Furthermore, even though CAP deliveries began in 1985, the water supply was substantially underutilized into the early 1990s. It had been anticipated that it would take many decades for municipal and industrial demands to grow into the available supply. Agriculture was expected to utilize the supply in the intervening time. That assumption proved erroneous, as the cost of the CAP water was unfavorable relative to groundwater supplies for many agricultural districts. Farmers in Central Arizona were not prohibited from using groundwater, provided such use was consistent with the conservation and water rights provisions of the GMA.

The supply underutilization was a concern to the CAP because of its requirement to cover costs and repay the federal government for a sizable share of the project's $3.6 billion United States Dollars (USD) construction costs. Less than full utilization of Arizona's Colorado River entitlement was also a political concern. Water unused by Arizona was available for use by the rapidly growing neighboring state of California. Arizonans were concerned that the more politically powerful California might become accustomed to using Arizona's water to meet the growing demands of Southern California's, rather than Arizona's, municipalities. The response from Arizona's water managers to problems of: (1) anticipated delivery cutbacks due to shortage conditions on the Colorado River; and (2) lack of direct utilization of Arizona's full Colorado River entitlement upon completion of the Central Arizona Project in the early 1990s, was multi-faceted, but rested heavily on the use of managed aquifer recharge to store Colorado River water for future recovery.

2.3. Underground Storage and Recovery in Arizona

The statutory provisions authorizing aquifer storage and recovery were added to the GMA in the mid-1980s and then further refined in 1994. Arizona law recognizes two primary types of managed aquifer recharge—direct and in lieu. Direct recharge is called underground storage in the statutes, with in-lieu recharge called groundwater savings. A permitting system governs the three main components of the storage process: (1) the storage facility; (2) water storage; and (3) water recovery [1,10].

2.3.1. Direct Recharge

The state recognizes a number of different direct recharge methods: spreading basins, injection wells, vadose zone wells, trenches/infiltration galleys, and in-channel projects. There is an enormous range in scale of current projects—from a 0.6 MCM/year (500 acre-foot per year (AF/year)) vadose zone well project in Chandler, Arizona, to the 185 MCM/year, (150,000 AF/year), fully automated Tonopah Desert project west of Phoenix, as pictured in Figure 2 and where infiltration rates exceed one meter per day [11]. The largest projects utilize spreading basins that cover tens of hectares of land. Construction typically involves removal of the upper layers of soil, basin shaping, distribution works, and the installation of monitoring wells.

Figure 2. Tonopah Desert Recharge Project. Source: Central Arizona Project [11].

There are extensive permitting requirements for proposed recharge projects. For instance, an evaluation of hydrologic feasibility will typically involve the use of numeric groundwater flow models to determine the extent of expected groundwater mounding. Projects must also avoid potential damage to surrounding property owners that can occur with rising water levels, and water quality must also be considered.

Infiltration rates vary from site to site, and even among basins, but rates of one to two meters per day are common. These high infiltration rates help keep typical annual evaporation losses to less than five percent (5%), and provide a cost-effective means of storing water. Maintenance includes periodic drying of basins, surface scraping and weed control.

2.3.2. In Lieu Recharge

The GMA's quantification of groundwater pumping rights for agriculture in 1980 made it possible for the second method, groundwater savings, that is, in lieu recharge (also generally referred to as indirect recharge, and elsewhere is called conjunctive use). These irrigation rights form the basis of a type of exchange in which CAP water or effluent is delivered to an agricultural groundwater rightholder, and the party supplying the alternative supply is credited for the amount of groundwater that would have otherwise been pumped. The credits earned through in lieu recharge are legally identical to those earned through direct recharge. Irrigation districts and individual rightholders participate in this program by obtaining a Groundwater Savings Facility (GSF) permit from ADWR, and arranging partnerships with those seeking to earn recharge credits. The GSF permitting process rests heavily on the existence of quantified groundwater rights and the prohibition on bringing new land into irrigation within Arizona's Active Management Areas, as well as financial arrangements regarding the price of the in lieu water to the irrigator.

