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Tapped out: how can cities secure their water future?

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Abstract

Cities around the world are struggling to access additional water supplies to support their continued growth because their freshwater sources are becoming exhausted. Half of all cities with populations greater than 100,000 are located in water-scarce basins, and in these basins agricultural water consumption accounts for more than 90% of all freshwater depletions. In this paper we review the water development histories of four major cities: Adelaide, Phoenix, San Antonio and San Diego. We identify a similar pattern of water development in these cities, which begins with the exhaustion of local surface and groundwater supplies, continues with importation of water from other basins, and then turns to recycling of wastewater or stormwater, or desalination of either seawater or brackish groundwater. Demand management through water conservation has mitigated, to varying degrees, the timing of water-system expansions and the extent to which cities rely on new sources of supply. This typical water development pattern in cities is undesirable from a sustainability perspective, as it is usually associated with serious ecological and social impacts as well as sub-optimal cost effectiveness. We highlight case examples and opportunities to invest in water conservation measures, particularly through urban–rural partnerships under which cities work with farmers to implement irrigation conservation measures, thereby freeing up water for ecological restoration and use by cities.

Keywords: Aquifer depletion; Desalination; Inter-basin transfers; Irrigation efficiency; River drying; Urban–rural partnerships; Urban water supply; Water conservation; Water scarcity

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Introduction

The freshwater sources (rivers, lakes or aquifers) vital to many cities around the world are running dry. More water is being removed from these water sources on an ongoing basis than is being delivered by precipitation, runoff and recharge. With little water left to support further urban growth, cities are struggling to secure additional water supplies.

Water use in cities and on farms has increased considerably over time. Historically, both urban and agricultural water planners have given much greater attention to accessing more water (i.e., supply management) rather than to limiting water use (demand management), even in drier regions with scarce water supplies. Little effort has been given to 'capping' water demands; instead, water use has expanded to the point that many freshwater sources are now heavily depleted (Postel & Richter, 2003). As a result, large rivers such as the Colorado, Yellow and Murray–Darling are now regularly running dry, and aquifers including the Ogallala in the USA, the Hai Basin in northern China, and the Upper Ganges in India and Pakistan have been heavily drained, particularly in arid and semi-arid regions (Gleeson *et al*., 2012; Scanlon *et al*., 2012; Wada *et al*., 2012; see Figure 1).

Global water use is expected to increase, particularly in cities. The global population has more than doubled over the past 60 years and it is rapidly urbanizing. In 1950, less than one-third of the population was urban; today, more than half of the world's inhabitants (including more than 80% of the US population) live in cities (United Nations, 2010). Small towns have burgeoned into cities and large cities have grown into mega-cities. At the global level, water use in cities has increased five-fold since 1950, reflecting not just urban population growth but also increasing per capita water use in many regions (Shiklomanov, 2000; World Economic Forum, 2009; FAO, 2012). Trends in a few industrialized nations such as the USA run counter to global trends. In these countries, considerable progress has been made in recent decades in controlling increases in urban water demands, primarily by reducing water use in thermoelectric power generation and other industrial processes (Kenny *et al*., 2009).

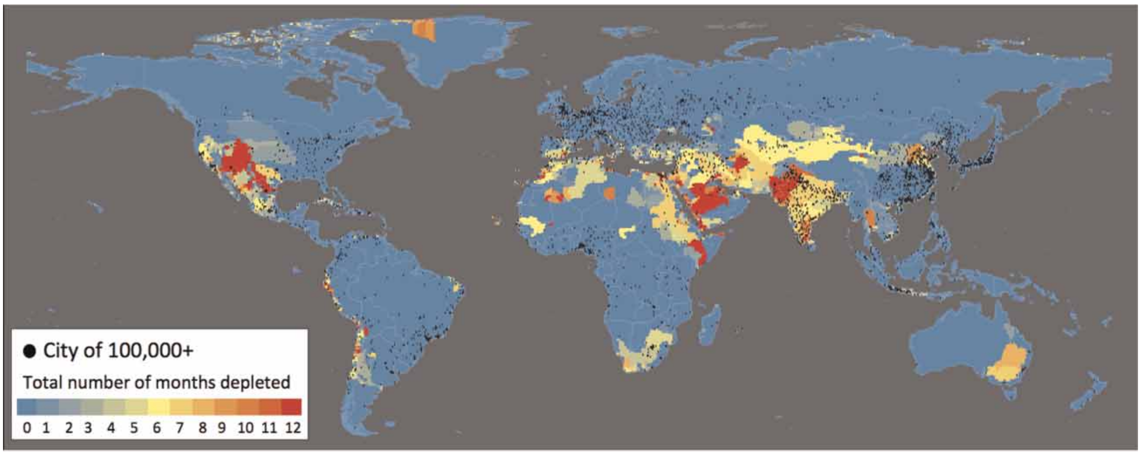

Fig. 1. Monthly water depletion. Half of all cities with populations >100,000 are located in water basins in which more than half of available water supplies are being depleted during some portion of the year. (*Source*: Hunger & Döll, 2008).

Water withdrawals, consumption and scarcity

Globally, water scarcity is expanding and intensifying. 'Water scarcity' as used here means the depletion of freshwater sources, reducing the volume of water remaining for further human use and ecosystem support. Depletion of a water source results from water consumption, resulting when some portion of the water taken from a freshwater source is not returned after use, thereby depleting the source (as differentiated from water withdrawal, which accounts for water removed without consideration of any that might be returned). Consumptive use also results when withdrawn water is returned to a source different to that from which it was withdrawn, thereby depleting the original source and often augmenting the receiving water body. For example, when groundwater is pumped for urban use it is almost always returned to surface water bodies, causing depletion of the source aquifer. Return flows may also be heavily polluted, exacerbating water scarcity.

Much of the water used for domestic and industrial purposes is eventually returned to a water body, e.g., toilets are flushed and cooling water in thermoelectric power plants is returned to rivers. Because much of this water is not consumed, efforts to reduce urban water use or recycle water usually make little difference in alleviating water scarcity. In total, the domestic, industrial and energy sectors account for less than 10% of global water consumption (Döll, 2009; Wada *et al.*, 2011; Hoekstra & Mekonnen, 2012).

Agricultural irrigation, in which more than half of withdrawn water is consumed (Shiklomanov, 2000), is the dominant cause of water depletions and scarcity, accounting for more than 90% of all water consumption globally. The global expansion and intensification of water scarcity since 1950 has predominantly been driven by increases in agricultural irrigation. During this period, the consumption of water globally for irrigation has tripled in volume, a trend that played a large role in enabling food production to more than double over the same period (IWMI, 2007). This growth in irrigation was facilitated by the construction of large water storage reservoirs, the availability of industrial-scale groundwater pumps, and government price subsidies for water and for electricity to pump water.

The strong influence of irrigated agriculture on water scarcity can be illustrated by looking at water consumption in the basins where medium- to large-sized cities are located. About 25% of the more than 1,200 water basins evaluated by Hunger & Döll (2008) experience water depletions greater than 50% in at least 1 month of the year (i.e., total water consumption divided by available water flows is >50%). However, of all cities with populations greater than 100,000, more than half are situated in these water-scarce basins (CIESEN, 2012), since most cities are located in regions where considerable irrigation is used for food production. As illustrated in Figure 2, more than 90% of the water consumed in water-scarce basins containing cities with at least 100,000 residents goes to agricultural irrigation, consistent with the global depletion levels noted above.

The fact that agriculture accounts for such a large proportion of water consumption does not absolve cities from responsibility for water scarcity. Based on population distribution, we would expect that at least half of all agricultural production is consumed in cities; some recent research suggests that it might be closer to two-thirds (Blackhurst *et al.*, 2010). We contend that cities must begin playing a much larger and broader role in resolving water scarcity issues for two primary reasons:

1. The water supply options available to at least half of all cities are being seriously constrained by agriculture's heavy depletion of freshwater sources. As a result, many of these cities are experiencing regular shortages, leading to water restrictions and cutoffs, disruptions in industrial production and

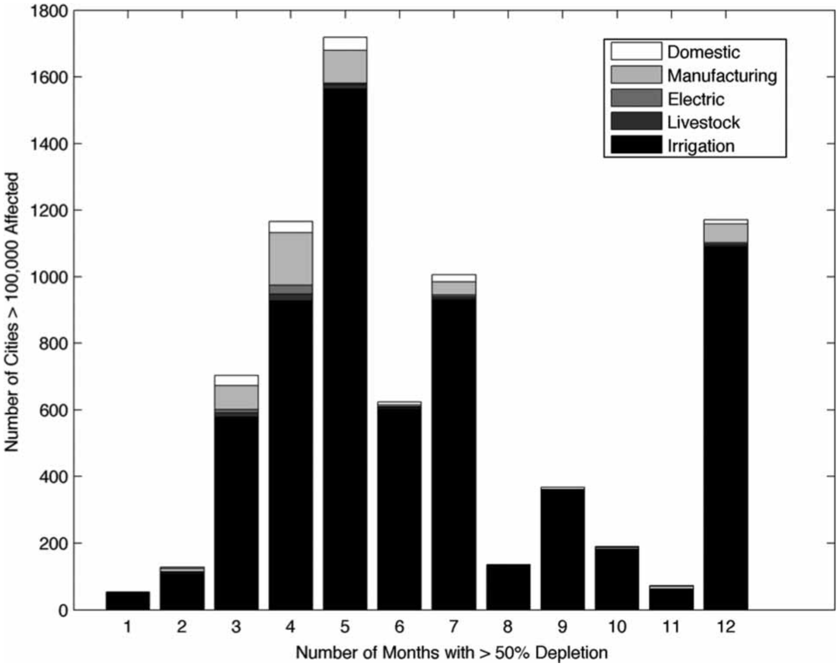

Fig. 2. Agricultural water consumption is a dominant cause of water depletions in basins that contain cities with populations of at least 100,000 and experiencing at least 1 month of water depletion greater than 50%. Each bar is segmented according to the percentage of water depletion attributable to each water use sector. (*Source*: Hunger & Döll, 2008).

electricity blackouts caused by the shortage of water to cool thermoelectric power plants or spin hydropower turbines – all of which translate into economic impacts.[1] With little fresh water left in their local water basins, cities have turned to other more expensive and energy-intensive water-supply options such as importing water from other basins or desalinating ocean water.

