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Conjunctive groundwater management as a response to socio-ecological disturbances: a comparison of 4 western U.S. states

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Abstract: Recent severe droughts in U.S. western and Great Plains states have highlighted the challenges that socio-ecological disturbances can pose for governing groundwater resources, as well as the interconnections between groundwater and surface water and the need to manage the 2 in an integrated way. Conjunctive management recognizes these interconnections and can be used to mitigate disturbances and achieve a variety of water management goals. However, comparative studies of how and to what extent various states have implemented conjunctive management strategies are few. Here we compare and assess the use of conjunctive management practices in 4 western states—Arizona, California, Nebraska, and Texas—with a particular focus on groundwater. Special attention is paid to factors of geography and infrastructure, degree of administrative (de)centralization, and monitoring and modeling in relation to conjunctive management. Despite the commonality of bifurcated regimes for groundwater and surface water, all 4 states have responded to disturbances with conjunctive management strategies in various ways. Although it has groundwater management challenges similar to those in the other 3 states, Texas has overall been slower to adopt conjunctive management strategies.

Keywords: groundwater, conjunctive management, Texas, California, Nebraska, Arizona

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Terms used in paper

Acronym	Descriptive name	State
AMA	active management area	Arizona
ASR	aquifer storage and recovery	-
ADEQ	Arizona Department of Environmental Quality	Arizona
ADWR	Arizona Department of Water Resources	Arizona
AGMA	Arizona Groundwater Management Act	Arizona
AWBA	Arizona Water Banking Authority	Arizona
CDWR	California Department of Water Resources	California
CAGRD	Central Arizona Groundwater Replenishment District	Arizona
CAP	Central Arizona Project	Arizona
CVP	Central Valley Project	California
DFC	desired future condition	Texas
EAA	Edwards Aquifer Authority	Texas
ESA	Endangered Species Act	-
GAM	groundwater availability model	Texas
GCD	groundwater conservation district	Texas
GDP	gross domestic product	-
IMP	integrated management plan	Nebraska
INSIGHT	Integrated Network of Scientific Information and GeoHydrologic Tools	Nebraska
IWRIS	Integrated Water Resources Information System	California
NRD	natural resources district	Nebraska
NDNR	Nebraska Department of Natural Resources	Nebraska
SWP	State Water Project	California
SWRCB	State Water Resources Control Board	California
SGM Act	Sustainable Groundwater Management Act	California
TCEQ	Texas Commission on Environmental Quality	Texas
TWDB	Texas Water Development Board	Texas
USGS	United States Geological Survey	-
WAM	water availability model	Texas

INTRODUCTION

Given historically unprecedented drought across the western United States since 2000, combined with urgent demands for riparian habitat recovery, increasing water demand associated with population growth, and conflicts between surface water and groundwater users, it is timely to consider how different states have responded to disturbances affecting groundwater governance through conjunctive management. Conjunctive management—"the coordinated use of surface water supplies and storage with groundwater supplies and storage (Blomquist et al. 2004)"— has enjoyed greater popularity over the years. This is partly because increased demands on scarce supplies have brought the connections between groundwater and surface water to the fore. The increasing popularity of conjunctive management is also based on its potential to address disturbances and achieve management goals by, for example, reducing exposure to drought, maximizing water availability, protecting water quality, increasing protection of aquatic life and habitat, improving security of water supplies, and reducing reliance on expensive and environmentally disruptive surface water impoundment and distribution systems (Blomquist et al. 2004). Conjunctive management "represents one of the most important responses to improving drought water-supply security and for long-term climate-change adaption (Foster and van Steenbergen 2011)."

But conjunctive management is practiced differently across jurisdictions and watersheds, and with varying results. Our aim is to account for these variations and provide a basis for learning from the experiences of other jurisdictions. Specifically, we compare and assess the use of conjunctive management practices in 4 western and Great Plains states—Arizona, California, Nebraska, and Texas—with a particular focus on groundwater. We emphasize groundwater because while use of the storage capability of aquifers is fundamental to conjunctive management, institutional arrangements for solving groundwater problems "have not been particularly successful" for various reasons (Schlager 2006) and are in more need of development compared to those for surface water. Crafting institutions for groundwater that are consonant with those for surface water is crucial for effective conjunctive management but is a challenge in states where groundwater and surface water are subject to separate ownership and regulatory rules. We chose to compare these 4 western states because they share commonalities in the types of challenges they face as well aspects of their groundwater institutions,[1] while still diverging in ways that provide a basis for comparison and study. All of the states discussed here depend heavily on groundwater to support large agricultural sectors. California, Nebraska, and Texas, in particular, sit atop 2 of the most agriculturally productive—and severely overdrawn—aquifers in the nation. The 4 states maintain separate legal doctrines for groundwater and surface water, despite other efforts to promote conjunctive management. None has a centralized statewide permitting system for appropriation of groundwater. All, in practice, rely on special local districts to manage groundwater. Additionally, all rely on courts for some measure of oversight and as catalysts for institutional change. Yet, the 4 states differ dramatically in geography, law, extent of local control, and means to coordinate conjunctive management across jurisdictions. Based on our comparison, we suggest that a state's institutions—primarily legal and administrative arrangements—are most decisive for the form that conjunctive management takes and degree of adoption.

The paper is structured as follows: the foregoing introduction; a brief description of the reasoning behind—and challenges associated with—conjunctive management; a comparison of how conjunctive management is practiced in Texas, Arizona, California, and Nebraska; a comparative examination of physical and institutional factors that account for these differences; and a conclusion highlighting future problems and opportunities for better groundwater governance and conjunctive management going forward.

THE USE OF CONJUNCTIVE MANAGEMENT TO ADDRESS WATER RESOURCE CHALLENGES

Conjunctive management can be broadly understood as "the coordinated use of surface water supplies and storage with groundwater supplies and storage (Blomquist et al. 2004)."[2] Managing groundwater and surface water conjunctively can reduce exposure to drought and flooding, maximize water availability, improve water distribution efficiency, protect water quality, and sustain ecological needs and aesthetic and recreational values (Blomquist et al. 2004). A common conjunctive management strategy is the recharge and storage of surface

[1] Following Ostrom (1990), we define institutions as sets of "working rules" that are "actually used, monitored, and enforced when individuals make choices about the actions they will take." So defined, organizations such as water management or regulatory agencies are not themselves institutions. Institutions can be both formal and informal, but our concern in this analysis is with formal institutions, such as laws and policies, that affect groundwater governance and conjunctive management.

[2] Conjunctive management is sometimes defined more narrowly, and in distinction from conjunctive use, as referring specifically to an integrated statewide legal and regulatory regime (e.g., Kaiser 2012). By that definition, none of the states reviewed here are "conjunctive management states." The broader conception we use here includes, and is interchangeable with, conjunctive use. For more detailed discussions of conjunctive use and management see, e.g., Blomquist et al. (2001); de Wrachien and Fasso (2002); and Sahuquillo and Lluria (2003).

water in aquifers when it is available in excess of demand, for withdrawal later when surface supplies are reduced, as during drought. Recharge may occur directly, via injection wells or percolation basins, or indirectly by using surface water instead (or "in-lieu") of groundwater, which allows for replenishment and storage through natural recharge. Conjunctive management can also involve actively managing groundwater withdrawals from tributary aquifers to maintain base flow to gaining streams.

In addition to actively managing water supplies, conjunctive management may be used to address conflicts among different water users. When groundwater pumping interferes with streamflows or reservoir levels, conflicts between surface water and groundwater users often emerge. As human surface water uses typically pre-date groundwater uses, pressure on state officials to regulate groundwater to protect surface water rights occurs. However, given the many desirable qualities of aquifers, not to mention that well owners often utilize groundwater for many years before its impact on surface water sources becomes apparent, state officials are often reluctant to place strict limits on groundwater pumping. Thus, state officials are placed in a particularly difficult position of making tradeoffs between 2 important types of water users and uses. Conjunctive management can be an important tool to address such conflict. Carefully designed conjunctive management projects may mitigate the effects of groundwater pumping on surface water flows. For instance, the Colorado Office of the State Engineer administers augmentation programs that allow groundwater pumpers to either lease surplus surface water for direct release into streams or for recharge projects to cover the effects of pumping on surface water flows (Blomquist et al. 2004; Colorado Division of Water Resources 2015).

Attempting to balance uses of hydrologically connected surface water and groundwater becomes more delicate if endangered species are involved. These types of conflicts are more challenging to address because they involve many more actors, from federal agencies to public interest groups to the many and diverse human water users; they threaten the development of new water projects or the federal re-licensing of existing projects, and, consequently, they are framed as zero-sum games. In this mindset, water allocated to endangered species is water taken from other types of uses and vice versa. For instance, as will be discussed, both Colorado and Nebraska are using conjunctive management to place more water in the Platte River at times most needed by endangered species (Birge et al. 2014). In Texas, the Edwards Aquifer is subject to a cap on non-exempt groundwater withdrawals and must be managed to balance withdrawals and springflows to maintain habitat for endangered species during critical dry periods (Votteler 2002; Gulley and Cantwell 2013). States have begun to use conjunctive management to address these more difficult challenges of balancing among different types of users and uses. These efforts have come late, so their effectiveness is not yet proven.

HOW IS CONJUNCTIVE MANAGEMENT PRACTICED? COMPARING CONJUNCTIVE MANAGEMENT IN TEXAS, ARIZONA, CALIFORNIA, AND NEBRASKA

Conjunctive management is highly location- and goal-specific, and thus, not surprisingly, the goals of conjunctive management vary across all 4 states in line with their different geography, history, legal regimes, and available physical infrastructure. Conjunctive management in Arizona is characterized by centralized state management for storing surplus surface water underground, both to meet the safe yield goals of the 1980 Groundwater Management Act and for long-term storage. California localities use conjunctive management to improve reliability and water quality, and to protect public safety. In Nebraska, conjunctive water management is pursued to maintain and protect surface water flows as required by interstate agreements. Like California, conjunctive management goals in Texas are multiple and vary geographically and among political jurisdictions. They are broadly similar to those in the other states, including underground storage and recovery of surplus surface water and reclaimed wastewater, mitigation of groundwater mining, maximization of ability to meet demands during disturbances such as droughts, and protection of minimum surface water flows.

