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CORRIGENDUM

Corrigendum: Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona (2016 *Environ. Res. Lett.* **11** 035013)

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In section 2.1.2 the following sentence inadvertently included part of a title of one of the references:

'The Delta-Mendota Canal (188 km) and Friant Kern Canal (F-K Canal, 245 km long (figure 1) are the primary CVP canals transporting international experiences of water transfers: relevance to India water from northern California to the southern Central Valley'

and should read as:

'The Delta-Mendota Canal (188 km) and Friant Kern Canal (F-K Canal, 245 km long (figure 1) are the primary CVP canals transporting water from northern California to the southern Central Valley'.

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LETTER

Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona

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Abstract

Projected longer-term droughts and intense floods underscore the need to store more water to manage climate extremes. Here we show how depleted aquifers have been used to store water by substituting surface water use for groundwater pumpage (conjunctive use, CU) or recharging groundwater with surface water (managed aquifer recharge, MAR). Unique multi-decadal monitoring from thousands of wells and regional modeling datasets for the California Central Valley and central Arizona were used to assess CU and MAR. In addition to natural reservoir capacity related to deep water tables, historical groundwater depletion further expanded aquifer storage by ~44 km^3 in the Central Valley and by ~100 km^3 in Arizona, similar to or exceeding current surface reservoir capacity by up to three times. Local river water and imported surface water, transported through 100s of km of canals, is substituted for groundwater ($\leqslant$15 km^3 yr^{-1}, CU) or is used to recharge groundwater (MAR, $\leqslant$1.5 km^3 yr^{-1}) during wet years shifting to mostly groundwater pumpage during droughts. In the Central Valley, CU and MAR locally reversed historically declining water-level trends, which contrasts with simulated net regional groundwater depletion. In Arizona, CU and MAR also reversed historically declining groundwater level trends in active management areas. These rising trends contrast with current declining trends in irrigated areas that lack access to surface water to support CU or MAR. Use of depleted aquifers as reservoirs could expand with winter flood irrigation or capturing flood discharges to the Pacific (0–1.6 km^3 yr^{-1}, 2000–2014) with additional infrastructure in California. Because flexibility and expanded portfolio options translate to resilience, CU and MAR enhance drought resilience through multi-year storage, complementing shorter term surface reservoir storage, and facilitating water markets.

1. Introduction

Climate extremes, such as droughts and floods, often result in insufficient water when it is needed and too much when it is not. Recently, many extreme droughts have ended with floods, offering opportunities to capture and store excess runoff. An estimated 35%–70% of droughts in the western US end in floods caused by landfalling atmospheric rivers (concentrated bands of water vapor transport ~400 km wide and several 100 km long within extratropical cyclones) [1, 2]. The intensity of climate extremes is projected to increase with climate change [3]. Climate extremes are challenging for water resources management but present opportunities for storing water for use during drought.

How can we manage water storage to address water supply variability related to droughts and floods? The traditional approach to managing water supply variability has been to store water in surface reservoirs during times of excess for use during droughts. Reservoir building in the US peaked in the mid to late 1900s and optimal locations for reservoirs have already been exploited in most regions. In addition, the population has continued to grow since the majority of reservoirs were built resulting in a reduction in per capita reservoir storage (e.g., 35% reduction since the mid-1970s in California, figure S1). Surface storage is also exacerbated by reductions in snow storage with climate change.

Many previous studies have suggested using the large volumes of groundwater stored in aquifers as a buffer against the high degree of variability and drought vulnerability of surface water supplies [4]. Relying on groundwater alone is insufficient in many semiarid regions because extraction rates often exceed natural recharge rates resulting in hotspots of groundwater depletion in different regions, with classic examples in the US High Plains, California Central Valley, and south central Arizona [5]. Storing excess surface water in aquifers can greatly enhance the reliability of water supplies.

How can we manage groundwater storage (GWS) to cope with climate extremes? Two basic approaches for managing GWS include (1) conjunctive use (CU) of surface water and groundwater and (2) managed aquifer recharge (MAR). Conjunctive use involves substituting surface water for groundwater; thereby, reducing groundwater pumpage and retaining groundwater in aquifers [6]. MAR can be considered an extension of CU whereby, instead of substituting surface water for groundwater, surface water is used to recharge groundwater [7]. Changes in GWS reflect the balance between inputs and outputs as follows:

$$\underset{\uparrow}{\Delta \mathrm{GWS}} = \underset{\uparrow}{\text{inputs}} - \underset{\downarrow}{\text{outputs}} = \mathrm{R_{NAT}} + \mathrm{R_{IRR}} + \mathrm{R_{MAR}} - \mathrm{Q_{NAT}} - \mathrm{Q_{PU}}, \quad (1)$$

where water inputs include natural recharge (R_{NAT}), recharge from surface water-based irrigation (R_{IRR}), and from MAR (R_{MAR}). Natural recharge can be derived from percolation of precipitation and of surface water. Water outputs include natural discharge (Q_{NAT}, flow to streams as baseflow or riparian evapotranspiration) and anthropogenic pumpage (Q_{PU}). GWS will only increase when total water inputs exceed water outputs, which can be achieved by increasing inputs through MAR and/or decreasing outputs by substituting surface water for groundwater through CU. The natural hydrologic system also functions as a groundwater bank, storing groundwater during wet periods through increased recharge and depleting groundwater during dry periods through continued natural discharge [8]. Because GWS responds to these various inputs and outputs, it is often difficult to isolate the impacts of CU or MAR.

The terminology related to various water management options can be confusing. The term 'managed aquifer recharge' is defined as 'intentional storing and treatment of water in aquifers' and is distinguished from nonmanaged recharge from other processes, such as irrigation [9]. However, aquifers do not distinguish between managed versus nonmanaged recharge. Various approaches to MAR include surface spreading basins, vadose zone dry wells, and direct recharge to aquifers using wells (aquifer storage and recovery, ASR) [10–13]. The term 'groundwater banking' is used throughout the western US and includes (1) MAR and (2) 'in lieu' recharge [13]. 'In lieu' recharge is CU with substitution of surface water for groundwater resulting in an equivalent volume of groundwater that is not pumped credited to the bank and no physical recharge structures are required [14–16]. Ideal regions for CU and MAR include alluvial plains with large rivers collocated with major aquifers [17].

The concept of resilience related to water resources and climate extremes in this study refers to the ability to recover from water shortages during droughts. Resilience includes short-term coping strategies and long-term adaptive capacity. In this study, increased GWS through CU and MAR should enhance system resilience to water shortages caused by droughts. Turner [18] recognized that resilience and vulnerability are complementary, with resilience focusing on system strengths and vulnerability on system weaknesses. Comprehensive analyses should consider technical aspects, socioeconomic factors, and governance issues; however, such analyses are rarely achievable with available data [18].

The objective of this study was to address the following questions related to GWS management to enhance system resilience to climate extremes:

(1) What is the storage capacity of aquifers for MAR?

(2) How are surface water and groundwater managed conjunctively?

(3) How do MAR systems operate?

(4) How do GWS changes from CU and MAR compare with traditional surface reservoir storage?

(5) What is the future potential for CU and MAR?