2. Cities are directly dependent upon agriculture for their sustenance.

Trends in urban water development

In this paper we describe the growth history of four cities located in water-scarce regions, with emphasis placed on the development of their water-supply systems. From our study of these cities (and the cursory review of many others, including those in Molle & Berkoff (2006)), we recognize a similar pattern of expansion in urban water supply systems that begins with the exploitation of local freshwater sources, continues with the importing of water from other basins, and then turns to recycling of wastewater or stormwater, or desalination of either seawater or brackish groundwater. Demand management through water conservation has mitigated, to varying degrees, the timing of water system expansions and the degree to which cities rely on new sources of supply.

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[1] See Nature Conservancy (2012) for a summary of the economic impacts of water scarcity.

This repeating pattern of urban water development has many negative consequences, as illustrated by our case studies. The substantial exploitation of freshwater sources – a result of growing urban demands on top of heavy agricultural use – has caused severe ecological damage, impaired ecosystem services and created health problems (Hundley, 2001; Fitzhugh & Richter, 2004; Forslund *et al.*, 2009). Groundwater depletion has led to increased electricity costs for pumping and to socio-economic disruption (Foster *et al.*, 2007; Scanlon *et al.*, 2012; Wada *et al.*, 2012). When cities extend their reach into other basins to access water supplies, they spread negative impacts over great distances. Energy-intensive technologies such as recycling and desalination are expensive, resulting in higher water bills for consumers as well as increased carbon emissions that accelerate climate change (Gober, 2010). Clearly, these environmental, social and economic impacts are unsustainable. With the pace of global urbanization quickening, new approaches to securing urban water supplies are urgently needed.

Fostering urban–rural partnerships

The inter-connectedness and dependency of cities on agriculture is the basis for the conclusions and recommendations put forward in this paper. A major conclusion is that considerable untapped potential exists for cities to form partnerships with agricultural water users to reduce water consumption on farms, thereby freeing up additional water supply for urban use while potentially reducing the water-related costs of farming, as well as farming's vulnerability to water shortages. Considerable precedence exists for such urban–rural collaboration, e.g., through 'payments for environmental services' (PES) that compensate rural communities for providing water benefits to urban or corporate interests (Dudley & Stolton, 2003). However, most such PES schemes to date have been focused on improving water quality rather than improving water availability.

Our analysis suggests that urban–rural partnerships can be a highly cost-effective water-supply strategy for both cities and farms, with long-term savings for cities accruing from reduced infrastructure construction costs and energy use when compared to other water-supply options such as inter-basin imports or desalination. Promising opportunities exist to free up the water presently used in agriculture through techniques such as reducing unproductive water consumption (e.g., through canal leakage, soil and reservoir evaporation), changing crop types, introducing rotational fallowing, temporary fallowing during droughts, or the elimination of low-value farming. While we acknowledge the many challenges inherent in this agricultural conservation strategy, we also highlight case studies in which this strategy has been successfully deployed.

A tale of four cities

In selecting cities for our analysis, we began by examining cities that are located in water basins with heavy levels of water depletion according to Figure 1. We selected four cities for deeper analysis: Adelaide, located just outside but dependent upon the Murray–Darling River basin of Australia; and three cities in the USA: Phoenix, located in the Gila River basin in Arizona; San Antonio, dependent on the Edwards Aquifer in Texas; and San Diego, which relies upon the San Diego, Colorado and Sacramento river basins in California. Each of these cities taps groundwater as well as river flow. Intentionally, we did not select for geographic, cultural, legal or economic diversity in our case studies; instead, we looked for cities that are well advanced in their struggles to secure additional water supplies. The water histories of these cities provide valuable lessons and cautions for other cities that are facing water scarcity due to either their location in naturally dry regions or very heavy levels of water depletion in their local basins.

Adelaide, Australia

Local sources. Europeans established the city of Adelaide along the River Torrens in the 1830s. As the city grew, nine water storage reservoirs were built in local watersheds from 1860 to 1977 (see Figures 3 and 4). Additionally, local groundwater sources became increasingly important, beginning in the 1950s but, as aquifer levels began declining shortly thereafter, it became clear that groundwater sources would yield only limited water supplies (Government of South Australia, 2011).

Water importation. Adelaide tapped into a major new source of water supply in 1955 with an inter-basin pipeline from the Murray–Darling River. It was followed with a second pipeline in 1973, substantially increasing the city's dependence on the Murray–Darling. Today, the city relies on these inter-basin imports for 40–90% of its supply, with greater dependence during dry years (Government of South Australia, 2005).

However, the Murray–Darling's ability to provide for Adelaide and other settlements is limited by the fact that river flows are heavily depleted by irrigated agriculture. Agricultural diversions began to take a heavy toll on the flow of the Murray–Darling as early as the 1880s (Sim & Muller, 2004; Sennett *et al*., 2012). It is estimated that average outflows of the river to the ocean have decreased by more than 60%, and the river now fails to reach the sea 40% of the time (Pincock, 2010). Less than 10% of water

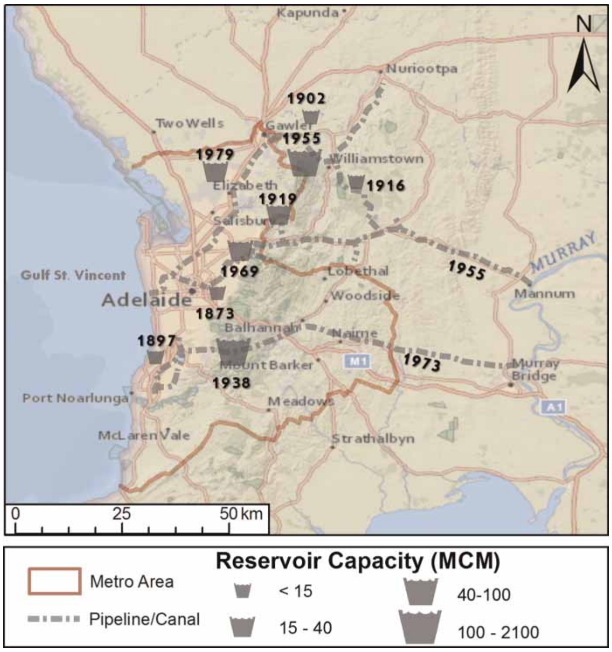

Fig. 3. Adelaide's water supply system includes nine storage reservoirs built between 1873 and 1979, along with two water importation canals from the Murray–Darling River. (*Source*: Government of South Australia, 2012).

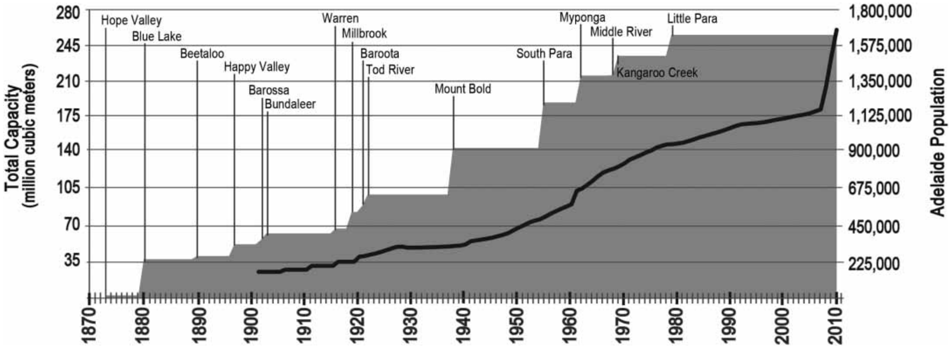

Fig. 4. Population growth and increases in storage capacity in Adelaide. Adelaide has added reservoir storage (shaded area) as a primary strategy to meet the growing water demands associated with population increases (line). Note that while the metro area's population has increased substantially in recent decades, no additional reservoir storage has been added. (*Sources*: Reservoir data from Government of South Australia (2012); population data from Australian Bureau of Statistics (2010)).

depletions in the basin are attributable to inter-basin exports; agriculture is responsible for more than 80% of depletions in the basin, primarily for growing rice, cotton, wheat and fodder crops for dairy cattle (Australian Bureau of Statistics, 2010).

South-eastern Australia experienced a severe drought from 1998 to 2010, placing great strain on all users of the Murray–Darling's waters and causing considerable ecological harm. Twenty of 23 sub-watersheds in the basin are in 'poor' to 'very poor' ecological health, and toxic blue-green algae blooms have occurred repeatedly in the basin (MDBA, 2010). Excessive levels of water depletion have not only dewatered aquatic systems but also caused elevated salinity and acidification (Pittock *et al*., 2010). Important habitats such as river red gum forests have declined substantially, and reduced reproduction of iconic species such as the Murray cod (Australia's largest freshwater fish) has been of great concern.