2.3.3. Accounting

In addition to permitting a recharge project itself, those proposing to store water must obtain a separate permit from ADWR, and must establish the legal right to source water. There are also reporting requirements for deliveries and both water levels and water quality from monitor wells at direct recharge facilities. This system of permits, monitoring, reporting and accounting helps maintain the integrity of the process, which is necessary to assure users that the water they bank can be withdrawn at a later date. To further ensure that only the volume of water added to the aquifer is eligible for recovery, losses due to evaporation are calculated and excluded.

The storage credit system distinguishes between water stored for recovery in the same calendar year and that left in storage for future recovery. Colorado River water left in storage beyond the calendar year in which the water was stored at a recharge facility is typically subject to a one time five percent "cut-to-the aquifer", which is stored water that cannot be recovered. This is a small but important contribution to aquifer storage.

2.3.4. Recovery

Under Arizona state law, the recharge program offers additional flexibility by allowing the withdrawal of stored water to take place in a different area than where the water was recharged. In this respect, Arizona's regulatory system relies on a mass-balance approach; the extensive recharge permitting and monitoring determines the volume of water contributing to the regional aquifer system, and the regulatory accounting then authorizes an equivalent amount of pumping to occur. The "recovered" water may be hydrologically distinct from the recharge activity, but it retains the legal characteristic of the source water that was stored.

Over extended periods of time this hydrologic mismatch can be detrimental, but the regional aquifer systems in the largest AMAs are relatively tolerant of pumping stresses. Moreover, from a policy perspective, allowing this disconnect has facilitated the earlier and more extensive use of renewable water resources than would have occurred with conventional treatment plants and distribution systems.

This same attribute has been a key underpinning of Arizona's Assured Water Supply program, which requires new housing developments to have a secure 100-year supply (which can be groundwater) while also requiring use of renewable supplies (through aquifer recharge).

The underground storage and recovery program established the essential building blocks—the regulatory infrastructure—for putting Arizona's Colorado River entitlement to full use, but that goal would require institutional innovation as well.

2.4. Arizona Water Banking Authority (AWBA)

The AWBA was established in 1996 to mitigate the impacts of Colorado River shortages, to create water management benefits, and to allow interstate storage [12]. However, each of those was in service to a larger policy objective—ensuring the full use of the available CAP supply, and thus Arizona's entitlement to the Colorado River, which was viewed as being at some risk from the neighboring states. Regulations enable California to utilize any Colorado River water not utilized by Arizona, and Nevada was exploring federal action to redress its comparatively small allocation. There was particular concern that the growing demands for water to support growth in these neighboring states would result in an effort to utilize Arizona's apportionment in the long-term. To meet its objectives, the AWBA would have to store several hundred thousand acre feet per year of CAP water that would have otherwise gone unused within Arizona. This task would require both political support and money. The 1996 state legislation establishing the AWBA received broad support [13].

2.4.1. Intrastate

The AWBA's role has grown over time, but its largest responsibility has been to improve the reliability of municipal CAP supplies during periods of extended drought on the Colorado River. The junior priority of the CAP supply leaves the supply susceptible to federally imposed reductions, which are expected to be an increasingly frequent occurrence in the coming decades. The cities in the Phoenix and Tucson metropolitan areas that depend on those supplies have been acutely aware of the risk posed by Colorado River shortages, and they supported the AWBA's goal of firming (increasing the reliability) of their supplies by banking the temporarily available CAP supply. Based on modeling of future Colorado River supplies and demands over a 100-year period, the AWBA set numeric storage targets based on the volume of CAP delivery contracts in each Active Management Area. Those firming targets totaled to more than 4493 MCM (3.643 MAF) (Refer specifically to AWBA Annual Report 2012, Table 5, p. 21.) [14].

In addition to municipal supplies, the AWBA was later given responsibility to firm certain CAP supplies allocated to American Indian tribes and to some western Arizona communities, whose allocations were equivalent to those of the CAP. CAP supplies have been instrumental in the settlement of contested surface water right claims by Native American Nations. Unsettled water rights create uncertainty for both the tribes and the cities, so settlement was a high priority for all parties.