Long-term data on CU and MAR systems since the 1960s in California's Central Valley and since the 1980s in central Arizona (figures 1 and 2) were used to address the above questions. This study is highly significant and timely because California and Arizona are currently experiencing their fourth year of drought (figure 3). The passage of the Sustainable Groundwater Management Act in California in 2014 focuses attention on water management options to cope with droughts. It will be interesting to see how much of the $2.7 billion allocated for expanding water storage in California will be applied to GWS relative to traditional surface water storage. A recent study indicated that GWS could provide six times more capacity than surface water storage for the same amount of funds [19]. California is also a major food producer in the

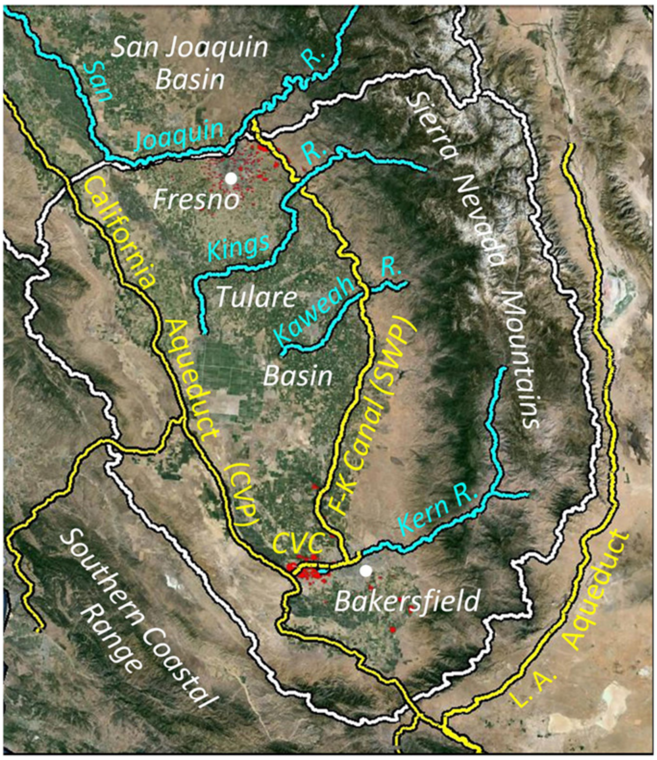

Figure 1. Infrastructure to support conjunctive use and managed aquifer recharge (MAR) in the southern California Central Valley. The primary basins are the San Joaquin and Tulare basins. Infrastructure to import water from the north includes the Friant–Kern (F–K) Canal (Central Valley Project, CVP), California Aqueduct (State Water Project, SWP), and the Cross Valley Canal (CVC) linking CVP and SWP (www.water.ca.gov/swp/cvp.cfm/). The MAR systems (shown in red) are located near the cities of Bakersfield (Kern County) and Fresno (Fresno County).

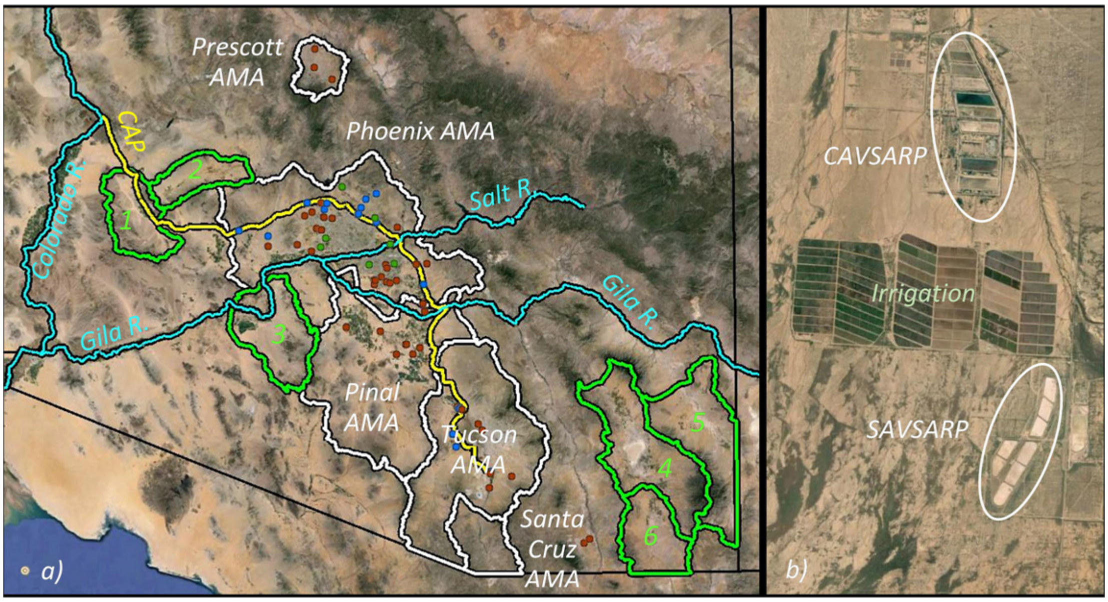

Figure 2. (a) Infrastructure to support conjunctive use and managed aquifer recharge (MAR) in Arizona. The active management areas (AMAs, outlined in white) include Prescott, Phoenix, Pinal, Tucson, and Santa Cruz. The basins outlined in green are irrigated basins without access to CAP surface water: 1. Ranegras; 2. McMullen Valley; 3. Gila Bend; 4. Willcox Basin; 5. San Simon Valley; and 6. Douglas Basin. The main rivers include the Colorado, Salt, and Gila. The Central Arizona Project (CAP) aqueduct transports water from Lake Havasu on the Colorado River to the Phoenix, Pinal, and Tucson AMAs. Managed aquifer recharge locations (spreading basins) are shown with water sources from CAP (blue circles), reclaimed municipal waste water (MWW, brown circles), and both sources (green circles, which may also include local surface water). (b) Image showing the Central and Southern Avra Valley Storage and Recovery Projects (CAVSARP, SAVSARP) spreading basins and irrigated region in between, located in the Tucson AMA.

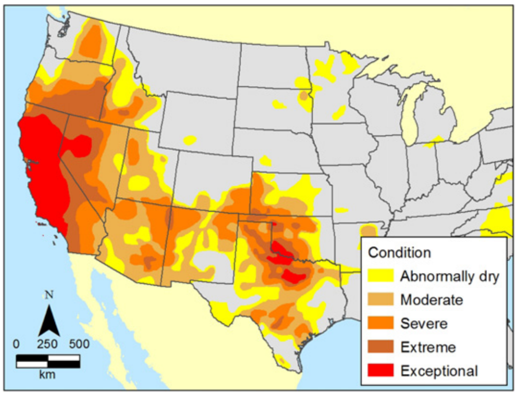

Figure 3. Distribution of drought with varying intensities in the Western US based on data for Oct. 28, 2014 showing exceptional drought in California (http://droughtmonitor.unl.edu/).

US, representing ~40% of the US fruit trees, nuts, and vegetables by area, with the Central Valley accounting for ~75% of these products in terms of farm value, relying almost entirely on irrigation [20]. This analysis focuses on the supply side of managing climate extremes through storage rather than reduction in demands.

This study is the first comprehensive compilation and analysis of primary quantitative data on water sources, deliveries, storage, and extractions for CU and MAR systems that the authors are aware of (figure 4). Unique aspects of the study include (1) the multidecadal records of CU and MAR components within the context of climate extremes and non-managed groundwater resources, and (2) detailed groundwater level monitoring, ground-based gravity data, and regional groundwater modeling to assess impacts of CU and MAR on groundwater resources. Drought resilience is evaluated in a qualitative sense by examining the impacts of CU and MAR on water supplies. By focusing on multiyear droughts, this study differs from many previous studies that concentrate on seasonal water management [16, 21]. While this study includes long-term performance data, most previous studies rely on simulation/optimization modeling of CU and MAR to assess the potential for CU or MAR [21–23]. This work complements previous studies that integrate various water storage options into California's water management strategy [24]. Economic issues are not discussed in detail in this study; however, this study builds on previous studies on economic impacts of various water portfolios, water markets, and drought management in the western US [16, 25, 26]. The effects of various water management strategies on agricultural output is addressed in previous studies [25]. Although we recognize that groundwater quality issues are extremely important [27, 28], space limitations of this paper preclude addressing water quality concerns. Results from this study should be very valuable to water managers in

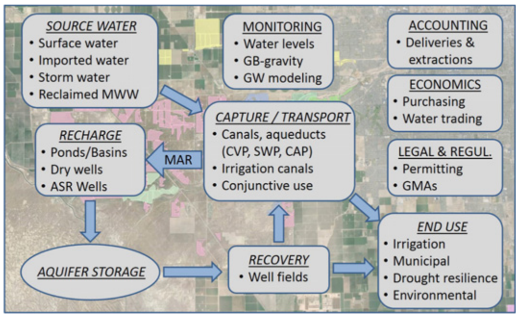

Figure 4. Schematic of components of conjunctive use and managed aquifer recharge (MAR) to enhance reliability of water supplies in response to droughts and floods. MWW is municipal waste water, ASR wells are wells designed to inject water into and recover water from an aquifer (aquifer storage and recovery). Infrastructure to transport imported water includes the California Central Valley Project (CVP), California State Water Project (SWP), and the Central Arizona Project (CAP). Monitoring includes water level measurements, ground-based gravity data [57], and groundwater (GW) modeling. Water accounting includes metering water deliveries to and extractions from MAR systems. Economic aspects include water costs and contracts relative to selling prices and water trading among groups. Legal and Regulatory aspects include water rights issues, permitting, and groundwater management acts. End users include irrigators and municipalities, options to increase drought resilience, and environmental flows.

many semiarid regions considering CU and MAR to cope with increasing climate extremes.