We compare how these 4 states have used conjunctive management to address groundwater challenges, including issues of transfers and of banking and technical capacity (monitoring and modeling, specifically). A summary of key governance attributes from the discussion is provided in Table 1.

Conjunctive management in Texas

Conjunctive management practices in Texas reflect several different aims, depending on the specific context. These include increasing flexibility, efficiency, and reliability; augmenting supply; replenishing depleted aquifers; improving water quality; and maintaining springflows and streamflows. The main types of conjunctive management practices used for these purposes that can be observed in Texas are aquifer storage and recovery (ASR), managed aquifer recharge, and the active management of groundwater withdrawals to maintain springflows to surface water bodies. In Texas, ASR is accomplished by injecting either treated river water into an aquifer or by piping groundwater from one aquifer into another, to

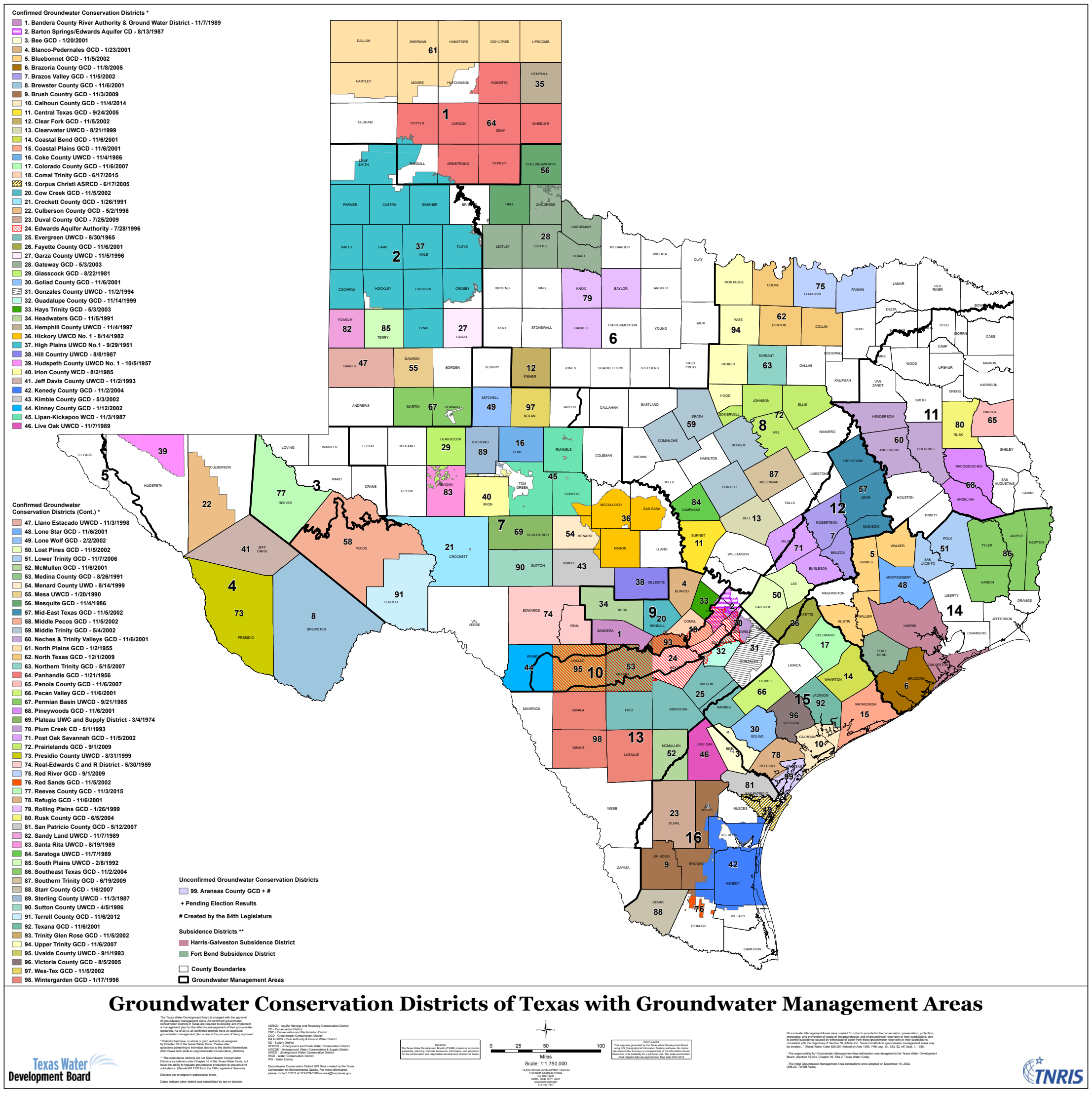

Figure 1. Texas groundwater conservation districts (GCDs) and groundwater management areas (GMAs). Map credit: Texas Water Development Board.

be withdrawn later from the same wells as needed. Managed aquifer recharge occurs by replenishing aquifers with highly treated wastewater via spreading basins. The management of groundwater withdrawals to mitigate the effects of pumping on surface water availability is generally not statutorily mandatory for management entities but can be incorporated into the management goals of groundwater conservation districts (GCDs).

Several water providers in Texas practice simple conjunctive use of 2 sources of water (Kaiser 2012), but conjunctive management that is active and involves more than 1 entity is unusual by comparison. For example, adoption of ASR has been extremely limited (Pirnie 2011), and to date there are only 2 "true" ASR projects in the state.[3] Although there is evidence that interest is increasing (Galbraith 2013; Kalisek 2014; Blaney 2015; Webb 2015), the handful of ASR proposals in the 2012 regional water plans together would create less than 1% of all proposed new water supplies (Kalisek 2014; Webb 2015). As described further in the paper, Texas' GCDs (Figure 1) are directed to address conjunctive groundwater and surface water issues in their management goals. While a few counties within Groundwater Management Area 8 (see Figure 1) have the goal of maintaining minimum amounts of streamflow/springflow in surface water bodies (Marbury and Kelly 2009), there is little indication in the literature that this requirement is typically translated in practice into conjunctive management in the form of pumping limitations. In any

[3] Although El Paso Water Utilities' recharge system has sometimes been classified as an ASR system (Pirnie 2011), strictly speaking, it can be better described as a "hybrid" managed recharge system because recharge and recovery are not done with the same wells; both spreading basins and older injection wells are used to recharge (Webb 2015).

event, the Edwards Aquifer Authority (EAA) is notable as the only case in the state where a management organization is statutorily obligated to manage and regulate groundwater withdrawals to maintain springflows during drought years.

Conjunctive management in Arizona

The chief purposes of conjunctive management in Arizona are to encourage use of renewable surface supplies (primarily the Colorado River); reduce groundwater overdraft; increase water supply flexibility, efficiency, and reliability; and augment supplies. Conjunctive management in Arizona is done primarily through an innovative and elaborate managed recharge program created by a 1986 act of the state Legislature. Conjunctive management activities consist mainly of direct and indirect (or "in-lieu") recharge and storage, mostly but not exclusively of "excess" or unused portions of Arizona's allotment of Colorado River water, which is conveyed by the Central Arizona Project (CAP) canal. The Arizona Department of Water Resources (ADWR) administers the aquifer recharge program, and recharge is carried out primarily by subsidiary organizations created by the state, mainly the Arizona Water Banking Authority (AWBA) and Central Arizona Groundwater Replenishment District (CAGRD).

In terms of volume, Arizona's recharge efforts are extensive, with more than 4 million acre-feet of Colorado River water, in-state surface water, and effluent having been stored (ADWR 2014b). Arizona is the state with the fourth most ASR facilities in the country, though several have become inactive due to clogging (Bloetscher et al. 2014). Geographically, Arizona's conjunctive management practices are relatively confined to the central part of the state—the Phoenix and Tucson metro areas primarily—because this region is where groundwater overdraft has historically been most severe; recharge facilities can be located relatively near the main CAP canal; and ADWR has special regulatory authority according to the Arizona Groundwater Management Act. Distribution of the active management areas (AMAs) and groundwater storage facilities are shown in Figure 2.

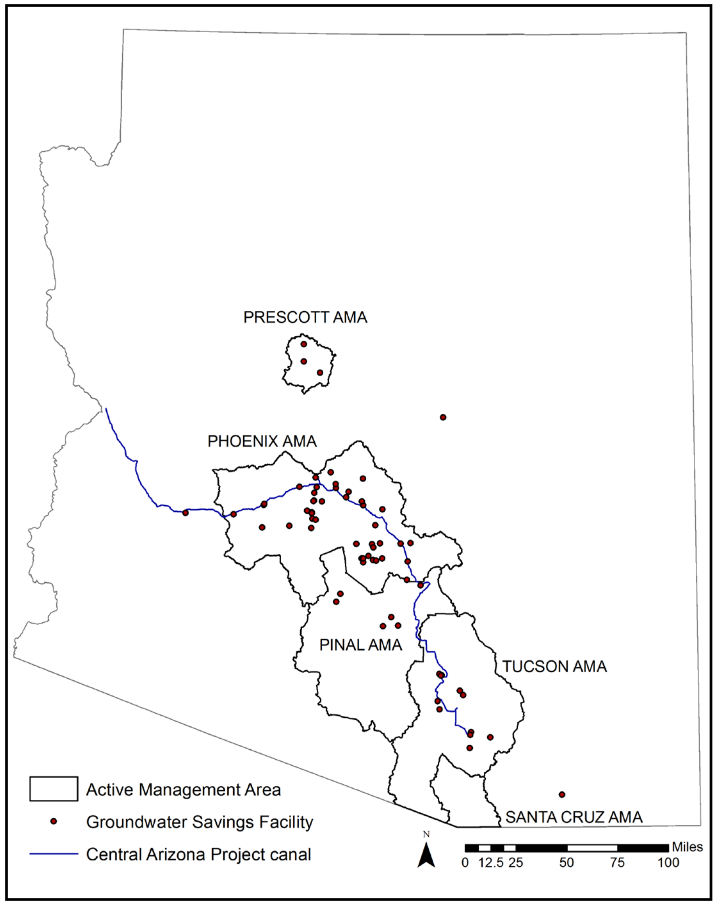

Figure 2. Arizona active management areas, groundwater savings facilities, and Central Arizona Project main canal. Map by authors with data obtained from Arizona Department of Water Resources.