To accomplish these ambitious goals, the AWBA was given access to several sources of funding, including a tax assessed on all property owners in CAP's three-county service area, a fee on groundwater pumping, and legislative appropriations from the state's general fund. Through 2012, the AWBA has expended some $197 million USD from these sources, and holds more than 3947 MCM (3.2 MAF) of long-term storage credits.

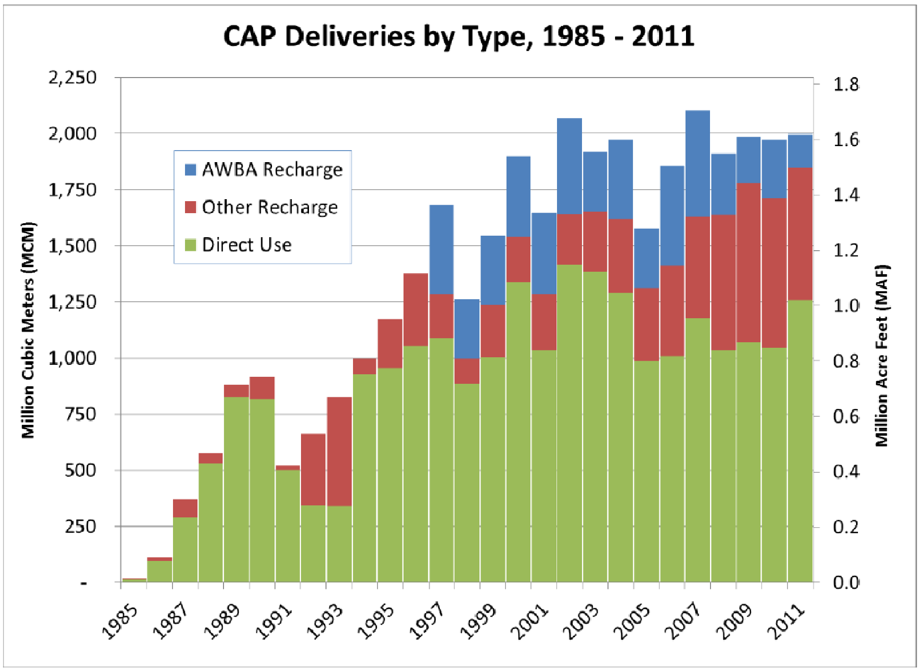
2.4.2. Interstate

The creation of the AWBA helped establish water banking as a major water management strategy within Arizona, but it also allowed for an innovative interstate banking arrangement with the neighboring state of Nevada. The overall program allows Arizona to use a portion of its Colorado River supply for the benefit of Nevada, but without altering the basic framework for how Colorado River water is allocated (the so-called "Law of the River") [15].

Interstate banking between Arizona and Nevada is governed by a series of agreements involving the AWBA, CAP, the federal government and counterparties in Nevada. The storage in Arizona is accomplished in the same manner as the AWBA's other recharge, but the recovery of the stored water is accompanied by an equal reduction in the diversion of Colorado River water into the CAP. That reduced diversion allows Nevada to divert a like amount of water from its upstream diversion point. Once again, it is the existence of an accounting system tied to quantified rights that permits this kind of complex transboundary exchange to take place. The scope of Arizona's interstate agreement with Nevada has undergone a number of revisions, with the most recent change reducing the likelihood that significant additional interstate banking will be undertaken. However, the AWBA has stored more than 740 MCM (0.6 MAF) on behalf of Nevada, at a cost of more than $109 million USD, and Nevada is also obligated to pay the cost associated with the eventual recovery of that stored water.

Figure 3 shows the breakdown of CAP water deliveries over time in acre-feet per year. The blue bar shows deliveries for AWBA storage, and the red shows deliveries for other recharge activities. It demonstrates graphically the critical role Arizona's storage and recovery statutes have played in enabling utilization of Colorado River water delivered through the CAP.

Figure 3. CAP water deliveries by type over time. Source: Central Arizona Project [16].