2. Background

2.1. Study area descriptions

The following provides background material related to climate extremes and transportation infrastructure and surface storage to support CU and MAR in the Central Valley and Arizona. Both regions are located in alluvial settings with coarse textured deposits which enhance percolation beneath surface spreading basins (figure S2). Legal and regulatory aspects related to CU and MAR are provided in SI, section 1.

2.1.1. Climate extremes

The southwestern US has been subjected to many long-term droughts within the past century. California is currently in its fourth year of drought (2012–2015) with 100% of the state in drought and 58% in exceptional drought during its maximum extent on October 2014 (figures 3 and S3) [29]. The most extreme drought on record occurred in 1976–1977, followed by a six year, less intensive drought (1987–1992), and more recent droughts in 2007–2009 and 2012–2015 (figure S4) [29]. Many droughts end in floods, with atmospheric rivers ending 35%–40% of droughts in California [1]. The 1976–1977 drought in California was followed by a wet 1978 and the 1987–1992 drought was followed by a very wet 1993 in southern California. These meteorological droughts translate into hydrologic droughts as shown by markedly different annual runoff between dry and wet years (e.g. 1990, dry and 1993, wet) in southern California (figure S5). Long wet periods occurred mostly in the 1980s (1978–1986) and 1990s (1992–2000). There is no strong relationship between wet and dry periods and El Niño Southern Oscillation (ENSO) in California [29].

Arizona is in its fifth year of drought (2011–2015) but the drought is less severe than that in California with 98% of the state in drought in July 2014 at its maximal extent but 0% under exceptional drought (figure S3). Time periods of historical droughts in Arizona are generally similar to those in California, mid 1970s, late 1980s, late 1990s to early 2000s and 2005–2009 (figure S4) [30, 31]. The mid 1970s drought ended in floods in south central Arizona in 1978 [30]. Tropical storms also result in flooding, e.g. Tropical Storm Octave, September–October, 1983. There are strong teleconnections between droughts and wet periods in Arizona and ENSO: droughts associated with La Niña and wet periods mostly related to El Niño [31]. Drought in the mid-1970s is associated with a strong La Niña and wet years in 1983 and 1997–1998 are related to strong El Niños (table S1). These teleconnections may extend into southern California.

2.1.2. Water transportation and storage

Long-term planning and investment was required to develop infrastructure to transport and store water from the source to the demand regions in the southern Central Valley and central Arizona. Construction of the Central Valley Project (CVP) project began in 1937 with the last of 22 reservoirs completed in the early 1970s (figure 1) The Delta-Mendota Canal (188 km) and Friant Kern Canal (F-K Canal, 245 km long (figure 1) are the primary CVP canals transporting international experiences of water transfers: relevance to India water from northern California to the southern Central Valley. The estimated construction costs of the CVP is ~$3 billion [32]. Construction of the State Water Project (SWP) began in the late 1950s with the original canals and 20 reservoirs completed in the early 1970s. The main transport system is the California Aqueduct (715 km long) (figure 1).

The Central Arizona Project (CAP) includes a 542 km pipeline from Lake Havasu on the Colorado River to Phoenix and Tucson (figure 2). The CAP was constructed between 1973 and 1993 to increase use of Arizona's Colorado River annual allocation water (3.5 km^3, 2.8 million acre feet, maf), with some of its allocation previously going to California (SI, section 2). The estimated construction cost of CAP is ~$3.6 billion [33].

3. Methods and data sources

The various components of CU and MAR systems evaluated in this study are shown in a schematic (figure 4). Data compilation was a major effort because data reporting on CU and MAR systems was minimal in California. The sources for various data are provided in SI, section 3. Information on subsurface reservoir expansion resulting from groundwater depletion was estimated from previous regional groundwater models [5, 34, 35]. Surface water deliveries for CU and MAR systems were compiled from California and Arizona Depts. of Water Resources (CA DWR, ADWR). Groundwater pumpage is reported for municipal and industrial sectors but is estimated for irrigated agriculture using groundwater models [35–38]. Impacts of CU and MAR on groundwater resources were evaluated by comparing water level hydrographs near MAR facilities in the Central Valley before and after CU and MAR operations and with regional GWS changes from modeling [36]. In Arizona, composite water-level hydrographs from time series of thousands of individual well hydrographs for the active management areas (AMA, Phoenix, Pinal, and Tucson) were compared to composite hydrographs for nearby regions outside areas of imported water (no CU or MAR, Gila, McMullen, Ranegras, San Simon, and Willcox basins) to assess the effects of CU and MAR on groundwater resources (SI, section 4). We used output from regional groundwater models for Arizona to assess GWS changes before and after CU and MAR operations. GWS was also estimated from synoptic ground-based gravity surveys in Phoenix and Pinal AMAs in Arizona [39]. Outputs from regional groundwater models were evaluated to put CU and MAR within the context of total water inputs and outputs (equation (1)). Detailed case studies based on the Arvin-Edison Water Storage District (AEWSD) in California and Avra Valley systems in Arizona are based on evaluation of annual reports and discussions with operators.

4. Results and discussion

The following sections address the questions outlined in the objectives, including development of aquifer storage capacity for MAR from previous groundwater depletion, understanding of CU and MAR in terms of different components schematized in figure 4, detailed case studies of MAR in the Central Valley and Arizona, and future potential for CU and MAR in California and Arizona.

4.1. What is the storage capacity of aquifers for MAR?

Deep water tables typical of aquifers in semiarid regions generally provide storage capacity to support CU and MAR. Little or no connectivity to surface water in many of these semiarid basins reduces losses to surface water. Deeper groundwater levels in the southern Central Valley (Tulare Basin, ⩽200 m) relative to the central and northern regions (San

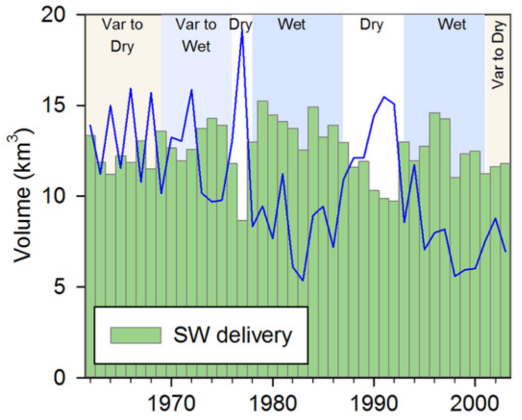

Figure 5. Variations in surface-water (SW) deliveries to and groundwater (GW) pumping in the Central Valley simulated by the Central Valley Hydrologic Model within the context of wet and dry periods [36]. SW deliveries account for ⩽70% of water use during wet periods whereas groundwater pumping represents ⩽70% of water use during droughts, particularly the 1976–1977 and 1987–1992 droughts.

Joaquin and Sacramento basins, ⩽30–50 m) suggest greater capacity for CU and MAR (figure S6). Water levels are also deep in south central Arizona providing capacity for CU and MAR [37, 38, 40].