In response to the drought and ecosystem impacts, a comprehensive draft Basin Plan was prepared by the Murray–Darling Basin Authority in 2010, calling for a 20% reduction in irrigated agriculture. The plan estimated that such a reduction would result in a loss of AUS$800 million in annual agricultural revenues (MBDA, 2010; but note that these estimates of economic impact have been hotly contested, e.g., by Grafton, 2011). The plan has been met with hostility in the agricultural community, stalling its implementation. The Authority's process has been criticized by some observers as a 'top-down experts-know-best approach to resolving environmental damage' that failed across the board to engage relevant stakeholders – environmentalists, irrigators, scientists and politicians (Sennett *et al*., 2012).

Water conservation. Adelaide has reduced its water use by 25% since 2003 by implementing water conservation measures (Government of South Australia, 2010). These water savings were largely achieved by reducing landscape watering around homes and businesses. The city estimates that water conservation measures will further reduce their 2025 demands by 8% (Government of South Australia, 2010).

Water recycling and desalination. As a result of increasing uncertainty in water imports from the Murray–Darling basin, the city of Adelaide is now turning toward water recycling and desalination to supplement its water supply in coming decades (Figure 5; Government of South Australia, 2010). The city is investing AUS\$1.8 billion (1.8×10^9) on a new desalination plant that will provide more than 25% of the city's water supply by 2013. The plant will run entirely on renewable energy from wind, solar and geothermal sources. The use of desalination will also enable the city to reduce its dependence on Murray–Darling imports from an average of 44% of its supply to 27% (Figure 5).

However, the high cost of Adelaide's water supply plans is posing a serious challenge for city residents because water prices have risen more than 400% in Adelaide since 2007, in large part due to the cost of the desalination plant (Martin & McGregor, 2011). About 15% of households in Adelaide are reported to be struggling to pay their utility bills.

Costs of future supply options. As illustrated in Figure 6, Adelaide has considered a broad range of future options with widely varying cost effectiveness, including the possibility of importing water from basins other than the Murray–Darling. The city's water supply plans are consistent with cost effectiveness to a large degree, given the emphasis on water recycling of both wastewater and stormwater. However, the city's investment in desalination is much more expensive than other available options.

While the city's decision to transition to desalination and recycling is causing water bills to increase substantially, it is important to view this transition from the perspective of long-term resource sustainability. Rarely has any city addressed the ecological and energy implications of its water supply options to the degree demonstrated in Adelaide; in this context, the environmental benefits of relieving pressure on the Murray–Darling River and the use of renewable energy to power the Adelaide desalination plant are quite notable.

However, the city's water supply plans do not yet appear to give agricultural water conservation sufficient attention. Fully 75% of all water used in South Australia goes to agriculture, including 14% of use in Greater Adelaide itself (Government of South Australia, 2010). Hence, agricultural water

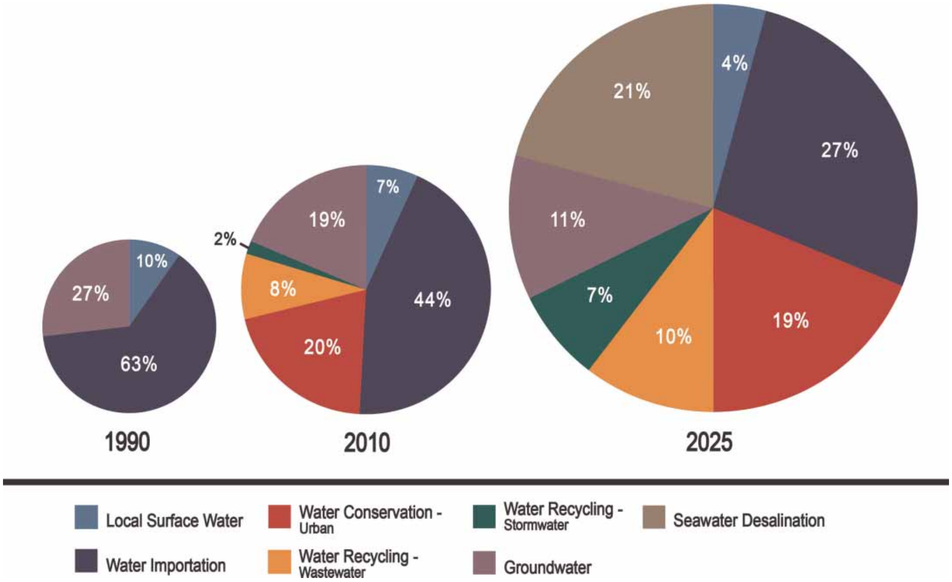

Fig. 5. Trends in water supply sources, Adelaide metropolitan area. (*Source*: Government of South Australia, 2010).

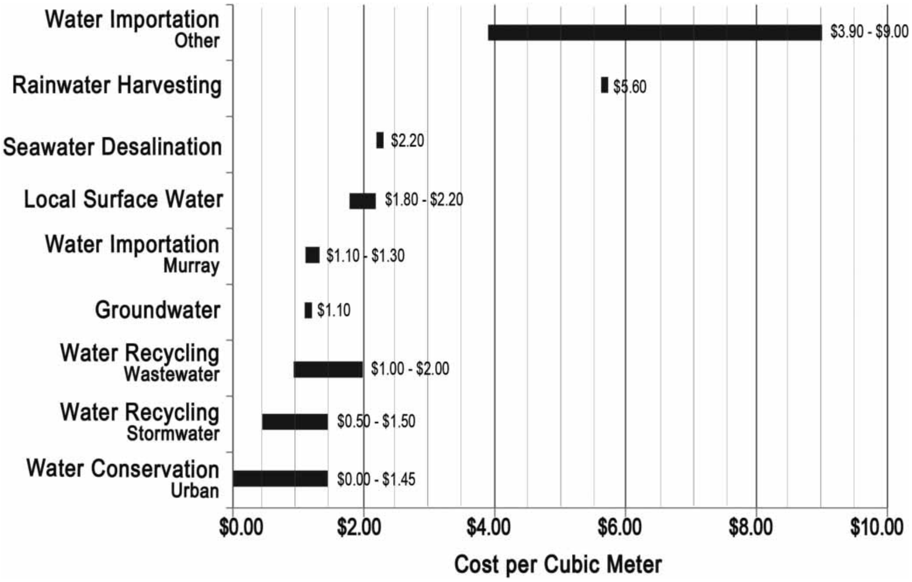

Fig. 6. Cost of future water supply options for Adelaide. (*Source*: Government of South Australia, 2005).

conservation appears to be a potential source of additional water supply for this area. In a comprehensive financial assessment of the Australian water sector in 2006, analysts observed that 'despite the availability of low-cost water in the major irrigation centres, water trading has not occurred with urban areas in most cases' (Marsden Jacob Associates, 2006).

Phoenix, Arizona

Local sources. When farmers of European descent first settled in the Gila River valley of central Arizona in the 1860s, they found extensive marshes and floodplain forests along the Gila River and its tributaries, including the Salt and Verde rivers (Rea, 1983). They also found an extensive system of irrigation canals built hundreds of years earlier by the Hohokam people, who disappeared from the area around 1450 AD (City of Phoenix, 2008). The Hohokam used stone and wooden tools to build more than 800 km of irrigation ditches that sustained a population of almost 50,000 for hundreds of years. The system was, in fact, the largest prehistoric irrigation system in North America (Roberge, 2002). The reactivation of the Hohokam ditches after 400 years of non-use inspired the city's naming as Phoenix, after the mythological bird that arose again from its ashes (Luckingham, 1989).

Industrious settlers quickly expanded the irrigation system of the valley with small dams and canals and planted water-intensive crops such as corn, barley and wheat (Luckingham, 1989; McNamee, 1994). Their diversions of water soon dried the Gila River completely during the growing season, a situation that largely persists to this day, except in reaches that are sustained by discharges from wastewater treatment plants or agricultural drainage.

The city of Phoenix was officially incorporated in 1871 with a population of 1,700 residents. The city was described as 'an oasis' known for 'eight months of heaven', but an undependable water supply and searing summer heat also meant 'four months of hell' (Salt River Project, 2012a). Substantial relief came in the form of the US National Reclamation Act of 1902, which provided federal loans for water projects. Local land owners collectively used their land as collateral to obtain a loan to build Roosevelt Dam on the Salt River, a Gila tributary, in 1911 (Figure 7).

After Roosevelt Dam was built, agriculture flourished in the Salt and Gila valleys (Autobee, 2009). By the 1920s, three additional dams were built downstream of Roosevelt Dam to increase water storage and electricity production (Salt River Project, 2012a). Two additional dams were built on the Verde River, another tributary to the Gila, in the 1930s and 1940s.

With a bolstered water supply and the arrival of air conditioning in the 1950s, the population of the Phoenix metropolitan area skyrocketed (Autobee, 2009; Figure 8). Competition between the city and farmers for limited water supplies continued to intensify. Speaking in 1987 on behalf of city dwellers, a vocal critic said: 'Agriculture is a dead industry in Arizona, kept alive only by government subsidies paid to grow surplus, water-intensive crops, such as cotton. Eliminate the subsidies, and Arizona could begin to solve her water problems' (Autobee, 2009).

The availability of industrial-scale groundwater pumps after World War II enabled farmers to shift toward increased use of groundwater. But as groundwater levels dropped by more than 100 m during the latter half of the 20th century (Schumann *et al*., 1986), the state government placed restrictions on groundwater use in 1980, thereby constraining its availability. Groundwater overdraft was reduced by 40% from 1985 to 1995. The state has set a goal of stabilizing aquifer levels by 2025 (Larson *et al*., 2009), requiring further reductions in pumping.