3. Policy Achievements

Arizona's key policy objective—putting its entire allocation of Colorado River water to use—was first achieved in the year 2000. That benchmark occurred in large measure because of managed aquifer recharge, particularly the storage performed by the AWBA. By taking all of the otherwise unused CAP water, the AWBA helped strengthen Arizona's negotiation position among the Colorado River basin states, particularly with California. Arizona's full utilization also contributed to pressure applied to the federal government to confront long-standing disputes about River accounting and management practices, including changes to the operation of the two largest reservoirs on the Colorado River.

The AWBA has not yet fully achieved all of the storage necessary to satisfy all of its 100-year in-state firming goals, but the overall progress is impressive. In aggregate, 3976 MCM (3.224 MAF) have been stored for intrastate purposes, compared to the target volume of 4493 MCM (3.643 MAF). That 88.5% overall ratio does mask some variation among the goals due to the differing funding sources available for storage. At 45%, the Tucson AMA's firming goal is the furthest from completion because of a comparatively unfavorable ratio of supplies requiring firming to the revenue from local property taxes. While the firming goal is based on a percentage of municipal and industrial water contracts, the revenue available is based on assessed property valuation. Given the costs of recharge and the firming target, the revenues available over the 20-year authorization of the AWBA are not projected to be sufficient to meet the firming goal.

The AWBA is expected to continue to store CAP water for at least the next ten years. The most recent ten-year projection indicates an additional 777 MCM (630,000 AF) of storage, and all of the goals being satisfied, with the exception of the Tucson AMA. During that period the AWBA's largest revenue source—the property tax—is scheduled to end in 2017, and the annual availability of CAP water for the AWBA has been diminishing as long-term CAP contractors have been using a greater portion of their entitlements. In the face of climate change and other supply challenges on the Colorado River, the sufficiency of the existing targets has been called into question, so an upward revision of the targets, along with an extension of funding is under consideration. It should be noted that the AWBA is not the only entity storing water at the several recharge facilities. Therefore, the future status of operations at the recharge facilities used by the AWBA will depend on the storage activities of others, such as holders of long-term contracts for CAP water.

The interstate banking arrangements with Nevada (upstream on the Colorado River) have also been successful, though the benefits are a bit more difficult to quantify. The most frequently cited benefit has been the cooperative spirit it has engendered between the two states, which is not a trivial feat given the potential for conflict over the terms of the Law of the Colorado River. With a much smaller allocation (370 MCM (0.3 MAF) for Nevada *versus* 3454 MCM (2.8 MAF) for Arizona), an explosively growing population, and few water resource options, Nevada's interests had the potential to align with California's in constraining Arizona's Colorado River water use. By storing some of Arizona's water for Nevada's future benefit, the interstate banking program provided a pressure release at a critical point in the changing circumstances on the Colorado River. The most recent modifications to the interstate banking agreements reduce the scale of what had been originally contemplated, but that too is an indicator of the willingness of the parties to reach accommodation as financial and water resource situations have changed.

4. Policy Challenges

The use of managed aquifer recharge has been an important and successful tool for advancing several of Arizona's long-term policy objectives. However, it is predicated on the future ability to recover (pump) the stored water in a manner that is hydrologically and economically feasible and is also consistent with Arizona's regulatory framework. While there had been several modest planning and policy efforts that have attempted to address recovery of the AWBA's stored water, it has taken until 2014 for the parties to release a recovery plan setting out the numerous scenarios and the framework for future recovery of stored water [17].

Recovery of the AWBA's stored water will involve close coordination between the AWBA and Central Arizona Project, along with state regulators and CAP customers who are willing and able to receive a portion of their CAP order in the form of previously stored water (*i.e.*, long-term storage credits earned by the AWBA). There are a number of methods that can be utilized to make these voluntary partnerships work, each of which relies on Arizona's regulatory and accounting system to track the credits and the associated pumping.

Concerns have also been expressed related to the long-term implications of Arizona's underground storage and recovery program. The program offers an important degree of flexibility, but some of that flexibility could be in conflict with sound long-term water management. In particular, the ability to recharge in one place and recover in another could exacerbate areas of localized overdraft. Through the statutorily required Management Plan process, ADWR has recently developed draft concepts that would vary the volume of stored water that is eligible to be recovered, depending on the location of storage and recovery [18]. The status of those specific proposals is unclear at this time, but the intent to examine the longer-term implications of the program is clear. In addition, should surface water for groundwater savings projects no longer be available physically or priced economically, irrigators have the legal right to return to groundwater pumping pursuant to the GMA. This reversion to groundwater pumping has implications for groundwater tables and physical availability of the stored water for recovery by the groundwater savings partners.