Here we focus on additional storage capacity created by groundwater depletion within the last century in California and Arizona. Total depletion in the Central Valley aquifer was estimated to be 154 km^3 (1900–2008) [5] based on previous regional models from 1880–1961 (58 km^3) [35] and 1961–2003 (71 km^3) [36] and GRACE satellite data (2004–2013, 25 km^3) [41]. Pumping associated with the recent drought has resulted in widespread declines in groundwater levels, particularly in the Tulare Basin (⩾30 m, Spring 2005–2015, figure S7). Groundwater depletion was greatest in the mid-1900s with groundwater level declines of 30–60 m for irrigation in representative hydrographs (figure S8). Subsidence up to 10 m has resulted in loss of aquifer storage in some parts of the Central Valley [42, 43]. Unconfined GWS is most relevant for surface spreading basins and varies temporally. Unconfined GWS depletion from the mid-80s to mid-90s was about 42 km^3, representing ~70% of total storage depletion during that period (59 km^3) based on output from the Central Valley Hydrologic Model (figure S9(a)). A similar decline in total storage (~63 km^3) that occurred during the predominantly dry period ~1998–2014 should create unconfined reservoir space of ~44 km^3, similar to the storage capacity of the largest 154 reservoirs in the state (47 km^3).

Aquifers in alluvial basins in south central Arizona were also heavily depleted in the last century. By 1980 an estimated 230 km^3 of groundwater had been withdrawn, with more than 50% derived from aquifer storage [5, 34]. Groundwater withdrawals provide an indication of depletion and increased from ~1 km^3 yr^{-1} in the 1930s to a maximum of ~6 km^3 yr^{-1} in the 1970s in Arizona (figure S10) [44]. Depletion is recorded in marked groundwater level declines in many of these alluvial basins with maximum declines ranging from 30 to 120 m in different regions [34] (figure S11). Subsidence up to 6 m and permanent loss of aquifer storage space also resulted from groundwater depletion [45]. The semi-confined parts of the aquifer system are hydraulically connected because aquitards are of limited extent. Expansion of the aquifer storage capacity is estimated to be ~100 km^3, ~3 times the capacity of the largest reservoir in Arizona and in the US (Lake Mead, 32 km^3).

4.2. How are surface water and groundwater managed conjunctively?

Conjunctive use generally involves using surface water mostly during wet periods when it is readily available and shifting to groundwater during dry periods. In the Central Valley of California, surface water is imported through the CVP and SWP canals and aqueducts to support CU (figure 1). The regional groundwater model budget (1962–2003) shows a general inverse relationship between surface water deliveries and groundwater pumpage [36] (figure 5 and table S3). Surface water deliveries represent ⩽70% of total water use during wet periods (e.g late 1970s to mid-1980s, mid-1990s, 13–15 km^3 yr^{-1}).The situation is reversed during droughts with groundwater pumpage representing ⩽70% of total water use (e.g. 1976–1977 drought, ⩽19 km^3 yr^{-1}; end of 1987–1992 drought, 14–16 km^3 yr^{-1}). Kern County in the southern Tulare Basin also shows a similar pattern between surface water use and groundwater pumpage within the context of wet and dry periods (figure S12 and table S4) [46]. Water sources for CU and MAR in Kern County (1970–2011) include the Kern River (mean 33%), other local rivers (11%), CVP (17%), and SWP (36%).

Reduced pumpage only increases GWS if recharge plus other water inputs exceed all water outputs (equation (1)); otherwise pumpage reductions only decrease the rate of GWS depletion. Recharge from surface water based irrigation increases GWS, as emphasized in previous studies [17] and additional natural recharge may occur in response to natural recharge during extremely wet periods. Irrigators in the Central Valley maintain surface water and groundwater based irrigation systems, which is essential for CU. The impact of CU on GWS is shown by oscillating groundwater level hydrographs during wet and dry periods (figure S8) relative to the regional net groundwater depletion of ~1.4 km^3 yr^{-1}, mostly in the Tulare Basin (figure S9 and table S2). Cumulative regional GWS in the Tulare Basin declines sharply during droughts and levels off during wet periods.

In Arizona, CU was facilitated by completion of the CAP aqueduct in 1993. CAP deliveries totaled

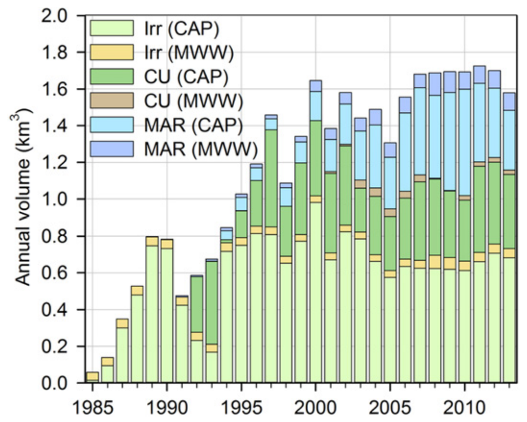

Figure 6. Time series of deliveries of water from different sources to support irrigation (Irr), conjunctive use (CU) (beginning in 1992) and managed aquifer recharge (MAR, beginning in 1994) in central Arizona. Sources include imported water from the Colorado River through the Central Arizona Project (CAP) aqueduct, reclaimed municipal waste water (MWW), and water from the Salt and Verde Rivers (Salt River Project). Data were obtained from http://cap-az.com/departments/water-operations/deliveries. Additional water sources prior to 1992 are not shown, including irrigation in Phoenix AMA with surface water from the Salt River, Gila Bend using occasional Gila River flows, and Pinal AMA using Gila River flows including reservoir storage.

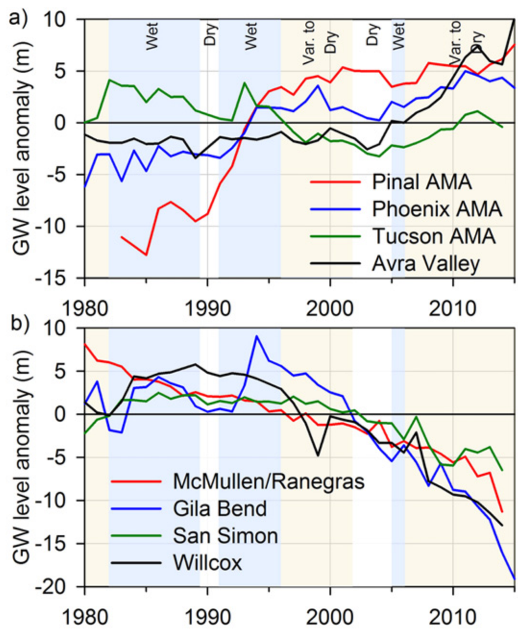

Figure 7. Composite groundwater (GW) level hydrographs (a) in the Phoenix, Pinal, and Tucson active management areas (AMAs) and (b) in areas outside the CAP delivery zones (McMullen/Ranegras (1, 2), Gila Bend (3), San Simon (5), and Willcox (4) basins). Numbers in parenthesis represent locations of basins in figure 2. Hydrographs in the AMAs represent the mean anomalies for 888 wells in the Phoenix AMA, 583 wells in the Pinal AMA, 995 wells in the Tucson AMA (2466 wells total). The Avra Valley hydrograph represents a subset of 251 wells in the Tucson AMA. Source: Arizona Department of Water Resources Groundwater Site Inventory (ADWR GWSI, https://gisweb.azwater.gov/waterresourcedata/GWSI.aspx).