Conjunctive management in California

There is no single overarching goal for conjunctive management in California, except, perhaps, to maintain reliability of water supply for uses as they currently exist. Even if this were the overarching goal, it would be because it is an aggregation of other conjunctive management goals at multiple scales, rather than a centralized policy. Conjunctive management is used to increase flexibility for local water management, for example in the Santa Ana Watershed (*e.g.,* SAWPA (2014a)). It is also used to augment supplies of freshwater in the Central Valley (CDWR 2014a). Elsewhere in the state, conjunctive management is used for environmental purposes, such as maintaining springflows and streamflows for critical habitats (CDWR 2014a; *cf.,* Bowling and Vissers 2015). Along the coasts, conjunctive management is used where jurisdictions are attempting to create or maintain barriers to saltwater intrusion. Additionally, in multiple places across the state, conjunctive management is used to reduce overdraft. Generally, though, conjunctive management is not a single purpose management technique in California. Even where only 1 purpose is stated, conjunctive management tends to have multiple water-management effects.

Although several localities in California are known to have long histories of engaging in conjunctive management (Blomquist et al. 2004), the true extent of conjunctive management in California is not entirely clear. A sampling of water management agencies in California found that conjunctive management is widely, though inconsistently, practiced throughout the state (Blomquist et al. 2004). An attempt in 2008 to facilitate the statewide sharing of conjunctive management information, the Integrated Water Resources Information System (IWRIS), "did not meet with considerable success"

Table 1. Comparative summary of key groundwater governance attributes of Arizona, California, Nebraska, and Texas.

	ARIZONA	CALIFORNIA	NEBRASKA	TEXAS
USERS[1]	(thousand acre-feet)	(thousand acre-feet)	(thousand acre-feet)	(thousand acre-feet)
Agriculture	1,900.0	9,740.0	4,820.0	5,710.0
Public supply and self-supplied domestic	686.5	3,330.0	312.3	1,560.0
Mining and industrial[2]	186.1	761.6	143.2	414.2
Thermoelectric power	86.6	37.1	5.9	43.5
LEGAL DOCTRINES				
Surface water	Prior appropriation	Riparian rights, Prior appropriation, Pueblo	Prior appropriation	Prior appropriation
Groundwater	American reasonable use	Correlative rights, Prescriptive rights	Correlative rights	Rule of capture, absolute ownership
STATE ADMINISTRATIVE AGENCIES				
Surface water	Arizona Department of Water Resources (ADWR) (quantity); Arizona Department of Environmental Quality (ADEQ) (quality)	California Department of Water Resources (CDWR); State Water Resources Control Board (SWRCB)	Nebraska Department of Natural Resources (NDNR); Nebraska Department of Environmental Quality	Texas Commission on Environmental Quality (TCEQ)
Groundwater	ADWR (quantity); ADEQ (quality)	CDWR (quantity); SWRCB (quality and assessment of rights)	Natural resources districts (NRD) (quantity; quality)	Texas Water Development Board (TWDB) (non-regulatory); TCEQ (quality and protection)
GROUNDWATER MANAGEMENT ORGANIZATIONS	Special districts (5 active management areas [AMAs])	*Historically*: Varied special districts (by specific legislation); adjudicated basins; and counties and municipalities *Sustainable Groundwater Management Act of 2015 (SGM Act)*: Groundwater Sustainability Agencies	Special districts (NRD)	Special districts (groundwater conservation districts [GCDs]; special-purpose districts: Edwards Aquifer Authority (EAA); Harris-Galveston Subsidence District; Ft. Bend Subsidence District)
Geo-political jurisdiction	Hydrogeologic boundaries	Mixture of hydrogeologic boundaries (can be surface water basins and/or groundwater aquifers) and political boundaries	River basins	GCDs and subsidence districts: county, sub-county, or multi-county aggregations; EAA is a mixture of hydrologic and political boundaries.
PLANNING	State covered by 7 planning areas; 10-year management plans are required through 2025 for each of the 5 AMAs and compiled by ADWR staff.	*Historically*: voluntary but tied to funding *SGM Act*: mandatory for high and medium priority basins and reviewed by state agencies; mandatory periodic updates *Adjudicated Basins*: dependent on specific court order, negotiated agreements, and watermaster	NDNR in cooperation with NRDs of fully appropriated or over allocated basins develop management plans; other NRDs may voluntarily develop plans.	Formal, mandatory, and statewide, by regional water planning areas; regional plans feed into State Water Plan compiled by TWDB; GCDs must develop management plans individually and plan jointly with other GCDs within groundwater management areas.
QUANTIFIED GROUNDWATER RIGHTS	Within regulated districts	Within adjudicated basins	No	Within management districts with permitting systems

[1] Fresh (non-saline) groundwater use in thousand acre-feet per year. Source: Maupin et al. 2014.

[2] Includes fresh groundwater for mining, livestock, aquaculture, and all other industrial uses.

Table 1. (continued) Comparative summary of key groundwater governance attributes of Arizona, California, Nebraska, and Texas.

MONITORING	Statewide monitoring network of approximately 1,800 wells; non-exempt wells metered inside AMAs; groundwater pumping reporting minimal outside AMAs	*Historically*: Done locally; CDWR coordinates with local monitors through voluntary program California Statewide Groundwater Elevation Monitoring, collects, and publishes non-confidential information; SWRCB samples wells to collect data on water quality *SGMA*: monitoring and reporting by Groundwater Sustainability Agencies *Adjudicated Basins*: dependent on specific court order, negotiated agreements, and watermaster	Wells are metered; statewide monitoring network	Well monitoring networks maintained by TWDB and by individual GCDs; non-exempt wells metered in municipal service areas, some GCDs, and within special-purpose districts
MODELING	ADWR maintains 7 groundwater models; coverage limited to the 5 AMAs and 2 irrigation non-expansion areas.	CalSimII, developed by CDWR and U.S. Bureau of Reclamation, models California's 2 largest water delivery systems; multiple hydrologic models of groundwater and surface water focus on the Central Valley	Hydrologic models of groundwater and surface water for fully allocated and over appropriated basins	Seventeen groundwater models cover the 9 major aquifers.
CONJUNCTIVE MANAGEMENT				
Goals	Encourage use of renewable surface supplies (primarily the Colorado River); reduce groundwater overdraft; increase flexibility, efficiency, and reliability; supply augmentation	Increase flexibility, efficiency, reliability; supply augmentation; maintain springflows and streamflows; environmental protection; saltwater intrusion barrier; reduce overdraft	Protect streamflows	Increase flexibility, efficiency, reliability; supply augmentation; maintain springflows and streamflows
Constructed, state-managed water delivery infrastructure?	Yes	Yes	No	No
Recognition of groundwater/ surface water connection	In practice within regulated districts but not formally	In practice within some special districts and municipalities; recognized by state agencies and legislature but legally distinct property rights.	Only in fully allocated and over appropriated basins	In practice within some special districts and by some municipalities; but not formally

due to only partial participation by water districts and lack of funding (CDWR 2014a). More recently, the California Department of Water Resources (CDWR) and the Association of California Water Agencies conducted a survey to inventory and assess conjunctive management programs throughout the state (CDWR 2015). The number of responses, however, has been limited. Nonetheless, there were 89 total reported conjunctive management programs across the state (See Figure 3 for the distribution of reported conjunctive management agencies). About one-third of these were located in the South Coast and another 37 programs were reported in the Tulare Lake region (CDWR 2015) In general, the state does not require systematic monitoring or reporting on conjunctive management, though this is likely to change as the Sustainable Groundwater Management Act (SGM Act) is implemented and tensions between surface water property rights and the goals of sustainable groundwater management rise.

Conjunctive management methods vary across the state. In coastal areas such as Los Angeles County and Orange County, surface water and treated wastewater are injected into aquifers for aquifer replenishment and water banking, and to provide a barrier to seawater intrusion (Drewes 2009; Department of Public Works 2015). In other districts, conjunctive management is used for flood control, drought relief, and local and statewide water supply reliability improvement (CDWR 2014a). Similar to Arizona, certain forms of conjunctive management in California are facilitated by the presence of large water projects, the State Water Project (SWP) and Central Valley Project (CVP), along with multiple, smaller interconnecting aqueducts, which redirect and deliver surface water across the state. Of the 89 reported active conjunctive management programs in California, 71% of respondents used water from the SWP and 24% from the CVP[4] (CDWR 2015). These constructed surface water delivery systems allow for direct recharge of groundwater aquifers with surface water in places that would ordinarily not have access to a reliable surface water supply.

Conjunctive management in Nebraska

Nebraska water users and water managers engage in conjunctive water management primarily to mitigate the effects of groundwater pumping on surface water flows, as required by the 2004 Groundwater Management and Protection Act. Conjunctive management allows Nebraska to meet its commitments under interstate agreements, such as the Republican Interstate River Compact and the Platte River Recovery Implementation Program by which the federal government, Colorado, Nebraska, and Wyoming are actively seeking to restore habitat and recover endangered species (PRRIP 2014). Like other states that have considerable interstate water delivery requirements, such as Colorado and Wyoming, but unlike the other states in this comparison, Nebraska does not engage in long-term storage of surplus surface water underground. Rather, most conjunctive water management occurs through the coordinated regulation and administration of groundwater pumping and surface water diversions.[5] Conjunctive water management takes place through integrated management plans (IMPs) developed by the natural resources districts (NRDs) (NRDs are shown in Figure 4). Currently, of the 23 NRDs, 9 are required by state law to engage in conjunctive water management and have approved IMPs, primarily in the Platte and Republican River basins, which are subject to interstate agreements. As an example, the Lower Republican Natural Resources District strictly regulates the amount of groundwater that may be applied to each irrigated acre in the district. In addition, it has the authority to shutdown groundwater pumping from wells located in a designated rapid response area, which encompasses wells closest to the river, if necessary, to meet interstate water delivery requirements (LRNRD 2011). Another 8 NRDs are voluntarily developing IMPs.