5. Possibilities for Water Banking Elsewhere

Experience in Arizona suggests that characteristics favoring water banking for water security include:

- An awareness that augmentation of water resources may be necessary to address groundwater depletion or future water imbalances of supply and demand, particularly those related to climate variability;
- Availability of a source of water that enables intermittent or continuous recharge;
- Favorable hydrogeology—e.g., an extensive, transmissive aquifer with significant storage capacity;
- A well-established regulatory and accounting framework that is adhered to by water users;
- Funding mechanisms to facilitate investment in water banking, water resources planning and management, and monitoring;
- An institutional arrangement that links policy with investment.

While it is desirable for all of these elements to exist, water banking can also be undertaken in places where hydrogeological conditions may be not nearly as favorable as in Arizona.

In many places there is an awareness of groundwater depletion, which is a global problem that has been accelerating [19]. However, water banking is not very common at present, with most managed aquifer recharge currently oriented to short-term storage, which has an early return on investment. Given the value placed on secure water supplies, it is possible to make better use of aquifers through appropriate conjunctive use of surface and groundwater resources, and the long-term banking of water in aquifers that are not exposed to evaporative losses [20].

In the last few decades research on managed aquifer recharge has also shown that water quality improvements occur within the aquifer, and when combined with complementary engineered treatments, as necessary, recovered water can be fit for a full range of uses [21,22]. This has the potential to expand the use of recycled water and urban stormwater as sources for recharge. This demonstrates that sources of water for recharge are more abundant than may be perceived when intermittent excess flows in natural streams were considered the sole untapped resource.

Storing and recovering fresh water in brackish aquifers may offer an additional opportunity for water banking. The generic suitability of brackish aquifers for recovery of stored fresh water using aquifer storage and recovery (ASR), which involves recharge and recovery via the same well, has been evaluated by Ward *et al.* [23]. Miotlinski *et al.* [24] have also demonstrated that if the conditions are favorable, aquifer storage transfer and recovery (recharge and recovery via separate wells) is possible in a brackish aquifer.

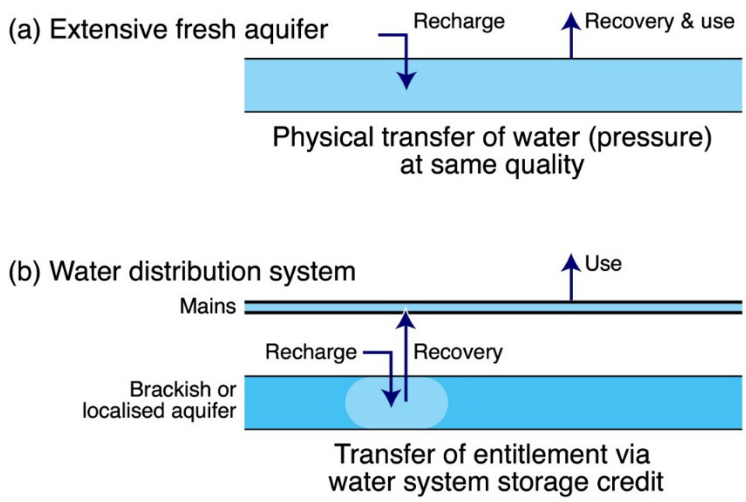
With the exception of hydrogeological conditions, the remaining factors for successful water banking relate to regulation and management.

For those considering the value of water banking and envious of Arizona's favorable hydrogeology and land availability for spreading basins, it should be pointed out that these are desirable, but not essential conditions. For example in the absence of an extensive transmissive aquifer, water may be banked in localized aquifers via a network of smaller recharge facilities connected to an existing water distribution system. In Australia, aside from Perth, few cities have aquifers similar to those of Tucson or Phoenix, but if water can be recovered from local, less transmissive and even brackish aquifers at drinking water quality, then the transmission and distribution system can act as a means to transfer entitlements generated at one place to a user located at another, as illustrated in Figure 4 [25].