30.5 km^3 (1983–2013). CAP deliveries for irrigation (17.4 km^3) represent 56% of total deliveries, peaking in 2000 at ~1 km^3 yr^{-1} (figure 6). Beginning in 1992, some CAP deliveries that replaced groundwater pumpage were classified and permitted as conjunctive use groundwater banking, termed 'in lieu recharge', totaling 7.6 km^3, 25% of total deliveries. To assess the impact of CU on groundwater resources, the Pinal AMA was selected because of the dominance of CU in this AMA and limited number of MAR spreading basins (table S5(b) and figure S13(b)). CAP deliveries to the Pinal AMA are used to supplement irrigation (9.0 km^3) and to support CU (2.5 km^3) by reducing groundwater withdrawals proportionally. Groundwater level trends in this AMA should reflect the net result of natural recharge, irrigation return flow, and CU. A cumulative composite hydrograph based on water-level records at 583 wells shows a large groundwater level rise in the early 1990s of ~12 m, followed by a more gradual increase of 8 m from 1993 to 2015 (0.2 m yr^{-1}) (figure 7(a)). The regional groundwater model also simulates a step increase in cumulative storage in the early 1990s of 1.5 km^3 (1991–1993) (figure S14(b)) [40], partly attributed to anomalously high precipitation (1992–1993) resulting in simulated recharge of 0.7–1.6 km^3 yr^{-1}, 1.4–2.8 times the long-term average (0.55 km^3 yr^{-1}). Most (33%–65%) of this recharge resulted from stream leakage in the Gila and Santa Cruz rivers (figure S15). Groundwater pumpage was also reduced in 1992–1993, ~50% of the long-term average, further contributing to the increased GWS (figure S14(b)). A much more gradual increase in GWS occurred from 1993 to 2009, ~0.1 km^3 yr^{-1}, totaling ~2 km^3, similar to that from ground-based gravity data in the 2000s (figure S16). This gradual storage increase is attributed to increased recharge from irrigation return flow using CAP and from CU. The regional model assumes an irrigation efficiency of ~70%, with 30% of irrigation water assumed to recharge the aquifer [40]. Therefore, recharge from irrigation (30% of 9 km^3, 2.7 km^3) is similar to the total amount of CAP water designated as CU (2.5 km^3). Although groundwater pumpage has been decreasing since the early 1950s, it exceeded groundwater recharge until the early 1980s. Elevated recharge during the wet period of the 1980s exceeded groundwater withdrawals, resulting in a net GWS increase. The Pinal AMA shows that the natural groundwater system functions as a bank with increasing GWS during wet periods (e.g. early 1980s and 1990s) and decreasing storage during droughts. CAP CU volumes are similar to estimated inputs from natural recharge and from irrigation return flow.

4.3. How do MAR systems operate?

In California, MAR systems in the southern Central Valley consist primarily of spreading basins at the surface, ~115 km^2 in area, 58% in the Kern Water Bank (figure 1 and S17). Only one of the 10 spreading

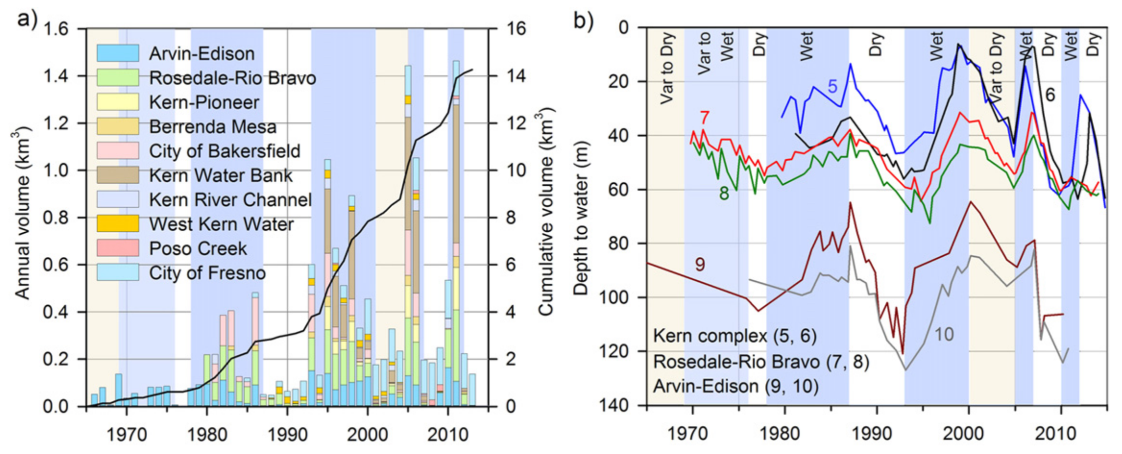

Figure 8. (a) Total deliveries of imported water to spreading basins in southern Central Valley, Kern County and (b) representative well hydrographs in the vicinity of Kern complex, Rosedale-Rio Bravo, and Arvin-Edison. The oldest spreading basin is Arvin-Edison (1966). Deliveries are low during drought years, highlighted with gray (1976–1977, 1987–1992; 2001–2002; 2007–2009, 2012–2014). Deliveries peaked during wet periods, including 1993 (0.6 km^3), 1995–1998 (0.5–1.0 km^3 yr^{-1}), 2005–2006 (1.1–1.4 km^3), and 2011 (1.5 km^3). The well hydrographs show depletions during droughts and recovery during intervening wet periods. Hydrograph well locations are shown in figure S23. Sources: California Statewide Groundwater Elevation Monitoring (CASGEM, http://water.ca.gov/groundwater/casgem/).

basins is in a river channel, the Kern River Channel MAR system. The MAR systems became operational at different times, ranging from the mid-1960s for Arvin-Edison, City of Fresno, and Rosedale-Rio Bravo and the 1990s for the Kern Water Bank, following the end of the 6 yr drought (1987–1992) (figure 8(a)). Reported ponding water depths in the spreading basins range from 0.5 to 1 m.

In Arizona, spreading basins cover an area of ~44 km^2, mostly in the Phoenix (53% of spreading basin area) and Tucson (37% of area) AMAs (figure 2). There are 69 spreading basins listed in the state, with only five in river channels (table S5). Phoenix accounts for 63% of the annual permitted volumetric storage rate (1.0 km^3 yr^{-1}), followed by Tucson at 27% (0.4 km^3 yr^{-1}).

4.3.1. Water sources and deliveries for MAR

Water sources for MAR systems in the southern Central Valley include the Kern River, local rivers, and imported water through the CVP (e.g. Friant Kern Canal and Delta Mendota Canal) and SWP (California Aqueduct), and connections between the two (Cross Valley Canal) (figure 1). Water deliveries to the MAR systems in the Central Valley totaled ~14 km^3 (mid-1960s–2013 (figure 8(a)). Nine of the 10 spreading basins are in Kern County. The top four of the 10 systems represent ~75% of total deliveries (figure S18). Deliveries to MAR systems in Kern County during peak wet years (e.g. 2005, 2011, ~1.3 km^3) represent ~30% of total surface water deliveries and ~45% of CVP and SWP deliveries to Kern County. Water deliveries were ⩽0.1 km^3 yr^{-1} during droughts.

Water delivered for MAR in Arizona totaled 7.3 km^3 (1994–2013), 75% from the Colorado River delivered through the CAP aqueduct (5.5 km^3), 19% from reclaimed municipal waste water (MWW, 1.4 km^3) and 6% from locally derived surface water (0.43 km^3) (figure 6). CAP deliveries to MAR spreading basins represent ~18% of total CAP deliveries to central Arizona, ranging from 0.05 km^3 yr^{-1} (1994) when the first spreading basin became operational to 0.3–0.6 km^3 yr^{-1} from 2003 to 2013. Reclaimed MWW is used for MAR because direct reuse of MWW is illegal in Arizona. MAR systems based solely on MWW represent 65% of MAR systems by number (50/77) but only 15% by permitted storage volumes in 2015 [47]. Waste water treatment plants are widely distributed in the AMAs (figure S19). Excess water from the Salt and Verde rivers as part of the Salt River Project, is input to the GRUSP MAR system in the Phoenix AMA (figure S25(a)). Water delivered to spreading basins totaled 4.1 km^3 to the Phoenix AMA, 2.5 km^3 to Tucson AMA, and 0.1 km^3 to Prescott AMA (figures S20 and S21). Storm water provides an additional source of recharge through an estimated 51 507 registered dry wells, with ~95% of the dry wells located in the Phoenix area (figure S22) [48].

4.3.2. Impacts of MAR systems on groundwater resources

Groundwater levels respond to natural recharge, recharge of excess applied irrigation, CU, and MAR, making it difficult to isolate impacts of MAR. In the Central Valley, water in MAR systems is generally stored over multiple wet years and extracted during droughts. For example, hydrographs adjacent to the Kern Water Bank, show large groundwater level rises during wet periods (⩽40 m yr^{-1}) and marked declines during droughts (5–7 m yr^{-1}) (figures 8(b) and S24). To evaluate the impacts of MAR we compare these hydrographs with the GWS from the regional model of the Central Valley which shows large declines in GWS during droughts with much less recovery during wet periods, resulting in an overall net storage decrease of 1.4 $km^3\ yr^{-1}$ [36] (figure S9(a)). The impact of MAR is also seen in the contrast in well hydrographs in the MAR regions (figure 8(b)) and areas where recent subsidence has been recorded, such as the estimated 2 m of subsidence in the El Nido area (southern San Joaquin Basin, figure S2) between 2007 and 2014 [41].