Arizona ranks first among US states in the proportion of native freshwater species at risk of extinction, and the early drying of the Gila and the damming of its tributaries were certainly major contributors

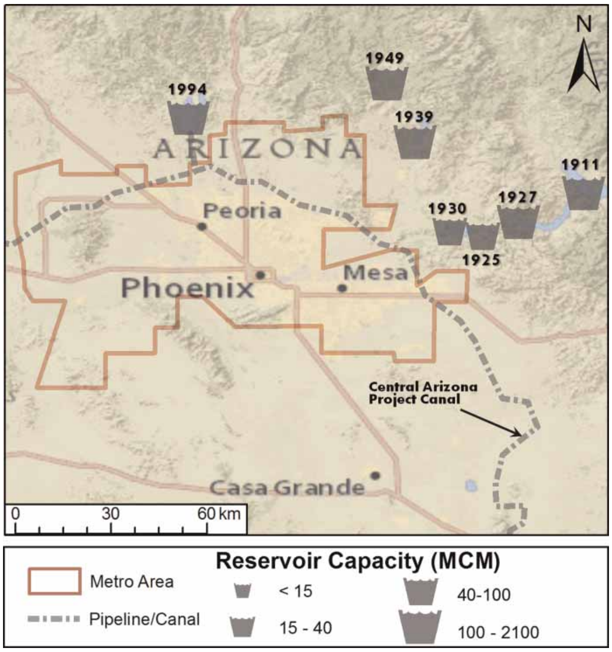

Fig. 7. The Phoenix metropolitan area's water supply system includes seven storage reservoirs, constructed between 1911 and 1994, as well as a major diversion from the Colorado River through the Central Arizona Project (CAP). (*Source*: Salt River Project, 2012b).

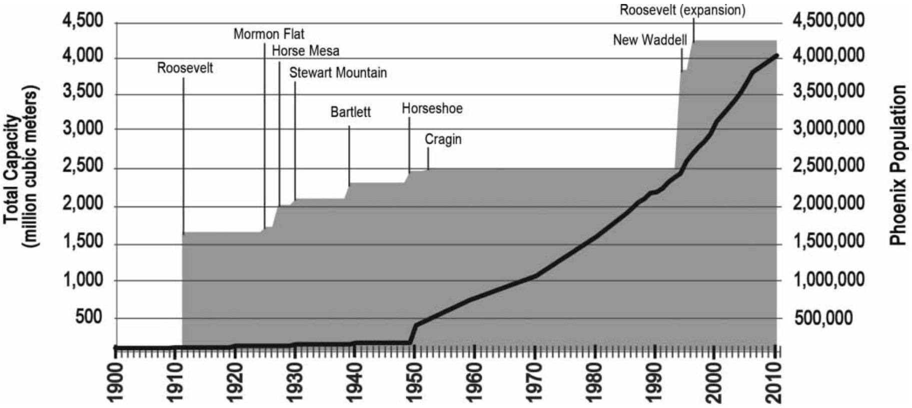

Fig. 8. Population growth and increases in storage capacity in Phoenix. As the population of the Phoenix metro area (line) grew during the past century, reservoir storage (shaded area) became a primary strategy for meeting growing water demands. No new reservoirs have been built since 1994, and none are planned. (*Source*: Salt River Project, 2012b).

to species imperilment (Nadeau & Medgal, 2011). The Colorado pikeminnow (*Ptychocheilus lucius)*, a predatory fish that once grew to 2 m in length and 90 kilograms in weight, was so abundant in the Gila and Salt valleys in the early 20th century that farmers had to pitchfork them out of irrigation canals to keep the canals from overflowing. Pikeminnow are now extinct in Arizona (Minckley, 1973; Postel & Richter, 2003). Groundwater declines in the Gila valley led to the replacement of riparian trees with desert shrubs and the extirpation of 29 bird species (Rea, 1983).

Water conservation. The Phoenix metro area's water situation benefitted considerably from the initial replacement of farms with housing developments during the city's post-World War II population boom because farms commonly use twice as much water per unit of area as housing does (Hirt *et al*., 2008). In the 1950s alone, more than 13,000 hectares of irrigated land was converted into residential or commercial use (Luckingham, 1989).

The city of Phoenix has been able to lower its per capita water use by 25% since 1990 through various water conservation measures (City of Phoenix, 2011). At least half of urban water use goes to outdoor landscaping (Baker *et al*., 2004; Gammage *et al*., 2011). The use of water for landscape irrigation in this desert region largely explains why per capita use in the metro area is at least one-third higher than the national average (Walton, 2010; Gammage *et al*., 2011). Clearly, opportunities exist to further reduce this aspect of urban water demand.

Agriculture continues to use more than one-third of all water consumed in the Phoenix metro area (ADWR, 2011), down from two-thirds in 1985. Within the Gila River basin as a whole, agricultural water consumption remains quite dominant, accounting for 72% of all depletions of surface and groundwater (US Bureau of Reclamation, 2004). Because of the ongoing groundwater overdraft in the Phoenix metro area, mandatory water allocation targets have been set by the state, based on irrigation efficiencies of 70–80% (ADWR, 2008). However, the low irrigation efficiencies in the upper Gila basin (ADWR, 2006) suggest considerable potential for water savings upstream of Phoenix that could benefit downstream users and river health, if water savings could be dedicated to instream flow and if Phoenix can secure rights to this water at a downstream location.

Water importation. As local water sources became increasingly strained in the mid-20th century, city leaders and farmers began to look to the Colorado River for additional water supply. After decades of intense lobbying in the US Congress, a huge new water importation project tapping into the Colorado was authorized in 1968, and the first water deliveries arrived in Phoenix in 1985 (Zuniga, 2000). The 528 km aqueduct known as the Central Arizona Project (CAP) was built at a cost of US$4.4 billion ($4.4 \times 10^9$), making it the most expensive water delivery project in American history (Hirt *et al.*, 2008). Much of the justification for the CAP was to provide farmers with a new source of water and thereby alleviate the overdraft of local groundwater sources. Urban critics of the project, concerned with its heavy price tag, called it a 'massive agribusiness handout' (Luckingham, 1989). But the CAP has proven to be an essential source of water for the rapidly growing metro area, providing more than one-quarter of the Phoenix area's water supply today (ADWR, 2011).

Phoenix's reach into the Colorado River further depleted a river with very little left to give (Figure 9). The river's delta began drying as early as the 1950s and water has flowed to the river's delta only episodically since that time, resulting in the reduction of the delta's wetland area by more than 90% (Cohen *et al*., 2001). Agriculture accounts for nearly 50% of depletions from the Colorado River. While the Salt and Gila rivers are tributaries to the Colorado (and thus the CAP is technically not an export of water from the larger Colorado basin), more than one-third of the Colorado's water flow is exported outside of the basin, including a portion to San Diego (discussed below; US Bureau of Reclamation, 2004).

Water recycling. Reclaimed wastewater provides 6% of the Phoenix metro area's water supply today (Figure 10), and is becoming a larger portion of the water supply mix over time. Reclaimed water is used for agricultural purposes, cooling of power plants and for the irrigation of urban landscape areas (City of Phoenix, 2007).

Costs of future supply options. Future growth in the Phoenix metro area will be supported by increased use of local surface and groundwater supplies as well as additional imports from the Colorado River (Figure 10). The city has projected that it will be able to continue using groundwater sources because it has been injecting under-utilized CAP water into the local aquifer systems (Gammage *et al*., 2011).

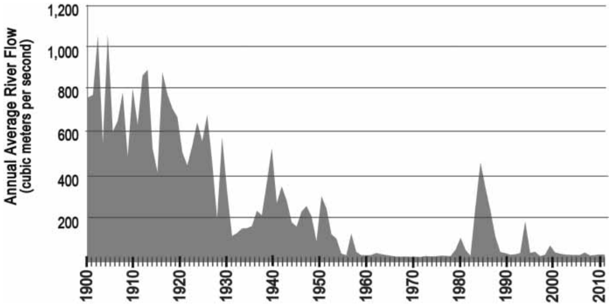

Fig. 9. River flows in the lower Colorado River have declined substantially since the completion of Lake Mead (Hoover Dam) in 1928. Other large structures built on the river include Flaming Gorge Reservoir and Dam in 1962 and Lake Powell (Glen Canyon Dam) in 1963. Large diversion canals depleting the river's flow were completed in 1940 (All-American Canal), 1941 (Colorado River Aqueduct) and in 1985 (Central Arizona Project). (*Source*: Data from US Geological Survey, Colorado River near Yuma; US Geological Survey (2012a)).

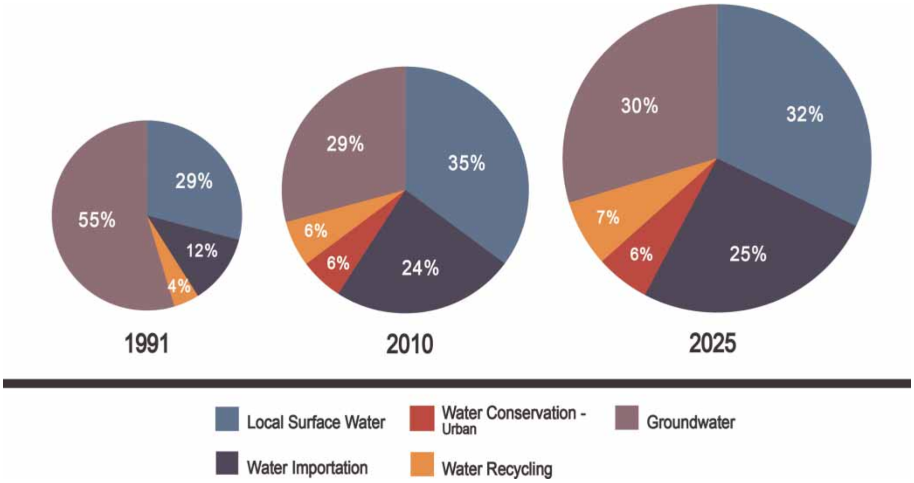

Fig. 10. Trends in water supply sources for the Phoenix metro area. (*Source*: ADWR, 2012).