Arizona also makes use of alternative forms of recharge, such as vadose zone recharge wells and buried infiltration galleries, in urban areas where land for infiltration basins is not available. One of the most advanced facilities is operated by the City of Scottsdale, which serves 87,000 active accounts within a 480 square kilometer (185 square mile) service area [26]. Scottsdale employs advanced reclaimed water treatment in conjunction with vadose zone injection and ASR wells [27]. ASR wells are used elsewhere in Arizona, and the method is equally suitable for confined aquifer systems, but, because this requires pre-treatment of the water, this is a more costly and less utilized approach [28,29].

In Australia, aquifer storage and recovery with urban storm water in a semi-arid area was found to be about ten times more expensive than the best infiltration basins but still considerably cheaper than seawater desalination [25]. Aquifer storage and recovery of recycled water was more expensive than infiltration basins but had significantly lower unit costs than storm water ASR and may provide material supplies of water for urban areas needing to secure water supplies in confined aquifers, as seen in Orange County, California [30]; Windhoek, Namibia [31]; and Perth, Australia [32]. However, a need for augmentation of water resources does not necessarily assure the existence of funding for water banking. Market failures can arise from poorly defined water rights, institutional fragmentation, incomplete accounting for the costs of evaporative losses from surface water storage, pricing that fails to fully account for supply reliability, a mismatch between the benefits of banking and those who bear the costs, and insufficient public or investor confidence to raise capital for water banking.

Figure 4. (**a**) In Phoenix the extensive fresh aquifer acts as a means to transfer credit from water recharged at one place to recovery at another, subject to water quality constraints; (**b**) Where aquifers are brackish or not highly transmissive, water needs to be recovered close to the point of recharge, and if this water is of suitable quality for transmission through the existing distribution system, this can create a credit that is transferable to other points on the system. Source: Dillon *et al.* [25].



6. Water Rights or Entitlements as a Precursor to Water Banking

In Arizona, the well-developed system of rights to use Colorado River has been key to the establishment of Arizona's water banking program. This system of contractual rights, coupled with a strong regulatory framework for water storage, has enabled successful operation to date of the AWBA. Awareness of the need for separation of entitlements to land and water is a starting point for reform in many parts of the world, including Australia, South Africa and now in at least one state of India, Jammu and Kashmir. The concept of an entitlement is required. In Australia, for example, an entity may hold an entitlement to water as a proportion or share of the total allocatable resource (that is after allowing for environmental flows). Allocations are the volumetric currency of the entitlement, and change if the allocatable resource changes. If the native groundwater system is over-abstracted, storage is in decline. Successive determinations of the allocatable volume will diminish and, in proportion, so will the allocations of all groundwater entitlements holders. In the case of source waters for recharge an entitlement is also required. A framework for incorporating managed aquifer recharge within this entitlement system is given by Ward and Dillon [33]. In Australia, an entitlement system for storm water and treated sewage effluent is not yet in place for most jurisdictions [34] but custodianship of storm water by municipal councils and of recycled water by urban water utilities is acknowledged, and so far dispute has not arisen concerning harvesting of these waters for recharge.

7. Conclusions: Tailoring Water Banking to Local Conditions

Different regions face different hydrological conditions and systems. Arizona has developed an approach to water banking based on its aquifer and surface water supply conditions in the context of its water infrastructure and regulatory framework. Currently, Australian water utilities are tasked with providing for future drought supplies, but there is no policy framework that builds incentives for investment in securing water supplies. During a recent drought, utilities in five cities established seawater desalination plants, most of which have subsequently been mothballed. The capital investment was massive and considerably greater than could have been achieved in most cases with managed aquifer recharge. (An example is described in a companion paper by Gao *et al.* [35].) So far there are no established funding mechanisms to facilitate investment in water banking in Australia. The costs of water delivered by the desalination plants have been more than 15 times higher than the previous marginal costs of supply. This is now being paid for by water utility customers through considerably higher water prices. It is timely, given that emergency supplies are in place for the short to medium term, to consider seriously an institutional arrangement that links policy with investment to ensure efficient achievement of water security objectives. The Arizona Water Bank Authority provides a salutary, and at this stage quite unique, example of institutional and policy reform, that combines an accounting framework and funding mechanisms for supply augmentation to improve the reliability of water supplies in the future. While motivations and potential for water banking will clearly vary across regions, it is hoped that this paper will inspire broad interest in uptake of such advanced groundwater management approaches.