Spreading basins in the southern Central Valley recharge the shallow unconfined aquifer; however, extraction wells are screened from the water table to deeper semiconfined to confined aquifers. Well nests screened at different depth intervals indicate that hydraulic gradients are downward in nearly all cases indicating the potential for downward movement from the shallow to deeper flow system (figure S24). The contribution from MAR to the deeper system will depend on lateral spread of increased storage through displacement in the shallow system relative to leakage rates through the confining layers. Lag times less than months with nearly equal magnitude change with depth suggest that the influence on shallow and deep systems is similar in many regions. The small head differences between the hydrographs in the Kern Water Bank suggest that the aquifers in this region are not strongly confined. Groundwater in the region of the MAR systems is a closed basin and does not discharge to surface water. Therefore, water inputs through MAR should not be lost through baseflow to streams.

In the Arizona AMAs, hydrographs from wells adjacent to spreading basins show rapid groundwater-level rises within a year after imported water was delivered to the basins although water levels in some basins were deeper than 100 m before spreading began (figure S25). The coarse sediments, particularly in the Tucson AMA, allow relatively rapid water transport to the aquifer. Groundwater level monitoring near the SAVSARP MAR system indicate that it took ~6 weeks for water to percolate from the spreading basin to the water table at a depth of 122 m and laterally 150 m to the monitoring well [49].

CAP deliveries to the Tucson AMA are primarily for MAR (1.5 km^3, 69% of total CAP deliveries to Tucson AMA). The composite water-level hydrograph based on water-level records at 995 wells for the post 1980 period shows water-level responses to wet and dry periods, peaking in 1993 and a decline through 2004 (0.5 $m\ yr^{-1}$), followed by a rise through 2012 (0.5 $m\ yr^{-1}$) (figure 7(a)). The regional groundwater model indicates that the increases in water levels in the early 1980s and 1990s are related to increased recharge in response to anomalously high precipitation, particularly in 1983 and 1993 [38] (figure S14(c)). The more recent increases in water levels correspond to simulated increases in recharge, consistent with MAR from CAP. The groundwater model provides a long-term context for the recent data and shows that GWS declined by ~8.5 km^3 from the 1940s to early 2000s because pumpage exceeded recharge, except during brief wet periods in 1983 and 1993. Stabilization of GWS in the mid-2000s corresponds to recharge exceeding pumpage and may be attributed in part to CAP MAR deliveries. The MAR spreading basins are mostly located in the Avra Valley subbasin and GWS reversed trends in 1980 in the subbasin and has increased since 2000 (figure S14(c)). Therefore, the impact of MAR can be seen in the well hydrographs and regional model.

The impact of the MAR systems in the AMAs is evident when comparing water level hydrographs in the AMAs with those in basins outside the CAP delivery zone and little or no access to local surface water. In contrast to the increases in groundwater levels in the AMAs that receive CAP water, groundwater levels in basins outside the CAP delivery zone show declines ranging from 0.5 to 1.3 $m\ yr^{-1}$ ranging from 1980 to 1997 onwards (figure 7(b)). These analyses underscore the importance of surface water replenishing GWS through CU and MAR when contrasted with nearby basins that do not have access to surface water. However, it is difficult to isolate the impacts of CU and MAR in systems subjected to wet and dry climate cycles with natural recharge also varying and groundwater pumpage changing in response to these climate cycles.

4.4. Case studies

The following sections provide additional details related to MAR operations using MAR systems in the AEWSD in the Central Valley and in the Avra Valley in the Tucson AMA as examples.

4.4.1. Case study in Arvin-Edison Water Storage District in the Central Valley

Large groundwater level declines related to irrigated agriculture (~2.5 $m\ yr^{-1}$, figure S26) led to creation of the AEWSD and purchasing of water to reduce groundwater depletion in the extreme southeastern end of the Central Valley. AEWSD is typical of irrigation districts in the Central Valley and purchases water from the CVP. AEWSD is almost hydrologically isolated by the surrounding mountains on most sides, protecting stored groundwater [50]. The area served by AEWSD is ~526 km^2, with 445 km^2 irrigated, 50% sourced from imported surface water and 50% from groundwater (figures S27 and S28). Low mean annual precipitation (155 mm, 6 inches), 90% in winter months (November–March), is out of phase with summer crop production (figure S29). In 1966, AEWSD began operation of its spreading basins, 7.1 km^2 in area, ~1% of the total area. Between 1966 and 2012 AEWSD delivered 6.4 km^3 directly to users for irrigation, and applied 2.6 km^3 in three spreading basins. Estimated evaporation losses are low (~1% of applied water). AEWSD is in an ideal location with access to CVP through the Friant Kern Canal, supplying 64% of total applied water, SWP through the Cross Valley Canal and Intertie Pipeline, accounting for 30%

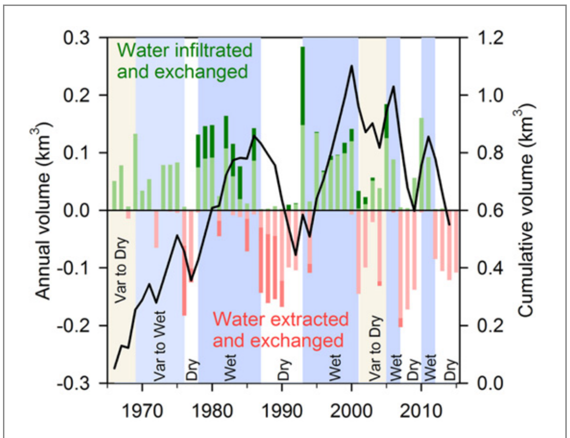

Figure 9. Water infiltrated and extracted (light colors) and water traded through exchanges (darker colors) in Arvin-Edison Water Storage District. Cumulative storage is shown in black. Drought periods are highlighted with gray. Water traded represents purchases from other entities, with annual imports of up to 0.12 km^3 in 1993 and annual exports up to 0.14 km^3 during droughts. Water deliveries peaked during wet years, ranging from 0.12 to 0.16 km^3 (1993, 1995, 2000, 2005, 2010) whereas extractions peaked during drought year, ranging from 0.10 to 0.19 km^3 yr^{-1} (1990, 1992, 2001, 2007–2009; 2013–2015).

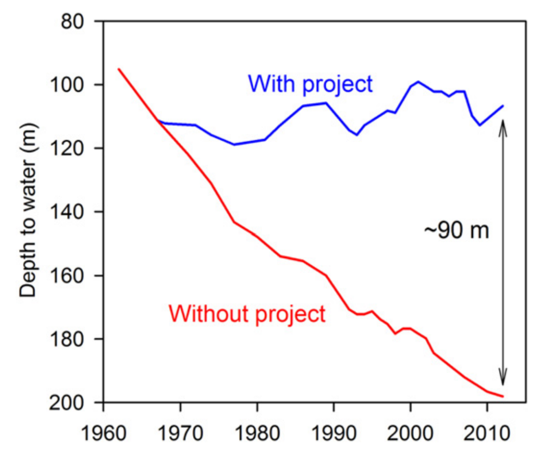

Figure 10. Water table depth with MAR (monitored) and without MAR (simulated) in the Arvin-Edison Water Storage District (AEWSD 2013).

of the water, and the Kern River, representing 6% of the applied water (figure S30). Water application from the Kern River was restricted to very wet years, peaking in 1998. AEWSD operates ~70 km of lined canals, 275 km of pipelines, ~50 pumping stations (figure S31) [51] and is continually investing in infrastructure to enhance operations. AEWSD is constantly expanding its network of partners with ~20 partners.

The water budget reflects the balance between deliveries and extractions (figure 9). A total of 2.6 km^3 was delivered to the spreading basins, and an estimated 1.8 km^3 was extracted from groundwater, resulting in a net delivery of 0.6 km^3. Water deliveries peaked during wet years, ranging from 0.12 to 0.16 km^3 whereas extractions peaked during drought years, ranging from 0.10 to 0.19 km^3 yr^{-1}. AEWSD has also enhanced the canal system to allow reverse flow [51].