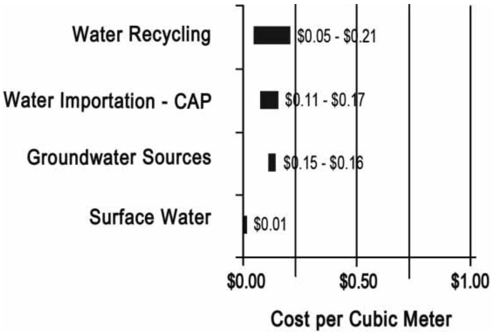

Fig. 11. Cost of future water supply options for Phoenix. (*Source*: City of Phoenix, 2011, 2012).

While a focus on increased water recycling is very important from a sustainability perspective, the metro area's reliance on imports from the Colorado River continues to grow, along with the ecological and energy impacts associated with these imports. Increased use of CAP water is attractive from a cost perspective (Figure 11) but other sustainability considerations would suggest a need for greater emphasis on local water sources, such as water conservation (both urban and agricultural) and recycling.

San Antonio, Texas

Local sources. San Antonio was named by a Spanish expeditionary party in 1691 while camping beside a crystal-clear spring that bubbled effusively from a limestone rock formation, later known as the Edwards Aquifer. This site had been occupied by Native Americans for more than 11,000 years. The Spanish did not settle in the area until 1720, when a mission was established.

The Spanish missionaries and their native labourers immediately began excavating an extensive system of irrigation canals, diverting water from the San Antonio Springs and nearby San Pedro Springs. The water flowed pure and clear, steady throughout the year. This water distribution system served as

San Antonio's water supply for almost 200 years. In early years it powered waterworks and mills, fed irrigation ditches, provided drinking water, helped fight fires and carried sewage downstream (Eckhardt, 2012a).

By 1890, numerous wells had been drilled into the Edwards Aquifer around San Antonio and, soon thereafter, the city began to rely on wells rather than the ditch system for its water supply. The city grew rapidly throughout the 20th century, averaging 36% growth in population per decade (Figure 12; US Department of Congress, 1990). Aquifer pumping rates quintupled from the 1930s to the late 1980s (Votteler, 2004; Figure 12), causing aquifer levels to drop precipitously during dry periods and causing spring flows to decline. During a severe drought in 1956, the springs dried up completely.

Pumping from the Edwards Aquifer increased in a largely uncontrolled manner until 1993 when a management entity called the Edwards Aquifer Authority was created. This authority was established in response to a federal lawsuit brought against the US Fish and Wildlife Service for failing to protect endangered species living in the aquifer and springs (Votteler, 2004). The court decision forced the state of Texas to limit aquifer withdrawals and guarantee minimum spring flows to protect imperilled species. The aquifer harbours a remarkable diversity of species, including blind, colourless catfish and salamanders found nowhere else (Longley, 1981).

With the creation of the Edwards Aquifer Authority, water allocation permits were issued to water users, limiting the volume of their use. Because these permits can be sold or leased, an active water market has developed. This market has created a strong stimulus for investment in water conservation because any water saved can be sold to other water users.

The Edwards Aquifer remained the sole source of water for San Antonio until 2000. Since then, the city has begun purchasing aquifer permits or leases from farmers and other aquifer users. It has also been investing in other water supplies such as, in 2002, tapping into another aquifer (the Trinity) and, beginning in 2006, importing water from an existing reservoir on the Guadalupe River.

Water conservation. San Antonio is widely known for its world-class urban water conservation efforts (SAWS, 2012a). In 1984, city residents were using 850 litres per person each day but, by 2007, that

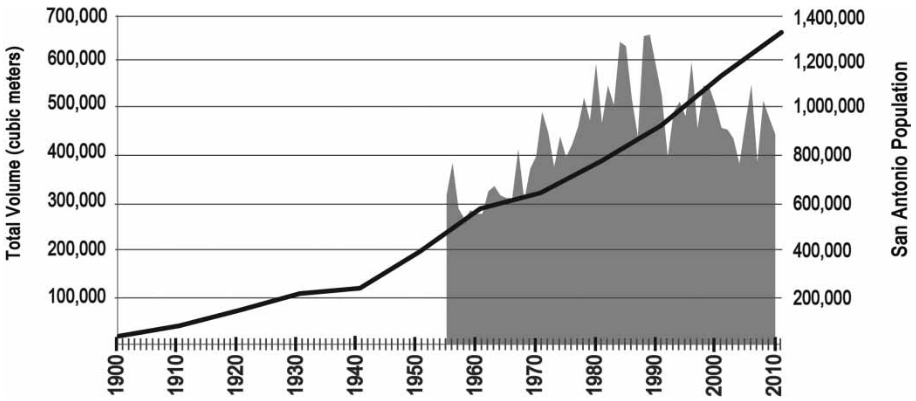

Fig. 12. Population growth and aquifer pumping volumes in San Antonio. Pumping from the Edwards Aquifer (shaded area) increased as the San Antonio metro area's population grew (line) until the 1990s, when pumping restrictions, water conservation and use of other water sources began to limit use of the aquifer. Note that Edwards Aquifer pumping has declined since 1990, even while population increased substantially. (*Source*: US Geological Survey, 2012b).

usage had been cut to 435 litres per day (i.e., nearly a 50% reduction), resulting in a substantial decrease in total aquifer pumping (Figure 12).

Since 1999, San Antonio has leased or purchased water rights from farmers who use the Edwards Aquifer. When the Edwards Aquifer Authority was created, farmers were granted rights to use approximately 6,000 m^3 of water per hectare each year. Half of each farmer's water allocation can be sold to other users if a farmer does not need it, providing considerable incentive for agricultural water conservation. The San Antonio Water System (SAWS) has purchased or leased more than 84 million m^3 of water from farmers, amounting to more than 10% of its total water supply (SAWS (2012c): personal communication). In addition, SAWS has invested in irrigation efficiency measures on the farms it owns.

These urban and agricultural water conservation programs have in large part enabled the city to keep its water prices among the lowest 10% of those in US cities (Growing Blue, 2012). There is clear potential to do more, however, particularly with agricultural water use: irrigation accounts for 25–33% of all Edwards Aquifer use during dry years (Eckhardt, 2012b) and agriculture accounts for 45% of all water use in the South Central Texas Region (SCTRWPG, 2010).

Water recycling. San Antonio has a long history of wastewater recycling. The city began applying raw sewage to farm fields as early as 1894. San Antonio's first wastewater treatment plant was built in the 1930s, enabling treated water to be applied to a growing area of farmland. The city pioneered the use of recycled water to cool power plants in the 1960s. In 2000, SAWS completed construction of the nation's largest recycled water distribution system. It supplies non-potable water equal to 20% of the volume that the city pumps from the Edwards Aquifer.

San Antonio also completed an 'aquifer storage and recovery' project in 2004 that enables the city to more fully utilize its water rights in the Edwards Aquifer by injecting surplus groundwater pumpage into another aquifer for storage. This facility proved its usefulness during droughts in 2006, 2008 and 2011 when water deposited in the storage and recovery aquifer was used instead of Edwards Aquifer water, thereby protecting Edwards spring flows for endangered species. The storage and recovery facility currently provides 16% of the city's water supply (Figure 13).

Costs of future supply options. San Antonio's population is expected to continue growing rapidly in coming decades. To meet the needs for more water, the city has plans to invest in groundwater importation from the nearby Carrizo Aquifer, and is considering desalination of both brackish groundwater and seawater. As illustrated in Figure 14, these new water sources are likely to cost much more than urban or agricultural conservation on a per-unit basis (SCTRWPG, 2010). Aquifer storage and recovery, while relatively expensive, is proving to be a highly effective strategy for drought management.

San Diego, California

Local sources. Spanish missionaries established their first California mission in San Diego in 1769 and immediately began growing crops in the fertile San Diego River valley using hand-dug wells in the river's floodplain. A small diversion dam was built in 1816 to deliver water from the river to the expanding mission population. By the early 1900s, six additional reservoirs had been built to serve the 18,000 residents of the growing city and farms in the river valley (Hill, 2002).