Acknowledgments

The authors would like to thank John Ward of CSIRO and Andrew Ross of the Australian National University, currently with UNESCO-IHP, for comments on an earlier version of this paper the journal's reviewers for helpful comments. We also thank University of Arizona (UA) graduate student Christopher Fullerton for editorial assistance and the UA Technology Research Initiative Fund for supporting this effort.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Megdal, S.B. Arizona's Recharge and Recovery Programs. In *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*; Resources for the Future: Washington, DC, USA, 2007; pp. 188–203.
2. Ronstadt, C.D. Underground Water Banking in the Western United States. *Rocky Mt. Miner. Law Inst.* **2012**, *58*, 1–8.
3. Mackun, P.; Wilson, P. Population Distribution and Change: 2000 to 2010, 2010 Census Briefs. Available online: http://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf (accessed on 24 July 2013).

4. Arizona Department of Water Resources. *The Arizona Water Atlas*; Arizona Department of Water Resources: Phoenix, AZ, USA, 2010.
5. August, J.L., Jr.; Gammage, G., Jr. Shaped by Water: An Arizona Historical Perspective. In *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*; Jacobs, K., Colby, B.G., Eds.; Resources for the Future: Washington, DC, USA, 2007; pp. 1–10.
6. Arizona Department of Water Resources. Arizona Revised Statutes (A.R.S.) Title 45, Chapter 1, Sections 101–117, 2013.
7. Colby, B.G.; Jacobs, K.L.; Eds. *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*; Resources for the Future: Washington, DC, USA, 2007.
8. Megdal, S.B. Arizona Groundwater Management. In *the Water Report*; Moon, D., Light, D., Eds.; Envirotech Publications: Eugene, OR, USA, 2012; pp. 9–15.
9. US Department of the Interior (USDOI). Record of Decision—Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead. Available Online: http://www.usbr.gov/lc/region/programs/strategies.html (accessed on 24 July 2013).
10. Arizona Groundwater Management Act. Arizona Revised Statutes (A.R.S.) Title 45, Chapter 1, Sections 101–117, 2013.
11. Central Arizona Project Tonopah Desert Recharge Project (TDRP). Available online: http://www.cap-az.com/index.php/departments/recharge-program/tonopah-desert (accessed on 24 July 2013).
12. Arizona Water Banking Authority. Arizona Revised Statutes (A.R.S.) Title 45, Chapter 14, Sections 2401–2491, 2013.
13. Pearce, M.J. Balancing Competing Interests: A History of State and Federal Water Laws. In *Arizona Water Policy: Management Innovations in an Urbanizing, Arid Region*; Resources for the Future: Washington, DC, USA, 2007; pp. 26–44.
14. Arizona Water Banking Authority (AWBA). Annual Report, 2012; Available online: http://www.azwaterbank.gov/Plans_and_Reports_Documents/documents/Final2012AnnualReport wletter.pdf (accessed on 24 July 2013).
15. U.S. Bureau of Reclamation (USBOR). The Law of the River. Available online: http://www.usbr.gov/lc/region/g1000/lawofrvr.html (accessed on 24 July 2013).
16. Central Arizona Project CAP Deliveries. Available online: http://www.cap-az.com/index.php/ departments/water-operations/deliveries (accessed on 16 February 2014).
17. Arizona Water Banking Authority; Arizona Department of Water Resources; Central Arizona Project. Recovery of Water Stored by the Arizona Water Banking Authority: A Joint Plan by AWBA, ADWR and CAP, 2014. Available Online: http://www.cap-az.com/documents/ planning/Joint_Recovery_Plan_FINAL_with_signed_preface.pdf (accessed on 18 May 2014).
18. Arizona Department of Water Resources Enhanced Aquifer Management Stakeholder Group. Available online: http://www.azwater.gov/azdwr/WaterManagement/AMAs/EnhancedAquifer ManagementStakeholderGroup.htm (accessed on 16 February 2014).
19. Konikow, L.F. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys. Res. Lett.* **2011**, *38*, doi:10.1029/2011GL048604.
20. Dillon, P.; Fernandez, E.E.; Tuinhof, A. Management of aquifer recharge and discharge processes and aquifer storage equilibrium. *IAH Contrib. GEF-FAO Groundw. Gov. Themat. Pap.* **2012**, *4*, 1–49.