Water percolation is slow, 30–140 mm d^{-1} based on data for Oct 2011 (AEWSD, 2013). The average percolation rate based on annual deliveries and spreading basin areas is 27 mm d^{-1}, peaking in 1993 (77 mm d^{-1}) with little or no percolation during droughts. Water extraction is also slow and includes 76 extraction wells ranging in depth from 240 to 320 m (figure S27). Monitoring wells (81) show that the average groundwater depth ranged from 115 to 193 m beneath the different spreading basins in August 2013 [52]. A long-term hydrograph shows stabilization of groundwater levels in the late 1960s, increases in the early 1980s, declines during the drought from 1987 to 1992 and increases in the late 1990s (figure S26). More recent monitoring data show increases during wet periods and declines during droughts, similar to well hydrographs near the Kern Water Bank (figure 8(b)).

There are limited data for the AEWSD system during the current drought; however, hydrographs near the Kern Water Bank show that declines during droughts exceed recoveries, resulting in net depletion during this drought. Depletion in the vicinity of these MAR systems is much less than the regional depletion simulated by the Central Valley Hydrologic Model for the Tulare Basin (1.4 km^3 yr^{-1}, figure S9(a)). Analysis by AEWSD indicates that groundwater levels would be about 100 m deeper (200 m versus 100 m deep) if MAR had not been operating and assuming pumping would have occurred at the same level (figure 10).

The economics of water storage is based on the ability to store water during wet years when water is available and prices are low and to extract water during dry years when the value of water is high. Deliveries of imported water are reduced during droughts because of reduced availability and endangered species issues (Delta Smelt), amplifying variability related to wet and dry periods. Because surface water is much less expensive than groundwater when available, AEWSD prices both sources similarly so that irrigators maintain both irrigation systems. The common water volume unit used in the US is the acre-foot, which is equivalent to 1230 m^3 or 1.2 $\times$ 10^6 liters (l). AEWSD has long-term (30–40 yr) contracts with the CVP to purchase water at ~\$10–\$20 af^{-1}. The selling price of water by AEWSD to its members increased from \$15 af^{-1} (1.2 $\times$ 10^6 l) in the mid-1960s to mid-1970s, to ~\$60 af^{-1} in 1990, \$80 af^{-1} (2000) and \$140 af^{-1} in 2012 [52]. The ~100 m shallower water table depth as a result of MAR reduces pumping costs by an estimated \$50–\$80 af^{-1} [53] resulting in 50%–60% savings in power costs for water. Power costs represent about half of the total water cost. During the current drought AEWSD promoted an internal market among its members with purchase costs for water pools highest at the beginning of the summer season to incentivize water movement to higher value users, ranging from \$400 af^{-1} in May to \$200 af^{-1} in July [51]. These costs are much lower than the external market, which ranges from \$1000 to \$2000 af^{-1} [54].

Farmers may pump groundwater into the canal for transfer to other users or to be purchased by AEWSD. The reliability of the AEWSD water supply has allowed farmers to switch from annual crops to more profitable perennial crops over time, mostly almonds and citrus, hardening their water demand, similar to trends throughout Kern County and in the Tulare Basin (figure S32).

4.4.2. Case study in Avra Valley in Tucson AMA

Avra Valley (1400 km^3) (figure 2(b)) evolved from a major agricultural area after 1940, a water supply that augmented local groundwater in Tucson in the 1990s, to a prominent reservoir for MAR after the mid-1990s. Additional details related to the Avra Valley system are provided in SI, section 5. Agriculture was supported by groundwater withdrawals that far exceeded annual recharge rates resulting in water-level declines of 1.3–1.4 m yr^{-1} (figure S33). Groundwater levels declined markedly and then stabilized in the 1980s corresponding to a wet period. With the Arizona GW Law of 1980, Avra Valley and the adjacent Tucson Basin were grouped into the Tucson AMA. When the CAP aqueduct reached Tucson, the City of Tucson developed MAR systems, mostly in Avra Valley to store water. The City of Tucson operates two MAR facilities that infiltrate CAP water in central and southern Avra Valley Storage and Recovery Projects (CAVSARP, SAVSARP) (figure 2).

Simulated groundwater withdrawals in Avra Valley were as much as 0.18 km^3 yr^{-1} from ~1940 to 1980, resulting in ~3.5 km^3 of storage depletion (figure S14(c)) [38]. Associated water-level declines were more than 30 m. Water levels and storage slowly recovered beginning in ~1980 concurrent with a wet period that continued through the late 1990s (figures S14(c), S33 and S34). Storage recovery rates increased after about 2000 following the establishment of the two recharge facilities (CAVSARP and SAVSARP) and two smaller facilities in northern Avra Valley.

Artificial recharge of CAP water in Avra Valley began in 1996 at the CAVSARP facility (11 basins, 1.3 km^2 in area, 33 withdrawal wells) (figure 2). The SAVSARP facility began recharge operations in 2009 (9 basins, 0.9 km^2 in area, 11 withdrawal wells). Cumulative deliveries of CAP water for recharge in Avra Valley increased from ~0.1 km^3 before 2001 to ~2.3 km^3 by 2015 (~65% to CAVSARP and SAVSARP) with an annual delivery rate of ~0.2 km^3 (figure S35), equivalent to the previous maximum annual groundwater withdrawal rate. Evaporation losses are low (⩽1% of storage) and there is a 5% cut to the aquifer, resulting in 94% of deliveries being credited as long-term storage for future extraction. The City of Tucson plans to expand the CAVSARP facility storage capacity (Thompson, 2015).

4.5. Comparison of surface and subsurface reservoir storage

It is important to understand the similarities and differences between groundwater and surface water storage systems for optimal management of water resources. Surface reservoirs generally accommodate rapid storage of large water volumes for seasonal or interannual timescales. Rates for expanding existing reservoirs range from \$1700 af^{-1} for expanding Shasta Reservoir by 0.6 maf (0.74 km^3) to \$2700 af^{-1} for expanding San Luis Reservoir by 1.3 maf (1.6 km^3) [55]. New reservoirs are also being proposed with similar rates (\$1800 af^{-1} for Building Sites Reservoir for 1.3–1.8 maf, 1.6–2.2 km^3). Studies also highlight that increasing reservoir storage capacity does not correspond directly to increased water deliveries because deliveries depend more on reservoir inflows. For example, expanding Millerton Reservoir in the Central Valley by 70% would only increase water deliveries by ~10% [24]. Optimal reservoir locations have generally been developed and adverse environmental impacts make permitting extremely difficult.

GWS through CU and MAR generally complements surface reservoir storage in many ways. MAR systems are characterized by slow infiltration rates, limiting their ability to rapidly respond to climate extremes [24]. Low intake rates for MAR systems require interim storage and coordination with surface reservoir storage. Recovery rates are also slow with 70–80 extraction wells in typical systems (e.g. AEWSD, Kern Water Bank) operating 24 h d^{-1} for 365 days of the year during drought periods to meet demand. Another advantage of subsurface storage is reduced evaporation losses. For example, estimated evaporation losses in AEWSD are ~1% of deliveries. Evaporation losses from the Lower Colorado River Basin (mean 1.6 km^3 yr^{-1}, 1971–2005 [56]) are similar to the volumes of water transferred through the CAP to support irrigation, CU, and MAR (1.4 km^3 yr^{-1}, 2000–2013). One of the big differences between surface and subsurface storage is the invisibility of subsurface storage and difficulties in isolating GWS changes from CU and MAR operations. There are no generally available reported costs for MAR systems. Recent analysis of grant applications for MAR systems in California estimated costs of \$400 af^{-1} (range \$90–\$1000 af^{-1}) [19]. These estimates are similar to the costs of water provided by AEWSD to farmers (⩽\$400 af^{-1} during the current drought). Analysis of the \$2.7 billion for storage in California indicates that subsurface reservoirs could provide six times more storage relative to surface reservoirs for this level of funding (10.4 versus 1.4 km^3) [19].