More direct forms of conjunctive water management, such as the use of infrastructure to store surplus surface water underground for return to the stream, is only just beginning to be experimented with. For instance, in 2011, the Nebraska Department of Natural Resources (NDNR) worked cooperatively with the Bureau of Reclamation, the Platte NRDs, and numerous irrigation districts, to capture flood flows, divert the flows into irrigation canals, and allow the water to percolate underground. NDNR estimated that about half of the water diverted was recharged, and half of the water recharged will return to the Platte over a 50-year period (NDNR 2014). The Central Platte Natural Resources District has also invested in direct recharge by acquiring surface water rights and collaborating with canal companies to use their canals for recharge (CPNRD 2015).[6]

Figure 3. Distribution of reported conjunctive management agencies in California. Map credit: California Department of Water Resources.

[4] Note: these figures are not mutually exclusive.

[5] See NRD Regulations at https://www.nrdnet.org/sites/default/files/state_map_water_management_status_14feb2014.pdf

[6] See a list of planned recharge projects at https://www.nrdnet.org/sites/default/files/water_sustainability_projects_map-_web_3.pdf

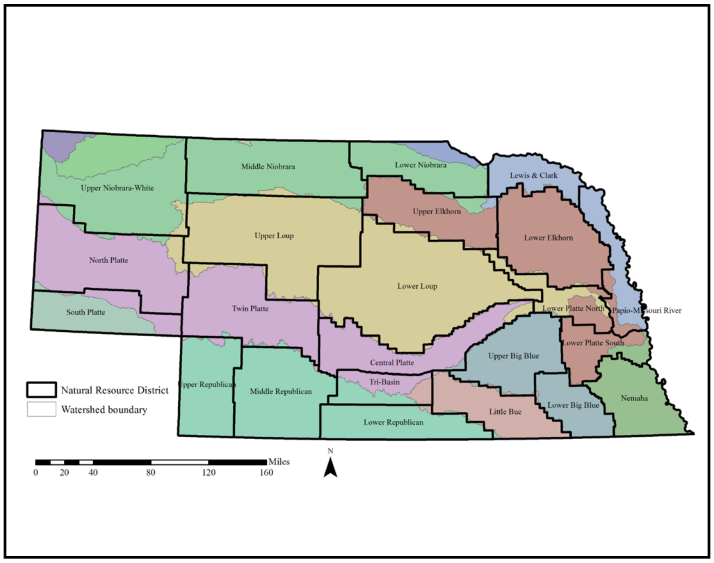

Figure 4. Nebraska natural resources districts (NRDs) and watershed boundaries. Map by authors with data obtained from Nebraska Department of Natural Resources.

WHAT ACCOUNTS FOR THE DIFFERENCES BETWEEN STATES?

Geography and infrastructure

The constraints of physical geography and the availability of infrastructure for water deliveries affect the goals, methods, and extent of conjunctive management across the 4 states.

Groundwater resources in Texas are distributed among 9 major and 21 minor productive aquifers that underlie a range of climatic and ecological regions; parts of the humid eastern Gulf Coast receive 6 or 7 times as much annual precipitation as in the semiarid west (Ward 2005). Texas depends on groundwater for approximately 60% of the 16.1 million acre-feet of water used in the state (TWDB 2012). Total groundwater usage in 2013 was estimated at 9.18 million acre-feet (TWDB 2015). While irrigated agriculture uses the lion's share of groundwater overall (about 80%) (George et al. 2011), municipalities are increasingly relying on groundwater, using about 15% of the state's total groundwater in 2008 to meet about 35% of urban water demands (TWDB 2012). Farming accounted for an average of 0.6% of the Texas gross domestic product (GDP) from 2009–2013 (BEA 2015).

Texas' prodigious groundwater resources underlie the basins of 15 major rivers, and groundwater is connected to surface water in numerous locations throughout the state (Parsons Engineering Inc. 1999; Scanlon et al. 2005). The unfortunate legacy of groundwater pumping in Texas is the desiccation of many naturally occurring springs (Brune 1981). In recent years, problems associated with groundwater pumping have included well interference, aquifer overdrafting and mining, and conflicts over transfers of water from rural to urban areas (Kaiser 2005). Groundwater depletion has also led to serious problems with subsidence and saltwater intrusion in the Gulf Coast region, which led to the formation of the Harris-Galveston Subsidence District.

Highly productive groundwater aquifers underlie the most heavily populated and agriculturally intensive areas of semiarid Arizona. Known as the basin and range lowland province among geologists and hydrologists, it contains deep alluvial basin-fill aquifers ranging from several hundred to several thousand feet thick that hold approximately 900 million acre-feet of water (Anderson et al. 2007). As is the case in most western states, the largest use of groundwater is for agriculture. Of the 2.5 million acre-feet of groundwater used annually, 1.9 million acre-feet, or 66% is used for irrigation (Maupin et al. 2014), and of that 1.9 million acre-feet of water, around 35% (662,711 acre-feet) comes from naturally occurring groundwater (i.e., excluding recharged/stored Colorado River water) in agricultural regions in the central to south central parts of the state (ADWR 2010a; 2010b; 2011). Farming comprised an average of 0.6% of the Arizona GDP from 2009–2013 (BEA 2015).

California's 515 alluvial groundwater basins vary in geology, groundwater quality, and means for recharge. The basins have the capacity to hold approximately 1.3 billion acre-feet of water (CDWR 1994), 450 million acre-feet of which is considered "economically feasible" to pump (CDWR 2003). Californians extract on average about 16.5 million acre-feet per year (CDWR 2014a). But not all water that is extracted is recharged. The majority of groundwater sites in California experienced a decrease in water levels between 2010 and 2014 (CDWR 2014b). California's Central Valley, which is responsible for the second largest amount of total groundwater withdrawals in the United States, after the High Plains Aquifer (Scanlon et al. 2012), continues to experience some of the worst shortages in the state, with over half of the long-term monitoring wells showing groundwater at or below historical low levels (CDWR 2014b)

California depends on groundwater more than any other state in the country (SWRCB 2014). In total, more than three-quarters of the state—roughly 30 million people—depend on groundwater for at least part of their drinking water (CDWR 2014a). Extracted groundwater typically meets between 30% and 50% of the water needs of agricultural, urban, and managed wetlands water uses in California (CDWR 2014a); in drought years like 2014, groundwater meets about 65% of all uses (Borchers and Carpenter 2014). Agriculture is by far the largest contributor to increased groundwater dependence during drought years (see, *e.g.*, Faunt 2009). Farming accounted for an average of 1.1% of the California GDP from 2009–2013 (BEA 2015).

Nebraska sits at the northern end of the High Plains, or Ogallala, Aquifer. The aquifer covers 175,000 square miles in parts of 8 states (McGuire 2014). However, Nebraska claims the greatest share of the aquifer with two-thirds of its land mass underlain by the aquifer (Miller and Appel 1997). In addition, the Nebraska portion of the aquifer exhibits the deepest saturated thickness of over 1,000 feet in the Sand Hills region in the north-central part of the state.

Groundwater from the High Plains Aquifer has played a key role in economic development in Nebraska over the last 6 decades. The 1950s witnessed the development and adoption of technologies, from diesel engines that powered deep, large-capacity wells to center pivot irrigation systems that currently allow Nebraska farmers to irrigate more land than farmers in any other state except California (Maupin et al. 2014; USDA 2012). As of 2010, Nebraska farmers applied 6.3 million acre-feet of water (4.8 million of it groundwater) to 8.3 million irrigated acres of cropland, using just over 97,000 registered groundwater wells (Nebraska Department of Agriculture 2014). By far, Nebraska's farming sector uses the most water, even though it produced only an average of 7.9% of the state's GDP from 2009–2013 (BEA 2015). Municipal and industrial uses of groundwater amounted to 380,000 acre-feet in 2010, about 8% of all groundwater use in the state (Maupin et al. 2014).

Arizona and California are both able to deliver surface water across their territories through statewide infrastructure—the CAP in Arizona, and the CVP and SWP in California. That infrastructure allows water providers and users to engage in in-lieu recharge, long-term storage, and—in California—assist with state-facilitated Drought Water Banks.[7] For instance, more than 4 million acre-feet of CAP, effluent, and intrastate surface water has been recharged by close to 100 different storage facilities (ADWR 2014b). The most recharge facilities and the largest volume of water are stored in the Phoenix AMA (ADWR 2014b). This is in large part due to favorable hydrogeological characteristics and the pre-existing infrastructure of canals from older irrigation districts, which allows for the transportation of CAP water to where it can be recharged (Blomquist et al. 2004).

It is also possible to employ infrastructure and conjunctive management in protecting surface flows. Nebraska NRDs are beginning to work with irrigation districts to use their systems of canals to recharge water that will percolate underground and return to the stream. As mentioned earlier, the NDNR worked with NRDs and irrigation districts to capture flood flows in irrigation canals for recharge into the High Plains Aquifer (NDNR 2014). In addition, the Central Platte NRD has acquired surface water rights and uses the associated water for conjunctive management purchases, recharging it through canals (CPNRD 2015).[8] In addition, the NRDs overlaying the Republican River Basin jointly purchased a plot of land, retired it from irrigation, and constructed pipelines from the parcel to streams tributary to the Republican River. During particularly dry years, such as 2014, the NRDs pump groundwater from the parcel and deliver it through the pipelines to the stream to remain in compliance with the Republican Interstate River Compact (Nebraska Cooperative Republican Platte Enhancement Project 2015).