By 1950, the metro area had grown to 557,000 residents (an increase of 500% in just 20 years) and its population growth rate showed no signs of slowing (Sholders, 2002; Figure 15). During the latter half of

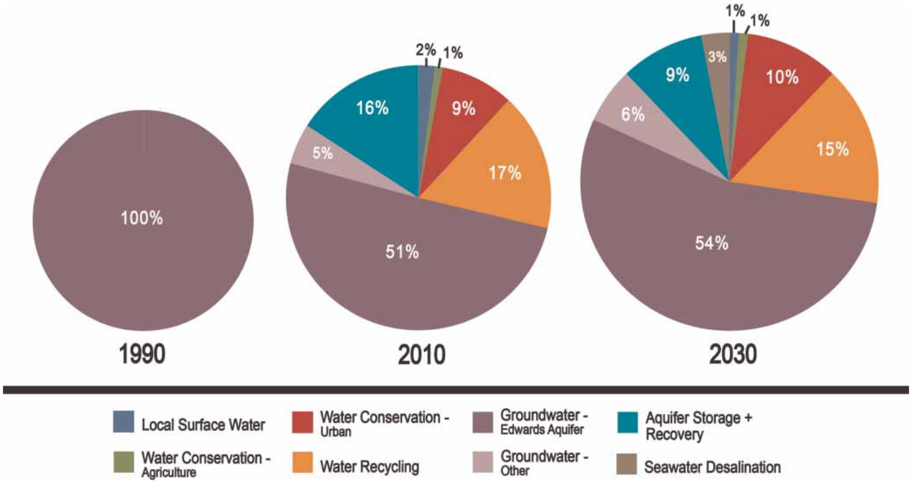

Fig. 13. Trends in San Antonio water supply sources over time. Note the diversification of sources, particularly the shift from 100% reliance on the Edwards Aquifer (through to 2000) to the aquifer providing only half of the city's water supplies today. (*Sources*: SCTRWPG, 2010; San Antonio Water System, 2012b).

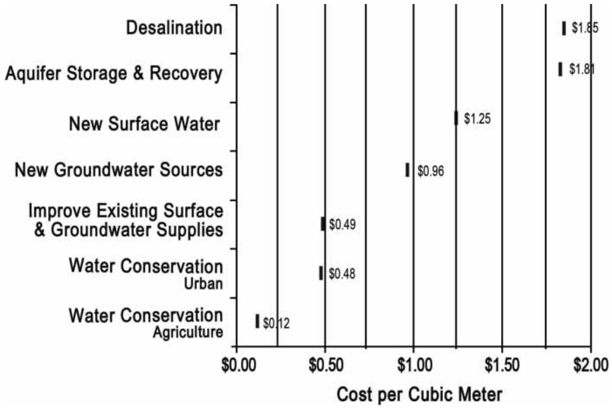

Fig. 14. Cost of future water supply options for San Antonio. (*Source*: SCTRWPG, 2010).

the 20th century, San Diego fully developed its local water resources, including both groundwater and rivers, by constructing dams on virtually all rivers in the area and tapping into multiple local aquifers (see Figure 16).

Water importation. The city experienced a severe drought from 1900 to 1916. The city's managers were so desperate that they offered US$10,000 to a local rainmaker named Charles Hatfield (said to be experienced in the use of 'strange and secret vapors') if he could cause enough rain to fill the city's water reservoirs (Hill, 2002). Unsatisfied with his results, the city council began looking hundreds of kilometres eastward to the Colorado River, and in 1926 authorized construction of a canal from the river to San Diego (Sholders, 2002).

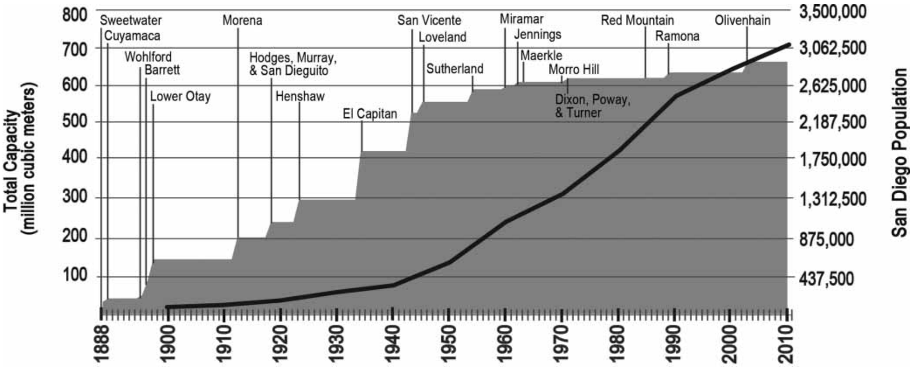

Fig. 15. Population growth and increases in storage capacity in San Diego. The construction of water storage reservoirs (shaded area) has been a primary water supply strategy for meeting the water demands of the San Diego metro area's growing population (line) since 1896. Very little additional reservoir storage has been added since the 1940s, when water importation from the Colorado River began. (*Sources*: Population data from San Diego History Center (2012); reservoir data from SDCWA (2012c)).

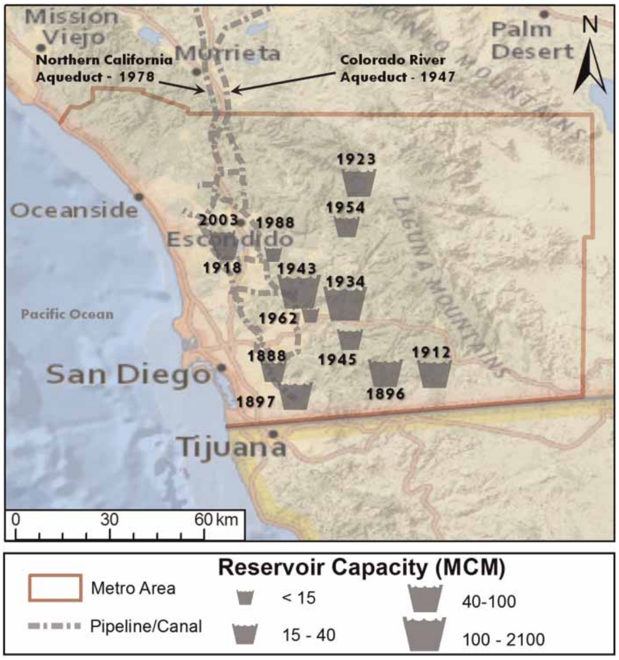

Fig. 16. The San Diego water supply system includes thirteen storage reservoirs as well as two major water importation projects, including one from the Colorado River and one from rivers in northern California. (*Source*: SDCWA, 2012c).

However, World War II disrupted construction plans for the aqueduct even while San Diego's population swelled to serve a naval base and other war-related industries and housing projects, consuming more than half of the city's available water supply (Sholders, 2002). Aided by an emergency Act of Congress, the Colorado River Aqueduct finally began delivering water to San Diego in 1947.

The city's population boom continued after the war, necessitating another inter-basin import of water. This time the water came from northern California's Feather, American and Sacramento Rivers as part of the State Water Project, completed in 1978. By 1991, 95% of the city's water supply was imported. Today, because of the addition of other water sources described below, imported water comprises 80% of the metro area's supply (Figure 17).

As discussed previously in the Phoenix case study, cumulative water extractions from the Colorado have severely depleted that river and caused serious ecological damage. The Northern California rivers that supply the State Water Project have been similarly compromised, impacting the Sacramento–San Joaquin Delta and contributing to a pronounced decline in salmon populations in those rivers (Fitzhugh & Richter, 2004).

Water conservation. Urban water conservation has been a normal part of the lives of San Diegans since water-saving measures were put in place during a severe drought in the early 1990s. Today, urban water conservation accounts for 11% of the city's supply and this figure is expected to grow to 14% by 2020 (Figure 17; SDCWA, 2012a).

In 2008, the state of California mandated a 30% water-use reduction for all agricultural water users reliant upon the State Water Project. Some San Diego metro area growers went out of business completely and others implemented conservation measures that resulted in a 55% reduction in agricultural use within 3 years, equivalent to an 8% reduction in the area's overall water use (SDCWA, 2011). As a result of urban and agricultural water conservation measures, consumer response to increased water pricing and other factors, San Diego's water use in 2010 was approximately the same as in 1995, while its population had grown by 440,000.

In 1998, the city negotiated a Water Conservation and Transfer Agreement with the Imperial Irrigation District that has become the largest rural-to-urban water transfer in US history (SDWCA, 2011). Beginning in 2003, farmers in the irrigation district have been compensated for implementing agricultural water conservation measures to free up water that is then transferred by canal to San Diego. The volume of savings is projected to increase over time, from 12 million m^3 in 2003 to 247 million m^3 by

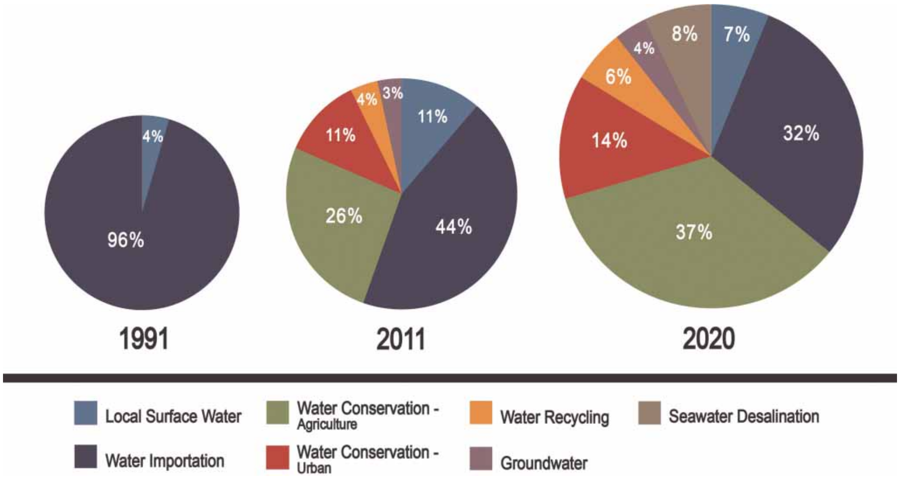

Fig. 17. Trends in San Diego water supply sources. Note that water conservation, both agricultural and urban, will account for more than half of water supply by 2020. (*Source*: San Diego County Water Authority, 2011).