It is important to understand that it is not surface versus subsurface reservoir storage but integrated management of both. The importance of surface reservoirs for capturing pulse flows has been highlighted in previous studies [8, 24]. Improved weather forecasting would allow pre-delivery of surface

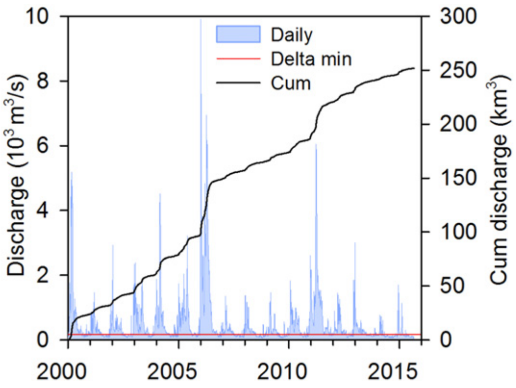

Figure 11. Daily discharge from the California Delta into San Francisco Bay. The red line represents 170 $m^3 s^{-1}$ (6000 $ft^3 s^{-1}$) flow considered to be the minimum (Delta minimum) required to maintain healthy environmental conditions. Cum. Cumulative. Source: US Bureau of Reclamation Central Valley Operations Office (USBR CVO, http://usbr.gov/mp/cvo/).

reservoir storage for CU and MAR, thereby enhancing reservoir capacity for increased storage. The increased linkages and feedbacks provided by an integrated surface and groundwater reservoir storage system increases flexibility, enhancing drought resilience, and providing greater opportunities for water marketing.

4.6. Future potential for conjunctive use and MAR

With increasing pressure to move towards more sustainable groundwater management, particularly in California, various options are being considered. Here we examine potential for expanding CU and MAR and some of the issues related to operations.

4.6.1. Storage capacity

There is adequate subsurface storage capacity based on naturally large depths to groundwater and past groundwater depletion in the southern Central Valley and in the Arizona AMAs to support future expansion of MAR. MAR is also being considered in the northern Central Valley, i.e. the Sacramento Valley. However, storage capacity is not as great (shallower water table depths, figure S6), soils are finer grained (figure S2), and surface water and groundwater are highly connected which could result in discharge of recharged groundwater as baseflow. Flood irrigation on fallow lands during winter periods is being evaluated to enhance recharge in this region and also in perennial crops during winter periods further south [24, 57, 58]. The similarity in recharge rates from irrigated agriculture and CU in Pinal AMA suggests that flood irrigation should be very effective in recharging aquifers. Inefficient flood irrigation based on surface water with efficient drip irrigation based on groundwater should increase groundwater recharge. The effectiveness and economic feasibility of different options will be critical in assessing various approaches.

4.6.2. Water sources for CU and MAR expansion

Future planning will need to consider the general over-allocation of water resources in many of these regions and increasing allocations for the environment, such as the San Joaquin River Restoration program in the Central Valley.

In contrast to the California Central Valley where deliveries through the CVP and SWP are reduced during droughts (figure 5), CAP deliveries in Arizona have been maintained despite the long-term drought since the year 2000. However, future CAP deliveries are vulnerable because CAP has a junior water right entitlement among the lower basin states including Colorado River exports to California (SI, section 2) [59] and the CAP allocation would be reduced first [60]. If this happens, Arizona may revert to pumping groundwater to maintain water supplies. The existing models could be used to test different scenarios relative to their impacts on GWS. Other options are also being considered to cope with reduced water allocations during droughts [61].

Expansion of CU and MAR in California and Arizona needs additional water sources (figure 4). The California Dept. of Water Resources is mandated to determine how much additional water is available for groundwater replenishment under the California Sustainable Groundwater Management Act. Flood flows to the Pacific Ocean from California that exceed environmental flow requirements could provide additional water to support CU and MAR expansion. Preliminary estimates of such flood flows in excess of 170 $m^3 s^{-1}$ (6 000 cfs) required for environmental flow quality standards from the California Delta based on data for December through March range from 0.6 to 2.0 $km^3 yr^{-1}$ (figure 11, table S6). However, considering both the proposed Twin Tunnel project (part of the Bay Delta Conservation Plan) that would provide an additional 255 $m^3 s^{-1}$ (9000 cfs) and the current limitations of the Delta pump capacity, these flows are restricted to $\leqslant$1.0 $km^3 yr^{-1}$. Expansion of the San Luis Reservoir or building of a new surface reservoir could increase water availability for these transfers by up to 1.6 $km^3 yr^{-1}$. In the Colorado River, surplus flows relative to the required allocation of 1.8 $km^3 yr^{-1}$ to Mexico have also occurred in the wet periods of the early 1980s (up to 21 $km^3 yr^{-1}$ in 1983) and also in 1993 (up to 6 $km^3 yr^{-1}$) and 1997–1998 (up to 6 $km^3 yr^{-1}$) (figure S36). The big question is how much infrastructure would be developed to support such episodic flows and what are the economics of such programs?

4.6.3. Hydrologic connections between inputs and outputs

While current practices in California and Arizona do not require operators to show hydrologic linkages between water inputs and outputs, future studies should move toward linking inputs and outputs in terms of upstream versus downstream and vertically relative to shallow and deep aquifers for infiltration and extraction. Large differences in head in wells screened at different depth intervals may indicate different degrees of confinement. For example, the City of Cottonwood has decided to use ASR rather than spreading basins for MAR because of confining layers between the surface and deeper extraction wells [62]. More detailed monitoring programs, including unsaturated zone monitoring, and modeling analyses could be used to assess the effectiveness of the CU and MAR programs.

The detailed performance data provided by CU and MAR systems in the southwestern US should provide data input for many other regions planning or advancing beyond 'spontaneous' CU [17] to more rigorous planned management. The complementary nature of surface water and GWS should be relevant to approaches to harvesting flood flows in different regions for drought management [63]. The relative merits of CU and MAR within the context of droughts and floods could be used in regions with proposed or built large scale inter-basin transfers [64], e.g. the South to North Water Transfer from the Yangtze River to the North China Plain [65, 66], and proposed east to west linkages in India [67].

5. Conclusions

Recent increases in climate extremes [1] related to wet and dry periods in California and Arizona require additional water storage to buffer water supply variability related to these extremes. In addition to reservoir capacity provided by naturally deep water tables in these semiarid regions, extensive groundwater depletion, mostly for irrigation during the last century, expanded subsurface storage reservoirs by 44–100 km^3 in the Central Valley and Arizona, respectively, corresponding to total reservoir storage in California and three times storage in Arizona's Lake Meade, the largest reservoir in the US.

Conjunctive use in California supported by imported water through the CVP and SWP canals and aqueducts shifted water sources from mostly groundwater use to conjunctive use of surface water ($\leqslant$70% during wet periods) and groundwater ($\leqslant$70% during droughts), greatly reducing pumping and allowing GWS to recover. Conjunctive use in Arizona accounts for ~25% of Colorado CAP deliveries which helped stabilize and reverse long-term GWS losses. MAR in the Central Valley and in Arizona represents 45% and 20% of imported water, respectively. CU and MAR in the Central Valley reversed previously declining groundwater level trends of up to 2.5 m yr^{-1} which contrasts with the net groundwater depletion from the regional groundwater model. Impacts of CU and MAR in Arizona can be seen from comparisons of recent rising groundwater level trends in AMAs (0.1–0.5 m yr^{-1}) with declining trends (0.5–1.3 m yr^{-1}) in irrigated areas that lack access to surface water to support CU or MAR.

GWS complements surface reservoir storage with slow rates of infiltration and extraction and long-term storage relative to rapid inputs and outputs with shorter term storage in surface reservoirs. The order of magnitude lower costs and reduced evaporation associated with subsurface storage offer significant advantages for long-term storage. Integrated management of surface and subsurface reservoirs should be used to optimally manage water supply variability with surface reservoirs capturing flood flows and transferring to aquifers for longer-term storage.

Flexibility translates to resilience. By expanding the portfolio of water sources in the southwestern US and increasing the options provided by water transportation infrastructure allowing water trading among users, CU and MAR enhance system resilience to drought in these regions. These management options should expand in the future with increased emphasis on more sustainable groundwater management. The infrastructure required and detailed monitoring and modeling data in these systems provide an indication of what is required to develop CU and MAR programs in other regions considering these storage approaches.

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