Unlike California and Arizona, Texas lacks a centralized water transportation system linking the various cities and farming areas. Most of the major agricultural areas are located in the western and southern parts of the state, relatively far from urban areas (TWRI 2012) and thus not linked by water infrastructure. Additionally, most areas of irrigated agriculture have access to either groundwater or surface water but not both; in 2000, only 2.4% (142,386 acres) of total irrigated land in the state was watered with both sources (TWDB 2001). The lack of co-located surface water and groundwater supplies in many areas likely limits the use of direct and indirect recharge strategies used so heavily in Arizona to reduce groundwater mining by irrigation districts. However, areas where infrastructure, surface water, and aquifers are co-located do exist. These areas include economically important and fast-growing regions such as the "extensively plumbed" (Ward 2005) Lower Rio Grande Valley, the upper Rio Grande area near El Paso, the Winter Garden area in Central Texas (Turner et al. 2011), and in the Gulf Coast region where a pipeline is being constructed to create a continuous link from the city of Corpus Christi to Lake Texana and the Lower Colorado River (Savage 2013). Corpus Christi plans to eventually store some of this surface supply in local aquifers via an ASR operation (Wythe 2008). Additionally, various other parts of the state contain groundwater basins suitable for storage and recovery of surface water sources (Webb 2015). El Paso Water Utilities' system for recharging reclaimed wastewater into the Hueco Bolson Aquifer has been in operation since 1985 to ameliorate groundwater depletion (Sheng 2005). The city of Kerrville operates an ASR system for surface water from the Guadalupe River that provides 10% of its annual deliveries (Kaiser 2012). More recently, the San Antonio Water System has implemented an ASR facility that pumps and transmits water from the Edwards Aquifer via pipeline to a nearby sandstone aquifer with superior containment.

Because it is a karst system, the effects of drawdown in the

[7] Note the California Drought Water Banks are not the same as "groundwater banking;" rather, they are state-directed and managed temporary water markets.

[8] See a list of planned recharge projects at https://www.nrdnet.org/sites/default/files/water_sustainability_projects_map-_web_3.pdf

Edwards Aquifer can quickly contribute to corresponding reductions in the rate and quantity of springflows to the streams they feed. The need to maintain these springflows even during drought to protect the endangered species that rely on them makes conjunctive management clearly necessary. Following the approval by the U.S. Fish and Wildlife Service in 2013 of the Habitat Conservation Plan for the Edwards Aquifer, an adaptive system of groundwater/surface water management has been implemented to manage the system more holistically, maintaining minimum springflows to streams during a recurrence of the drought of record, such as a voluntary irrigation suspension program (Gulley and Cantwell 2013).

Institutional factors affecting conjunctive management

One striking observation that emerged from our comparison of these 4 states concerns the relative lack of adoption of conjunctive water management in Texas. California, for example, has dozens of ASR projects and the ability to employ statewide drought water banks (Blomquist et al. 2004). Arizona has been directly and indirectly recharging surface water into aquifers since the 1990s, and Nebraska has developed interesting ways for protecting surface flows using minimal infrastructure and well-integrated hydrologic models.

Because all states have surface water co-located with alluvial aquifers, geography alone cannot explain the variation among conjunctive management practices, or why Texas engages so minimally in conjunctive management in comparison to other western states. We suggest that the different institutional arrangements across the 4 states and within them at the local level best account for the differences. In the following discussion, we examine the relevant laws that promote and constrain conjunctive management in each of the 4 states. With that background in hand, we then draw out 2 main points of comparison: (1) the role of coordination and (de)centralization in promoting conjunctive management and (2) arrangements for monitoring, modeling, and sharing information.

Texas

After decades of laissez faire groundwater development punctuated by several severe droughts, Texas has begun moving toward active coordinated management of its groundwater resources. At the same time, Texas has sought to preserve local autonomy and a tradition of decentralized groundwater management.

Texas applies different property rights regimes to surface water and groundwater. The state owns surface water in Texas and holds it in trust for the public. Since 1967[9] surface water has been allocated on the basis of the prior appropriation doctrine of "first in time, first in right" and administered through permits granted by the state to appropriate specific quantities of water.

In contrast, groundwater has historically been minimally regulated compared to surface water because of being privately, rather than publicly, owned. In Texas, landowners are considered to have "absolute" ownership of percolating groundwater within their territory and, according to the rule of capture, may pump groundwater even to the detriment of their neighbors without penalty, although the Texas courts have imposed minimal limits in cases of malicious pumping, negligent pumping that results in land subsidence, or waste (Kaiser 2011).[10]

In practice, local GCDs and other special districts can impose constraints on groundwater property rights. Without a GCD, however, groundwater pumping is not subject to any legal limitations beyond the minimal restrictions associated with the rule of capture. The creation of GCDs was authorized by the Groundwater Conservation District Act of 1949, and at present, there are 100 GCDs, which fully or partially cover 177 of the 254 counties in Texas, and together have administrative jurisdiction over approximately 83% of the groundwater used in the state (TWDB 2015). A GCD is "an alliance of groundwater users who are granted authority by the state to locally manage and protect groundwater supplies within a defined jurisdiction (Lehman 2004)." Locally elected boards of directors carry out permitting decisions, adoption and alteration of district rules, and so forth. GCDs have been described as "almost infinitely variable" (Porter 2013) and may be inactive or proactive in terms of setting rules on users' pumping activities. While there is evidence that they do have some limiting effect on groundwater depletion (Foster 2009), they have been critiqued as often lacking "meaningful protection and management of groundwater (Kaiser 2005)." Still, as the basic political building blocks of groundwater management in Texas, they may be instrumental for increasing adoption of conjunctive water management.

The term "conjunctive management" has been statutorily defined in Texas, and the Texas Water Code (Texas Constitution and Statutes 2015) directs the GCDs (§36.1071(a)) and the 16 regional water planning groups (§16.053(e)(5)) to consider conjunctive water issues in their management plans. Additionally, GCDs are directed, via the periodic groundwater planning process, to take into account surface water–groundwater interactions in their aquifer management goals, known

[9] Between 1600 and 1967, surface water was governed by Spanish civil law, Mexican civil law, both at once, and the English riparian doctrine (Kaiser 2011).

[10] See Hardberger (2013) for a recent analysis of key court cases and legislative activity related to the nature of groundwater ownership in Texas.

as desired future conditions (DFCs) (Mace et al. 2008). But as Kaiser (2012) points out, the Water Code does not specify how exactly that is to be done, and in practice the adopted goals range from the protection of surface flows to simply acknowledging surface water–groundwater interactions.

The Texas Legislature authorized the use of injection wells for ASR of surface water in 1995. However, adoption of ASR has been limited (Pirnie 2011). At present, there is no state-level program for promoting, facilitating, or administering conjunctive management or ASR, as there is in Arizona. Overall, Texas has historically not made the use of conjunctive management a legislative and policy priority.

Arizona

Over the last 3 decades, water use in Arizona has been shifting from groundwater to surface water as the result of 2 related events: the passage of the 1980 Arizona Groundwater Management Act (AGMA) and the completion of the CAP in 1992 (Anderson et al. 2007). Prior to 1980, statewide, the ratio of groundwater use to surface water use was roughly 3:2 (Murray and Reeves 1977); by 2010, the ratio was closer to 3:4 (Maupin et al. 2014). For particular municipalities, the switch from groundwater to surface water was even more dramatic. Tucson relied on groundwater for 100% of its water in 1985, but by 2006 that was cut almost by half to 53% (Megdal 2012). The AGMA provided the regulatory foundation for limiting groundwater use, and the CAP provided the surface water source to the most populous regions and intensive agricultural areas.

The AGMA's main contributions to Arizona groundwater governance are an administrative structure with planning and management authority, and quantified groundwater rights for certain users. It created the ADWR and 4 (later 5) AMAs to implement, regulate, and manage groundwater. The AMAs overlay the most heavily used groundwater basins. Irrigated agricultural acreage is generally prohibited from expanding within these areas. The more heavily populated AMAs of Prescott, Phoenix, and Tucson share the goal of "safe yield," defined as a long-term condition in which annual groundwater withdrawals do not exceed natural recharge, to be achieved by 2025 (ADWR 2014a). The remaining 2 AMAs—Pinal and Santa Cruz—have management goals matched to their settings. Pinal AMA, which is heavily agricultural, was assigned the goal of preserving agricultural economies for as long as possible while also preserving future water supplies for non-irrigation uses (this goal is commonly referred to as "planned depletion") (ADWR 2014a). The Santa Cruz County AMA, which encompasses the only perennially flowing stretch of the Santa Cruz River, has the goal of maintaining "a safe-yield condition in the active management area and to prevent local water tables from experiencing long term declines" (ADWR 2014a). The AMAs, as subdivisions of the Department of Water Resources, are required to adopt 10-year plans that consist of a variety of conservation requirements for municipal, industrial, and agricultural sectors. The increasingly strict conservation requirements, combined with other requirements of the AGMA discussed later, were intended to realize the goals of each AMA.

The ADWR quantified groundwater pumping rights of agricultural and industrial users within the AMAs. The only sectors not granted quantified groundwater rights were municipal and residential uses, although their groundwater use is regulated. Assured Water Supply Program rules, adopted in 1995, require that a water provider demonstrate a 100-year supply of water sufficient to cover all new and existing uses (Megdal 2012). Municipal water utilities within AMAs have met these requirements with diverse portfolios of water, primarily Colorado River water delivered through the CAP; effluent, recharged groundwater; and groundwater allocations. Developers and municipal and private water providers without direct access to surface supplies can use groundwater to supply new developments and still meet the assured water supply program requirements through enrollment with the CAGRD, which replenishes groundwater pumped in excess of amounts allowed by ADWR. The CAGRD primarily relies on recharging CAP water to meet its obligations to its members, but it also holds a portfolio of different types of water.