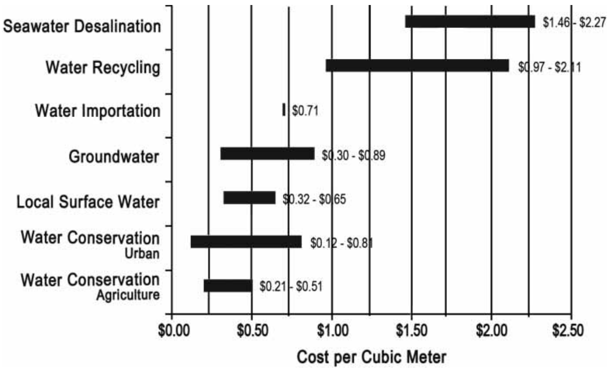

Fig. 18. Costs of future water supply options, San Diego. (*Source*: Fermanian Business & Economic Institute, 2010).

2021. A subsequent agreement involves lining two major irrigation canals to reduce leakage, enabling an additional annual transfer of 96 million m^3. Together, these agricultural conservation measures will provide 37% of city water supply by 2020 (Figure 17; SDCWA, 2011).

Similar approaches may be available to the city within its own home basin. Nearly 30% of all water depletions in the San Diego River basin go to irrigated agriculture (Solley *et al*., 1998).

Water recycling. The city first began producing recycled water for landscape and golf course use from its wastewater treatment plants in 1997. Recycling now provides 4% of water supply, with plans to increase to 6% by 2020 (SDCWA, 2012b).

Desalination. In an effort to further diversify its water sources, San Diego is now building two seawater desalination plants. These facilities are expected to provide 7% of the city's water supply by 2020.

Costs of future supply options. San Diego's future water supply plans (Figure 17) depend heavily upon water conservation, both in urban water use and in agriculture through the agreement with the Imperial Irrigation District. These water conservation strategies will account for more than 50% of planned water supply increases by 2020, making the city a global leader in using conservation as a source of urban water supply (SDCWA, 2011). As illustrated by Figure 18, these are highly cost-effective investments (FBEI, 2010). On the other hand, nearly 20% of future supply will come from desalination, which is the most expensive source available. The risks of climate change and associated projected shortfalls in imports from both northern California and the Colorado River are clearly influencing these water supply decisions (SDCWA, 2011). Any efforts to reduce the pressure on these water imports will bring ecological, energy and social benefits as well.

Case study summary

Our review of city water supply systems suggests a fairly similar history of water development. This history has been strongly influenced by changing technological capabilities over time; aqueducts for moving water from one place to another and storage reservoirs have been built for more than 5,000 years but the advanced industrial processes required to safely recycle or desalinate large volumes of water have only recently become available. The per-unit cost of water has also been a primary factor in setting priorities among water supply options.

Water conservation stands out as a striking anomaly in the history of urban water development. Frugality in water use is as old as human history, yet it was not broadly adopted as a primary urban water strategy until the 1970s and 1980s, when water-efficient indoor plumbing fixtures and water-saving irrigation technologies became widely available and cost effective. Similarly, technologies and practices for irrigation efficiency have improved considerably in recent decades. The adoption of both urban and agricultural water conservation remains highly variable, however. Most cities in the world have not taken the steps that San Diego and San Antonio have to either implement water conservation measures or integrate conservation into their planning for the coming decades. As a result, cities are causing unnecessary ecological and social problems while incurring higher than necessary costs that are passed along to consumers.

We have summarized the water development history of the four cities reviewed in this paper in Figure 19. This pattern suggests a fairly common history:

- Cities initially tap their local water supplies until they become exhausted. We found numerous cases in which a city shifted from groundwater to surface water (or vice-versa) as their first source became heavily depleted from combined agricultural and urban use. Construction of reservoirs has been important in enabling cities to more fully exploit local surface water supplies.
- Cities next turn to inter-basin imports of water. Toward the end of the 20th century, such water imports began to be scrutinized more heavily for their environmental and social impacts as well as their cost, providing a stimulus for cities to turn to water conservation instead of adding new imports.
- Cities then begin implementing water conservation. Many cities began conserving water in earnest by the 1980s, with growing attention and investment in recent decades.
- Cities next implement water recycling. Recycling of wastewater or stormwater became a notable portion of urban water supplies beginning in the 1990s, and its use is expanding rapidly.
- The use of desalination is still quite limited (serving less than 1% of global water consumption) but growing. Its use is hampered by its high relative cost to other water supply options due to energy requirements but, as cities are faced with limits to water importation, desalination is becoming a viable option.

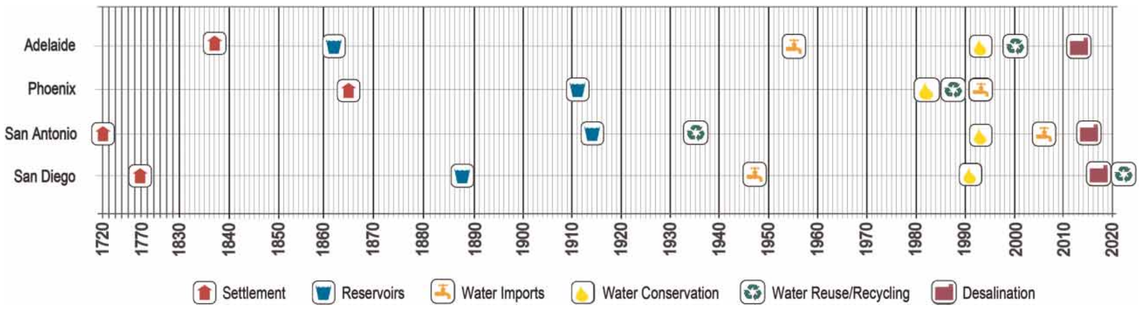

Fig. 19. The water development history of each of the cities reviewed in this paper differ to some degree, but general trends can be seen across them that indicate early investment in developing local water sources, followed by water importation, water conservation and recycling, and in some cases, desalination.

Our review of future water supply plans in our four case study cities suggests another important trend: a return to local water options. Water importation is rapidly losing its appeal both because it is expensive to move water over long distances (owing to high energy costs) and because other basins are also experiencing water scarcity. It is clear that continuing to search for a distant oasis is simply not a sustainable strategy from economic, social and environmental perspectives (Fitzhugh & Richter, 2004).

Our review revealed substantial cost savings (typically 50% but often much more) associated with conservation strategies, as compared to other local supply options (see case studies and Table 1). Options such as wastewater recycling and desalination involve long-term energy costs that are expected to become ever-more expensive in coming decades (FBEI, 2010). Despite the cost and energy savings associated with water conservation, cities have only begun to tap its potential.

Table 1. Cost comparisons of water supply options; negative values represent net cost savings.

	US$ per m^3
Texas water planning regions (16 plans)[1]	
Desalination: seawater	0.85–1.85
Desalination: brackish	0.28–0.62
Water importation	1.06–1.91
Water recycling	0.03–0.77
Groundwater wells	0.02–1.06
Surface water reservoirs	0.33
Urban water conservation	0.04–0.46
Industrial water conservation	0.17
Golf course water conservation	0.23
Agricultural irrigation efficiency	0.02–0.18
Reduced leakage irrigation canals	0.01
Lower Colorado River Authority[2]	
Desalination: seawater	2.34
Desalination: brackish	0.91
Surface water reservoir	1.99
Dredge existing reservoirs	13.79–213.30
Water importation (surface and ground)	0.97–1.54
Groundwater wells and storage/recovery	0.96–1.81
Water recycling: wastewater	0.36
Urban water conservation	0.36
Agricultural water conservation	0.11–0.15
Transfer/conversion of agricultural rights to urban	0.02–0.04
Brush management	0.01–0.23
Southern California water strategies[3]	
Desalination: seawater	0.81
Desalination: groundwater	0.61–0.97
Agriculture to urban water transfers	0.57
Water recycling	0.81
Surface water storage	0.62–1.14

(*Continued.*)

Table 1. (*Continued.*)

	US$ per m^3
Groundwater storage	0.47
Local stormwater capture	0.28
Urban water conservation	0.17
Charting our water future[4]	
Desalination (reverse osmosis)	0.76
Rainwater harvesting: agricultural	0.38
Removal of alien vegetation	0.36
On-farm canal lining	0.07
Municipal leakage repair	−0.28– + 0.16
Water importation	0.07–0.50
Deep groundwater	0.06–0.08
Municipal reservoirs	0.06–0.19
Large infrastructure	0.04
Shallow groundwater	0.04
Wastewater reuse	0.04–0.35
Artificial recharge	0.04–0.14
Sprinkler irrigation	0.04–0.22
Small-scale irrigation infrastructure	0.03
Irrigation scheduling	−0.10– + 0.01
Drip irrigation	0.01–0.05
Industrial conservation	−0.01
Reduced over-irrigation	−0.02
No-till farming	−0.10– − 0.05
Efficient faucets (domestic)	−0.46– − 0.10
Efficient showerheads (domestic)	−0.60– −0.25
Industrial reuse	−0.5

[1] *Source*: Texas Water Development Board (2012).
[2] *Source*: LCRA Water Supply Resource Plan (2010).
[3] *Source*: Los Angeles County Economic Development Corporation (2008).
[4] *Source*: 2030 Water Resources Group (2009); includes assessments for India, China, Brazil, South Africa.

Our review suggests that the first place to look for water savings is in irrigation, both urban and agricultural. For example, Adelaide, San Diego and Phoenix continue to use more than 50% of their water to irrigate landscape areas and golf courses (Government of South Australia, 2010; Gammage *et al.*, 2011; SDCWA, 2011). These cities can look to San Antonio, which had cut its outdoor use by 30% by 1995, or the Irvine Ranch Water District in California, which cut its outdoor use by 46% from 1992 to 2004 (McCormick & Walker, 2010).