21. Kazner, C.; Wintgens, T.; Dillon, P.; Eds. *Water Reclamation Technologies for Safe Managed Aquifer Recharge*; IWA Publishing: London, UK, 2012.
22. Vanderzalm, J.; Sidhu, J.; Bekele, G.-G.; Pavelic, P.; Toze, S.; Dillon, P.; Kookana, R.; Hanna, J.; Barry, K.; Yu, X.; *et al*. *Water Quality Changes During Aquifer Storage and Recovery*; Water Research Foundation: Denver, CO, USA, 2009.
23. Ward, J.D.; Simmons, C.T.; Dillon, P.J.; Pavelic, P. Integrated assessment of lateral flow, density effects and dispersion in aquifer storage and recovery. *J. Hydrol.* **2009**, *370*, 83–99.
24. Miotlinski, K.; Dillon, P.J.; Barry, K.E.; Kremer, S.; Pavelic, P. Recovery of injected freshwater from a brackish aquifer with a multi-well system. *Ground Water* **2013**, doi:10.1111/gwat.12089.
25. Dillon, P.; Pavelic, P.; Page, D.; Beringen, H.; Ward, J. *Managed Aquifer Recharge: An Introduction*; Waterlines Report No. 13; National Water Commission: Canberra, Australia, 2009.
26. City of Scottsdale Water Resources Department About the Water Department. Available online: http://www.scottsdaleaz.gov/Water/about? (accessed on 24 July 2013).
27. City of Scottsdale Water Resources Department Adequate Water Supply and Water Supply Planning (WSP). Available online: http://www.scottsdaleaz.gov/Water/Water_Supply_Planning/Sustainable_Supply/ (accessed on 24 July 2013).
28. Arizona Department of Environmental Quality (ADEQ) Reclaimed Water Regulations and Aquifer Protection Permits. Available online: http://www.azdeq.gov/environ/water/permits/reclaimed.html (accessed on 24 July 2013).
29. Arizona Department of Water Resources (ADWR) Groundwater Recharge Regulations. Available online: http://www.azwater.gov/azdwr/WaterManagement/ (accessed on 24 July 2013).
30. Mills, W.R. The quest for water through artificial recharge and wastewater recycling. In *Management of Aquifer Recharge for Sustainability*; Dillon, P.J., Ed.; A.A. Balkema: Amsterdam, The Netherlands, 2002; pp. 3–10.
31. Murray, E.C. Windhoek, Namibia: Designing a large-scale borehole injection scheme in a fractured aquifer. In Proceedings of the International Symposium on Mixed and Augmented Reality, ISMAR *2005*, Vienna, Austria, 5–8 October 2005; pp. 127–132.
32. Water Corporation. Water forever—Whatever the weather: Drought Proofing Perth. Available Online: http://www.watercorporation.com.au/~/media/files/about%20us/planning%20for%20the%20future/perth-10-year-water-supply-strategy.pdf (accessed on 22 May 2014).
33. Ward, J.; Dillon, P. Principles to coordinate managed aquifer recharge with natural resource management policies in Australia. *Hydrogeol. J.* **2012**, *20*, 943–956.
34. Parsons, S.; Dillon, P.; Irvine, E.; Holland, G.; Kaufman, C. *Progress in Managed Aquifer Recharge in Australia*; Waterlines Report Series No. 73; National Water Commission: Canberra, Australia, 2012.
35. Gao, L.; Connor, J.D.; Dillon, P. The economics of groundwater replenishment for reliable urban water supply. *Water* **2014**, *6*, submitted for publication.