California

Groundwater governance in California has largely been a local issue (Blomquist 1992; Sax 2002; Langridge 2012). Owners of overlying land can pump groundwater for "beneficial use" up to the "safe yield" point (Katz v. Walkinshaw 1903), and the allocation of groundwater between competing landowners must be "a fair and just proportion." If there is more groundwater in a basin than what overlying landowners need to fulfill their reasonable and beneficial uses, the "surplus" groundwater is available for appropriation and can be used outside of the basin (Foley-Gannon 2000; Blomquist et al. 2004). However, there is no statewide mechanism for determining whether a basin has groundwater in surplus of what the landowners have a right to. As such, groundwater appropriators have depended on private negotiations and litigation to be certain of their rights.

As a rule, California legislation relating to groundwater has focused on empowering local districts to manage groundwater resources. The State Water Resources Control Board (SWRCB) and the CDWR are responsible for coordinating, funding, and very recently overseeing local groundwater agency management. There are over 20 types of districts with statutory authority to manage and provide water for beneficial uses. Most groundwater districts are guided by the Groundwater Management Act, passed in 1992.

Although the legislation provides a method and substantive suggestions for creating a groundwater management plan, local agencies were not mandated to adopt or implement such a plan (§10750.4). The Act has been amended twice to increase substantive statutory requirements for groundwater management, including rules for data collection, monitoring, recharge, and public engagement. For instance, the 2011 amendments clarified the duties of local agencies to provide information to the public (§10753.4(2)).

In 23 basins and 1 stream system, groundwater management and defined limits for groundwater extraction have been decided through court adjudication (CDWR 2014c). All but 2 of the adjudicated basins are located in Southern California. Litigants in water basin adjudications usually negotiate "in the shadow of the court" and reach a stipulated settlement determining groundwater property rights and basin management (see Blomquist and Ostrom 2008). The court appoints a special watermaster, agreed to by the parties, to administer and enforce the judgment and to periodically update the court as to the status of basin.

In 2014, after several years of severe drought, the California Legislature passed 3 bills[11] granting new powers to, and imposing additional duties on, local groundwater management organizations and the State. Together these bills are called the SGM Act. The SGM Act applies to all groundwater basins in California classified as "high" or "medium" priority.[12] If basins fail to form sustainability agencies by June 2017, then the SWRCB may intervene. Groundwater Sustainability Agencies are required to form management plans with statutorily required elements to further the goal of "sustainable" management (§10727.2). The CDWR reviews and evaluates the plans. Those plans need to be implemented by 2022, or 2020 in the case of basins with conditions of critical overdraft. At all stages of planning and implementation, California, through the CDWR and the State Water Resources Control Board, retains the ability to review and intervene in local decisions (§10733; 10733.2; 10735). In addition, Groundwater Sustainability Agencies are given greater powers to enforce their plans, through imposing fees to fund management (§10730) and fines and civil litigation to encourage compliance (§10732). The SGM Act attempts to maintain California's tradition of local management, while providing mechanisms for better coordination, consistency, and review.

[11] Assembly Bill 1739 (Dickinson), Senate Bill 1168 (Pavley), and Senate Bill 1319 (Pavley).

[12] Adjudicated basins are required to form "Groundwater Sustainability Agencies," which can be pre-existing local groundwater agencies.

Nebraska

In Nebraska, groundwater and surface water are governed separately, although more recently integration is occurring. Surface water is governed by the NDNR using the prior appropriation doctrine (Hoffman and Zellmer 2013). A number of river basins have been adjudicated, and rights have been quantified and issued a priority date. In contrast, groundwater is governed by the doctrine of correlative rights, and its use is managed in a highly decentralized fashion through NRDs, which allow water users, primarily irrigators, to manage their own groundwater supplies. Each district is governed by an elected board supported by an executive director and a small staff with operations funded through property taxes (Jenkins 2009).

The districts engage in a wide variety of programs, but by far their most important programs and policies center on groundwater management. Shortly after their creation, the Nebraska Legislature adopted the 1975 Groundwater Management Act that allowed NRDs to create groundwater management areas, with the approval of the NDNR (Hoffman and Zellmer 2013). The creation of a groundwater management area allowed the sponsoring NRD to adopt a variety of regulations, from well spacing requirements to pumping limits, to well moratoria (Fricke and Pederson 1979; Hoffman and Zellmer 2013). A decade later, the Legislature adopted the Groundwater Management and Protection Act that extended the authority of NRDs to regulating and protecting water quality, and by the following year all NRDs had a groundwater management plan in place (Edson 2013). Currently, NRDs actively manage groundwater in partnership with one another and the NDNR.

Most NRDs also engage in integrated groundwater and surface water management, which was motivated by interstate water agreements. In 2002, the U.S. Supreme Court found Nebraska in violation of the Republican River Compact because of the effects of groundwater pumping on surface water flows (Final Settlement Stipulation 2002). In addition, Nebraska entered into an interstate agreement to protect and recover endangered species in the Platte River Basin in central Nebraska, which also required more active management of groundwater pumping to limit effects on surface waters (Aiken 1999; Schlager and Blomquist 2008; Hoffman and Zellmer 2013). The Nebraska Legislature responded in a variety of ways to these interstate events, but 2 pieces of legislation are particularly notable, both for the groundwater regulatory powers adopted and the financing mechanisms created to fund investments in conjunctive water management. In 2004, the Legislature adopted LB 962, which allows the NDNR to designate river basins as over or fully appropriated (Nebraska Revised Statutes §46-713(3)). Once the NDNR makes such a declaration, new wells and surface water diversions are prohibited. Furthermore, the NRDs affected by such a declaration are required to develop IMPs to limit the effects of groundwater pumping on surface water flows. IMPs are developed in cooperation with the NDNR and subject to its approval. In addition, in 2010, the Legislature adopted LB 862 that provides NRDs with funding mechanisms to pay for IMPs and projects through a combination of property taxes, user fees, and bonds (Hoffman and Zellmer 2013; Edson 2013). Also, the Legislature has made available additional millions of dollars through various grant programs for which conjunctive water management projects are eligible (Hoffman and Zellmer 2013). As Hoffman and Zellmer (2013) conclude, “Nebraska’s efforts towards integrated management have the potential to support more adaptive approaches to water resources management and could serve as a guidepost for other western states trying to find better ways to integrate divergent legal and institutional systems to manage water resources.”

In the following subsections, we delve more deeply into administrative structures and practices across the states that intentionally engage in conjunctive management, and compare those structures and practices to Texas before providing a more in-depth analysis of the challenges Texas faces in actively embracing conjunctive management.

Coordination and (de)centralization

While all 4 states rely on at least some level of local coordination with the state government, the jurisdiction and authority of state agencies differ across the 4 states, with varying levels of centralized control.

Two state-managed agencies—AWBA and CAGRD—are responsible for coordinating most of the in-lieu recharge and conjunctive management in Arizona. The AWBA, the biggest conjunctive management actor in the state, was created in 1996 to fully use Arizona’s CAP allocation and to provide storage for municipalities in the event of a shortage on the Colorado River (Megdal 2007). Although it does not own or manage projects, the AWBA obtains water storage permits from ADWR and then delivers CAP water to recharge sites managed by other water purveyors. AWBA account holders earn credits for this storage that can be recovered during drought, adding more certainty for cities. However, the quantity of excess CAP supplies available to banks has steadily decreased as the demands of higher priority users have increased, a trend that is expected to continue and possibly worsen depending on the hydrologic conditions on the Colorado River (AWBA 2014).

A subsidiary of the Central Arizona Water Conservation District that manages the CAP, the CAGRD was created in 1993 amid ADWR’s development of its Assured Water Supply rules, which limited the use of groundwater to supply new subdivisions. The CAGRD was given the ability to obtain and recharge CAP water to offset groundwater mining for urban growth. CAGRD currently has a “portfolio” of long-term water supplies that “yield” about 43,568 acre-feet per year, the majority of which historically has come from recharge of CAP supplies (CAGRD 2015).

California, like Arizona, engaged in a centralized approach to conjunctive management in its construction and operation of massive infrastructure (the SWP) to facilitate recharging overtaxed aquifers with surface water. But, unlike Arizona, California’s approach to governing the details of conjunctive management for groundwater has been far more decentralized and complex. California does not centrally monitor conjunctive management, nor is there an overarching conjunctive management goal for the state (see discussion on Nebraska). Instead, the purposes and methods of conjunctive management vary across the state. Groundwater transfers, 1 among multiple methods of conjunctive management, serve as an example of a method that has been left to local government control. Most of the agricultural lands in the Central Valley contract with SWP and CVP to provide surface water for irrigation (which percolates into aquifers) and to purposefully replenish aquifers.[13] The legal status of surface water stored underground is ambiguous in California, but in general, the stored underground water can be either physically pumped or the rights to pump can be leased and traded to other locations that have insufficient surface water to meet demand. Large-scale, out-of-county transfers are very rare because of a combination of protectionist county ordinances combined with constraints on transfers through the California Bay Delta and other environmental concerns (Hanak 2003; Hanak 2005; Hanak and Stryjewski 2012). As such, most groundwater transfers are local; these types of transfers have been increasing over time, as surface water has become an increasingly unreliable water source (Hanak and Stryjewski 2012).

Nebraska takes a more involved approach to coordinating conjunctive management, although the types of conjunctive management are more limited in that state. Most conjunctive water management in Nebraska occurs through the coordinated regulation and administration of groundwater pumping and surface water diversions.[14] The NDNR and NRDs jointly develop IMPs that are crafted to match the physical, social, legal, and economic settings of each NRD. For instance, the Republican River NRDs have adopted IMPs with the goal of carefully regulating water diversions so that Nebraska returns and remains in compliance with the Republican Interstate River Compact (LRNRD 2011).

Consonant with Texas’ generally decentralized approach to groundwater management, conjunctive management is

[13] Aquifer replenishment to assist with irrigation in the Central Valley was a driving goal behind the construction of SWP.