The promise of urban–rural partnerships

Our study highlights the reality that many growing cities are badly in need of new, low-cost and reliable sources of water. These water needs will intensify as the global population exceeds 9 billion

(9×10^9) by 2050, with 70% of that population residing in cities (United Nations, 2010). Meeting these water needs will become ever-more challenging as agricultural production doubles by 2050 to feed the growing global population (IWMI, 2007).

Yet cities need more than water, and many of the goods on which they depend come from the same farms that drive water scarcity. This inter-dependency between cities and farms suggests considerable opportunity and rationale for cities to form water partnerships with farmers, to the benefit of both parties. If cities could help farmers consume less water, this could free up a new source of water supply for the city while potentially improving the price and reliability of agricultural products (Ward & King, 1998; Gober, 2010). In this light, collaborative stakeholder and governance processes that facilitate an informed, exploratory dialogue about the economic and cultural values attached to water, and opportunities to re-allocate water use in the basin, can improve understanding of the needs of various water users (both urban and rural), as well as opportunities to optimize the shared values of water.

This urban–rural strategy is promising for numerous reasons:

- First, water shortages are having huge ecological, social and economic impacts. Because agriculture is by far the biggest water consumer, any attempts to reduce water scarcity-related impacts *must* address agricultural water use. Only in rare instances can water scarcity within a basin be alleviated to any measurable degree through non-agricultural water strategies. This is a reality that governments and cities must come to grips with immediately.
- Second, it may be possible to increase farm productivity – important to global food security – through the use of more efficient irrigation technologies, due to more precise water and fertilizer application, while avoiding increases in water consumption (see for example IWMI, 2007; Dunn *et al.*, 2010; Dixon *et al.*, 2011).
- Third, cities can provide new sources of funding to incentivize or compensate farmers for making investments in water savings. Farmers are often reluctant to invest in agricultural conservation measures – even with the prospects for productivity increases and reduced water costs – because the associated cost–benefit ratios and payback periods are in many instances insufficient to compel farmers to invest in them *en masse*. Cities can help tip this balance.
- Fourth, when agricultural water conservation takes place upstream of cities, the water savings that remain in a river *en route* to downstream urban areas will directly benefit ecological health, ecosystem services and recreational opportunities.
- Finally, cities stand to save money because investing in agricultural water conservation can be a highly cost-effective strategy for securing new water sources.

There are formidable hurdles to forming urban–rural partnerships (see Table 2), but the payoff is too big to ignore: in many basins, a reduction of agricultural consumption of just 15–20% can yield a substantial volume of water; at the global level, this level of reduction in agricultural water consumption would make more water available than all the water consumed in cities and industries today. We use the phrase 'urban–rural partnerships' here because successful negotiation of agreements among farmers and cities will require considerable mutual trust and respect if hurdles such as those listed in Table 2 are to be avoided or minimized. Undoubtedly, the existence of a mature water market, such as exists in Australia's Murray–Darling basin or in the Edwards Aquifer of Texas, would greatly facilitate both temporary and permanent trading of water among all users (Productivity Commission, 2010) but, in the absence of formal markets, these urban–rural exchanges will necessarily be more collaborative in nature.

Table 2. Examples of hurdles that can complicate water trading between cities and farms.

Cities may not be situated downstream or even proximate to agricultural areas, making it difficult or costly to deliver any saved water to a city. It is crucial to ensure that any water saved on farms can actually be delivered to the point of urban use.
When water rights or permits are not sufficiently well defined, the rights of farmers or cities to negotiate a transfer will be very difficult, if not impossible. On the other hand, even when rights are well defined, other legal impediments may limit the ability to transfer water or to ascertain the amount that can be transferred. Of particular concern is the possibility that other water users will intercept the saved water before it reaches the city, even when such use is not consistent with legal allocation rights and priorities.
Water savings from reduced agricultural consumption can be difficult to quantify and deliver to cities, and over-counting of savings potential has been commonplace (IWMI, 2007; Foster & Perry, 2010). As with all PES schemes, ensuring the actual delivery of the assumed quantity of benefits is of utmost importance. With respect to agricultural water conservation, the transaction must be based on a reduction in consumptive agricultural use, not water withdrawals (Gleick *et al.*, 2011).
Regulatory agencies are less comfortable with urban investments in agricultural water conservation as a secure source of supply, making approval of water supply plans more difficult or time-consuming.
Farmers may be hesitant to share or sell water to cities, fearing that cities have the power to simply take water from farmers once they begin to view agricultural water as a new source of supply.
Because water costs to farmers have been heavily subsidized in many countries, many policy analysts believe that farmers should be required to make water efficiency improvements without additional compensation (see for example Productivity Commission, 2010; Pittock, 2011).
Because many farmers have already invested in water-saving measures, it is unfair to reward ‘laggards’ with financial support or exclude earlier adopters from receiving compensation from cities.
Water leakage or runoff from farms may be supporting important habitats or other human uses, which can be compromised when more efficient farm practices are implemented or leakage is curtailed.
Climate change may cause irrigation demands to increase in the future, reducing savings associated with agricultural conservation measures. Care must be taken to ensure that farmers retain sufficient water allocation to maintain full productivity, even during droughts.

There are many rich and pertinent lessons to be learned from the case studies in this paper, as well as others such as those summarized in Table 3. While each of our four case study cities have engaged in rural-to-urban transfers of water to varying degrees, the urban–rural relationships in three of our cities began not as a mutually-rewarding partnership but instead as an acrimonious ‘arranged marriage’ facilitated by federal governments. In both the USA and Australia, the states generally hold primary authority over water allocations except in the case of inter-state basin disputes or endangered species concerns. San Diego’s relationship with the Imperial Irrigation District took form under pressure from the US Federal Government, which directed the state of California to reduce the amount of Colorado River water the state was using so that California’s use of the river would come into alignment with the seven-state Colorado River Compact. Because San Diego would no longer be able to import the same volume of Colorado River water, the city was highly motivated to work out a water conservation deal with the Imperial Irrigation District. San Antonio’s ability to negotiate water transfers with agricultural users was facilitated by a federal court decision mandating that the state of Texas regulate use of the Edwards Aquifer through the issuance of groundwater permits (because of endangered species concerns), which then became a tradable commodity that enabled San Antonio to purchase water permits from farmers.

In both California and Texas, the agricultural community was initially quite hostile to increased regulation of water use, federal intervention and the transfer of water to cities which had long competed with farmers for water supplies. Over time, those hostilities have waned, in large part because the

Table 3. Examples of urban–rural water transfers.

San Diego – Imperial Irrigation District, California	In 1998, the San Diego County Water Authority entered into a 'Water Conservation and Transfer Agreement' with the Imperial Irrigation District. Under this agreement, the irrigation district has since implemented a variety of conservation measures including rotational fallowing, irrigation efficiency measures and canal lining, and has transferred the rights to use the saved water to San Diego. These agricultural water conservation measures will provide nearly 40% of the city's water supply by 2020 (SDCWA, 2011).
Zhanghe Irrigation District, Hubei Province, China	Water allocations to agriculture were decreased by two-thirds from the late 1970s to mid-1990s in order to provide more water for domestic and industrial (including hydropower) uses. By implementing new irrigation techniques, farmers were able to double crop yield per hectare and triple the yield per m^3 of water, resulting in net increases in agricultural production (Hong *et al*., 2001).
Murray–Darling River Basin, Australia	Since 2007, the 'Restoring the Balance' programme in the basin has resulted in more than 4,100 water trades between the Australian Government (for environmental flow restoration) and agricultural water rights holders (Australian Government, 2012). These transactions have restored more than 990 million m^3 of river flow per year at a cost ranging from US\$0.17 to 2.40 per m^3.
Western United States	As reported in the Water Strategist[1], from 1987 to 2009 a total of 2,269 separate water rights transactions were completed between farmers and cities in 12 states in the western US, yielding 7.6 billion (7.6×10^9 m^3 per year. Costs have varied greatly, from less than US\$0.01 to more than \$16.00 per m^3.
San Antonio Water System (SAWS), Texas	Since 1999, SAWS has purchased or leased 255 different agricultural water rights, amounting to more than 84.4 million m^3 per year at a cost ranging from US\$0.36 to 2.20 per m^3 (San Antonio Water System, 2012b).
Lower Colorado River Authority, Texas	As part of its water supply planning to the year 2100, the Authority has proposed amending agricultural water rights to enable some portion to be used for industrial and power generation purposes. To provide increased reliability of irrigation in its river basin, the Authority is investing in agricultural water conservation measures including use of new rice varieties, on-farm practices, precision grading, multiple field inlets, conservation tillage, tail-water recovery, canal lining, delivery system improvements, conservation ponds and structure replacements (LCRA, 2010).

[1] See: http://www.bren.ucsb.edu/news/water_transfers.htm (accessed 15 May 2012).

compensation paid to farmers to reduce their water consumption is quite attractive, if only for its certainty as measured against the climate-influenced vagaries of farm revenues. It will be interesting to see whether a similar relaxation of tensions plays out in the Murray–Darling basin of Australia.

Agricultural water conservation holds considerable promise as a source of future water supply for cities. But forming productive urban–rural partnerships will require considerable site-specific assessment and collaboration (Colorado Agricultural Water Alliance, 2008; Gleick *et al*., 2011). While formidable challenges exist, we believe that the benefits of urban–rural partnerships will be well worth the effort.

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