[14] See NRD Regulations at https://www.nrdnet.org/sites/default/files/state_map_water_management_status_14feb2014.pdf

typically localized as it is in California. Conjunctive management goals are typically established by individual entities such as city water utilities, which use managed aquifer storage. Three currently existing examples of this are the El Paso Water Utilities, city of Kerrville, and San Antonio Water System, as mentioned earlier. However, conjunctive management proposals also develop among the 16 regional water planning groups during the state-mandated water planning process (Webb 2015).

The Edwards Aquifer and the EAA that manages the aquifer constitute an important and unique exception to the hands-off, atomistic approach to conjunctive management in Texas. Unlike other aquifer systems, the state legislature made protection of surface flows from the aquifer a statutory goal to avoid federal intervention related to an Endangered Species Act (ESA) violation in the 1990s (Votteler 1998; 2011). Consequently, developed management practices and programs are designed with this aim in mind. The level of administration and oversight that occurs in the EAA makes it more akin to Nebraska's approach than to other management organizations in the rest of Texas.

Monitoring, modeling, and information availability: the foundation of conjunctive management

It is important to note that successful conjunctive management is not cost-free but instead requires labor and resources for monitoring surface water and groundwater flows—particularly the interactions between them—and administering some type of accounting system to keep track of "banked" surface water. Otherwise, it is difficult or impossible to determine whether management practices are actually having the desired effects and ensure that stored water is quantified and secure over time.

In Arizona, aquifer recharge and recovery within the 5 AMAs relies on an innovative and complex set of accounting systems of water deposits, credits, and withdrawals managed by CAGRD, AWBA, and the various permitted users who report water use to ADWR. This is supported by data collected by ADWR's Hydrology Division on groundwater levels statewide, groundwater use within the regulated areas of the state, well discharge measurements, and some water quality measurements. In addition to operating a network of 113 automated monitoring wells, ADWR manually measures 1,700 index wells annually (ADWR 2012).

Data collection activities support 7 regional groundwater models used to predict groundwater availability under different pumping and recharge scenarios. Five of these models cover the intensively pumped basins encompassed by the AMAs and the other 2 cover 2 critical areas where groundwater affects streamflows: the Upper San Pedro River riparian zone in southeastern Arizona and the Yuma area in the southwest corner. In the Santa Cruz AMA, efforts have been made to account for surface water–groundwater interaction between alluvial groundwater basins and the Santa Cruz River (Shamir et al. 2007).

A combination of state and local monitoring in California is used to support local and regional planning for conjunctive management goals, including water quality. At the state level, monitoring and reporting is intended to assist coordination between multiple local and regional conjunctive management plans and to prevent conflict between them (CDWR 2014a). California has separate monitoring programs for groundwater quality (Groundwater Ambient Monitoring & Assessment Program) and groundwater elevation (California Statewide Groundwater Elevation Monitoring). Each program has separate enabling legislation and is implemented by different state agencies. Monitoring is done through coordination of state government with local agencies.

At the sub-state level, in addition to local agency monitoring, watershed associations have also formed regional monitoring systems. For instance, the Santa Ana Watershed Partnership Association created a regional monitoring group, the Basin Monitoring Task Force, which collects and compiles monitoring data on nitrogen loads in surface water and groundwater. That information is then used to coordinate basin and water district plans that recharge aquifers with surface and recycled water to meet water quality objectives (SAWPA 2014b). Regional monitoring systems, however, are unlikely to be developed around aquifers that have not been adjudicated. The lack of clarity in groundwater property rights leaves an open question as to "how to resolve the ownership/extraction rights related to water that has been artificially added into a multi-jurisdictional/multi-land owner groundwater basin (CDWR 2014a)." Resolving this includes determining ownership and liability, especially in cases where artificial recharge prevents natural recharge—to which all overlying landowners would have had a correlative property right (CDWR 2014a).

In addition to monitoring, California has also invested in integrated models. Models of groundwater–surface water interaction in the Central Valley, like the Central Valley Hydrologic Model, are intended as tools to help water managers decide between different conjunctive management options (see Faunt 2009). Surface water hydrologic models, like CALSIM II and DAYFLOW, are also used indirectly, but with great significance, to determine relative entitlements to surface water deliveries from CVP contractors, who use the water for irrigation and aquifer recharge, and environmental concerns (Ziaja and Fullerton 2015). These 2 models were used by the U.S. Fish and Wildlife Service to help determine the extent to which joint operation of the CVP and SWP imperiled the endangered species in the Bay Delta. That determination in turn affects how much surface water from those delivery systems is available for aquifer recharge (Ziaja and Fullerton 2015).

In Nebraska, monitoring and modeling of water supplies, water demands, and actual water use underpins conjunctive water management and is undertaken primarily by the NDNR and the NRDs. The NRDs gather a variety of types of information that the NDNR uses in its modeling efforts. Wells are metered and NRDs read the meters at least once per year. Also, NRDs collect information on water uses and crops raised. The NDNR, which administers and regulates surface water, requires the measuring of all surface water diversions. It also maintains current records of surface water rights and their priorities. In addition, the NDNR works cooperatively with the U.S. Geological Survey (USGS) to operate a stream gage network and a groundwater well network.

The NDNR- and NRDs-collected hydrologic data is used for integrated hydrologic models that incorporate a groundwater model, a surface water operations model, and a watershed model that captures land uses. The NDNR has developed integrated models for 7 different regions. The models are used to determine over appropriated and fully appropriated status of river segments, to forecast annual compact water delivery requirements and to assist water managers in analyzing the effects of different conjunctive water management programs. Furthermore, in early 2014, the NDNR unveiled INSIGHT, or Integrated Network of Scientific Information and GeoHydrologic Tools. It consists of the data and models used by the NDNR but with a series of user interfaces that allow citizens and public officials to readily access water data organized by basin.[15]

Consistent with the administrative separation of groundwater and surface water, Texas divides water monitoring and modeling duties between agencies and thus is not designed to be conducive to supporting conjunctive management. Groundwater quantity monitoring occurs generally at the state level, by the Texas Water Development Board (TWDB), and at the local level, through individual but overlapping networks of wells within each GCD. The TWDB also runs a groundwater quality monitoring program, sampling 600–700 wells and springs plus 200 or more samples submitted by non-TWDB staff (George et al. 2011). Groundwater quality is also monitored to some extent by water utilities, GCDs, the USGS, and the Texas Commission on Environmental Quality (TCEQ) (George et al. 2011). The TWDB recently added more than 80 years of groundwater-level measurements to its Water Data for Texas website.[16] TCEQ monitors surface water flows and quality.

Like the rest of the GCDs, the EAA maintains a network of wells but, due to its far larger operating budget, also retains a technical hydrological staff with the capacity to conduct groundwater modeling in-house instead of relying solely on the TWDB or private consultants. Currently the EAA maintains 5 water quality monitors distributed between 2 key spring sites (EAA 2013).

The TCEQ uses a water availability model (WAM) to evaluate permit applications for surface water. Groundwater modeling is housed within the TWDB, which operates 17 different groundwater availability models (GAMs) covering the 9 major aquifers and 95% of the groundwater used in the state (TWDB 2013). The GAMs are used to estimate the anticipated effects of different pumping amounts on available groundwater supplies under different scenarios. This estimation is foundational to the development and adoption of DFCs and the primary way that springflows and surface flows can be incorporated.

While the WAM and GAMs both have some capability to incorporate groundwater–surface water interactions, "there has been little interaction between the surface water and groundwater availability models" (Mace et al. 2007), and thus integrating them to better model groundwater–surface water interactions has been pointed out as an important need (Scanlon et al. 2005; Mace et al. 2007; Sansom 2008). Additionally, "[t]o have any hope of accurately simulating surface water–groundwater interaction, there have to have been studies on quantifying that interaction," including measurements of springs over long periods under climatic changes and groundwater pumping, and gain–loss studies (Mace et al. 2007). Scanlon et al. (2005) identified the lack of studies in Texas directly documenting surface water–groundwater interactions as "one of the most critical deficiencies of water-resource knowledge in the state."

Relative disparities in adoption of conjunctive management: what about Texas?

While it is beyond the scope of this paper to exhaustively consider barriers to various types of conjunctive management projects throughout Texas, some general observations seem warranted on the basis of the foregoing comparative discussion that hopefully lend insight to future water management strategies.

First, some types of conjunctive management such as indirect recharge are infeasible because of the limitations of infrastructure, geography, and hydrogeology noted earlier.

Second, there is evidence that the primary reason for lack of adoption of ASR has not been a lack of awareness among water utilities, but rather that laws and regulations have not kept up with the pace of technology and science (Pirnie 2011). Without some assurance that the water stored in an ASR project will not be interfered with or taken away by someone else, conjunctive management is unnecessarily costly or unlikely to happen (Blomquist et al. 2004). Texas has historically lacked such an assurance, and this has even contributed to the cessation of an

[15] INSIGHT may be accessed at http://dnr.ne.gov/insight/

[16] http://www.waterdatafortexas.org

ASR operation in Midland (Pirnie 2011). Additionally, Pirnie (2011) reported that as of 2011, only 22 GCDs in the state had any rules related to aquifer storage and recharge and/or ASR projects, and 3 even had rules prohibiting them. In an effort to address these institutional hurdles, the Texas Legislature recently passed HB 655, a bill designed to streamline and clarify permitting requirements for ASR projects, which in the past differed depending on whether the source water supply was above or below ground (Pirnie 2011). The bill is also intended to add certainty that injected surface water would be recoverable at a later date by generally exempting the pumping of surface water stored underground in an ASR project from the various GCD rules limiting groundwater pumping, unless withdrawn in excess of the amount stored.

Third, and more broadly, there has been a lack of hard limits to water use in many cases beyond simple physical availability, whether on groundwater pumping or instream flows. In Nebraska, designation of fully allocated basins and interstate treaty obligations fostered the development of conjunctive management. Arizona was forced by the Carter administration to control groundwater depletion in order to receive the CAP. In Texas, mining an aquifer is still a permissible management goal and indeed is the norm among the High Plains GCDs that rely on the Ogallala Aquifer. However, the state instream flows program has been working to establish minimum flow requirements on major rivers and streams (Kelly 2011), and concern for managing groundwater to maintain baseflow and springs seems likely to increasingly impose limits on withdrawals in some areas. And although unique in Texas, the EAA's management system is an example of what may be done when limits are imposed on withdrawals.

Looking forward, Kaiser (2012) has suggested that because of having to consider groundwater–surface water interactions as part of the DFCs planning process, GCDs "may become the preferred agency for protecting surface water flows in gaining rivers and streams." Barring a major overhaul of groundwater governance system in Texas, it makes sense that if groundwater is to ever be managed to maintain surface flows, GCDs will have to play a role given their status as regulators. However, we observe a combination of factors that may make this unlikely, at least in the near term.

For one, the groundwater planning process and many GCDs are still relatively new. Many districts were created in the 21st century and the staffs do not have much experience yet. It takes time for managers and state agencies to determine water availability, set groundwater management goals that protect surface flows, and devise evaluation metrics that can be monitored and assessed periodically.

Additionally, it is difficult to imagine the development of the kinds of monitoring networks required to assess the effectiveness of conjunctive management practices that may be developed by GCDs through the DFC process when many GCDs have fewer than 3 staff members, who in some cases are not even full-time employees (Porter Jr. 2013). More technical support is needed in certain areas from the state if conjunctive groundwater management by GCDs is to be effective and have a more sound, defensible basis in physical data on aquifer conditions and connections to surface water bodies. Recognizing the variation in the magnitude and types of resource needs among the nearly 100 districts, 1 proposal suggested creating a special Groundwater District Enhancement Fund that would be administered by the TWDB to funnel state funds to where they are needed (Marbury and Kelly 2009). These funds could be used for different purposes such as developing data collection for improving scientific understanding of aquifers and their interactions between groundwater and surface water, developing better local scale models that are useful for districts, and for purchasing technical equipment for monitoring groundwater and surface water flows and interactions (Marbury and Kelly 2009).

Last, according to Texas case law,[17] there is no legal prohibition or liability for pumping groundwater connected to springs, even if a spring is completely dried up as a result (Kaiser 2005).[18] On paper, GCDs are empowered to prevent this by setting pumping limits to maintain springflows. But if maintaining a minimum flow rate during a severe drought would require significant pumping curtailments, the district may risk a lawsuit from a permit holder who believes the limitation amounts to a regulatory takings, based on the absolute ownership doctrine, as articulated in the controversial *Edwards Aquifer Authority v. Day* decision.[19] And since management goals are non-binding, there is no penalty if they are not met. Thus these institutional factors may inhibit the possibility of meaningful conjunctive management by GCDs with regard to springflow protection.

On the other hand, Welles (2013) has argued that even if Texas common law inhibits conjunctive management of connected groundwater and surface water, this obstacle can potentially be

[17] Two key court cases in which groundwater pumpers were not held liable for diminishing springflows are *Pecos County Water Control and Improvement District No. 1 v. Clayton Williams*, et al., 271 SW2d 503 (1954) (see, e.g., analysis by Kaiser (2005) and Porter Jr (2014) and *Denis v. Kickapoo Land Co*, 771 SW2d 235 (Kaiser 2005).

[18] It is important to note that when underground water is contained in sand, gravel, or soil underneath or laterally connected to a defined watercourse, it is considered to be "underflow," which is governed as surface water and thus not part of a private groundwater right. However, underflow is a legal construction rather than a hydrological term and determining what is and is not underflow, and whether or when a groundwater user is pumping underflow, is not exactly straightforward (Kaiser 2012).

[19] For analyses of the Texas Supreme Court's ruling in *Edwards Aquifer Authority v. Day* 369, SW 3d 814 (S.Ct. 2012) see, e.g., Newman (2012), Hardberger (2013), and Johnson and Ellis (2013).

overcome: "[t]he state's common law doctrine is less important to its ability to achieve successful conjunctive management than the extent to which it embraces a 'management doctrine'—a comprehensive statutory scheme that provides a consistent legal foundation for regulation and supports the flexibility required to manage diverse groundwater basins. A statutory management doctrine that allows managers to limit groundwater pumping and promotes managing hydrologically connected groundwater and surface water as one resource is required to meet the challenges of the future."

Texas' paradigm has been depletion of groundwater followed by increasing reliance on surface water (Ward 2005), but the limits of this approach are becoming increasingly apparent. Recent drought has led to calls for new reservoirs in Texas (as well as in California), but recharge and recovery projects may be preferable from a cost–benefit perspective in some cases. It has been pointed out that "well-managed recharge projects tend to be lower in cost than surface storage alternatives and often avoid negative environmental impacts" (Western Water Policy Review Advisory Commission 1998). Recent cost comparisons by California researchers have placed the cost of groundwater recharge in the range of $90–$1,000 per acre-foot, which compares favorably to reservoir expansion ($1,700–$2,700 per acre-foot) and seawater desalination ($1,900–$3,000 and above) (Choy et al. 2014). Another recent comparison also found groundwater storage one of the least expensive water supply options available (Hanak and Stryjewski 2012). Storage and recharge projects can also reduce costs indirectly "by deferring expansion of water treatment plants and distribution systems" (Webb 2015). They also have the added benefit of not being susceptible to evaporation losses.

However, it should be noted that a number of ASR projects in the United States have been unsuccessful, hampered by financial and physical problems (Bloetscher et al. 2014). They require careful evaluation and, as discussed previously, may require expansion of monitoring and data collection. Nevertheless, their relative cost effectiveness combined with the recent passage of legislation to create a more favorable regulatory environment for ASR projects may increase their evaluation, adoption, and implementation, thus following the lead of states like Arizona and California.

Finally, the foregoing discussion suggests that, overall, for conjunctive water management in general to be a viable water management tool in Texas, Texas would do well to follow in the footsteps of the other states by encouraging local jurisdictions and districts to engage in it and provide the supporting infrastructure to ensure it happens. These states may be particularly instructive given California, Nebraska, and Texas' shared commitment to decentralized groundwater management. At present, it seems unclear whether Texas' GCDs will play a meaningful role in conjunctive water management. Nevertheless, given the commitment to local management and the importance of surface water–groundwater connections and springflows in the state, it may be instructive to examine more closely the experiences with integrated water management plans and integrated hydrologic modeling by the NRDs in Nebraska. They could offer guidance in managing groundwater to maintain surface flows within a decentralized governance system.

CONCLUDING REMARKS

We have emphasized the challenge of responding to the various kinds of disturbances that can pose problems for groundwater governance in U.S., such as drought, interstate conflicts, and endangered species protection. We have focused attention on conjunctive management, which is increasingly recognized as a useful "toolbox" for responding to, and ameliorating, the negative impacts that disturbances can have on water supplies. A few key points emerge from our review of conjunctive management in the 4 states.

First, all 4 states have bifurcated administrative regimes, which is a historical legacy of the legal separation of groundwater and surface water. This separation permeates almost everything from permitting and regulating to monitoring and modeling. Despite this general institutional hurdle, each of the 4 states has used conjunctive management practices to varying degrees to respond to or mitigate the impacts of socio-ecological disturbances.

Facts of geography and infrastructure are major factors determining where conjunctive management can be done and in what ways. While California and especially Arizona rely on large centrally managed canals, Nebraska uses natural stream channels and, more recently, irrigation canals.

Aspects of conjunctive management with room for improvement were also identified. While all 4 states have taken steps to improve the monitoring and reporting of water resource data, some important gaps remain, e.g., inability to obtain water use information from private landowners and local agencies in California. Additionally, integration of groundwater and surface water models appears to be an important need in both California and Texas.

Texas has committed to decentralized groundwater management through local districts and directed them to consider groundwater–surface water interactions in their management goals. However, outside of the unique EAA, integrated management of groundwater and surface water to maintain streamflows and springflows appears to be limited and potentially hampered by legal factors and a lack of information on groundwater-surface water interaction, which is needed integrated modeling is to be done with any effectiveness.

Finally, we discerned a relative lack of adoption of conjunctive management between Texas and the other 3 states. The more water-constrained, semiarid cities such as El Paso and San Antonio have gained reputations as innovators in water management. Yet, Texas in general has historically not taken the next step to active conjunctive management to meet its water sustainability goals to the extent that some other western states have. However, the recent passage of legislation designed to address institutional barriers to aquifer storage and recovery projects, combined with increasing interest among water planners and recognition of the comparative cost effectiveness compared to reservoir construction, seems likely to lead to increasing implementation of ASR projects.

Drawing from the experience of Nebraska, Arizona, and California, the widespread adoption of conjunctive management in Texas could benefit from increasing constraints on aquifer depletion. While none is perfect, each of the other states has institutional mechanisms that place enforceable limits on pumping groundwater. In Nebraska, these come from the legal obligations placed on the state through an interstate compact; in Arizona, limitations come from legislation passed in response to a federal condition on the CAP; and in California, constraints come from the common law doctrine of correlative rights. Texas largely lacks any similar constraints, with the notable exception of those imposed by the ESA to protect the habitat provided by the Edwards Aquifer. The entity with jurisdiction over the Edwards Aquifer, the EAA, remains 1 of the few in Texas with a reputation for proactive conjunctive management practices. In other words, there is growing evidence in the West that where property rights to groundwater and surface water are treated separately, legally enforceable limits on groundwater pumping are fundamental to successful conjunctive management.

In all cases, conjunctive groundwater management only seems to be more important given the need for greater flexibility of water provisioning in light of rapid population growth in the Southwest region, ever-increasing competition within and between states for fully and over-allocated water supplies, threats to habitat, and the recent prognoses of increased aridity (Seager et al. 2007) and drought risk (Cook et al. 2015) associated with climate change for the Southwest and Great Plains states.

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