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THE TEXAS WATER JOURNAL is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management, research, and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

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Cover photo: Lake Austin Dam on the Colorado River, June 15, 1935. Photo CO8484, Austin History Center, Austin Public Library.

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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

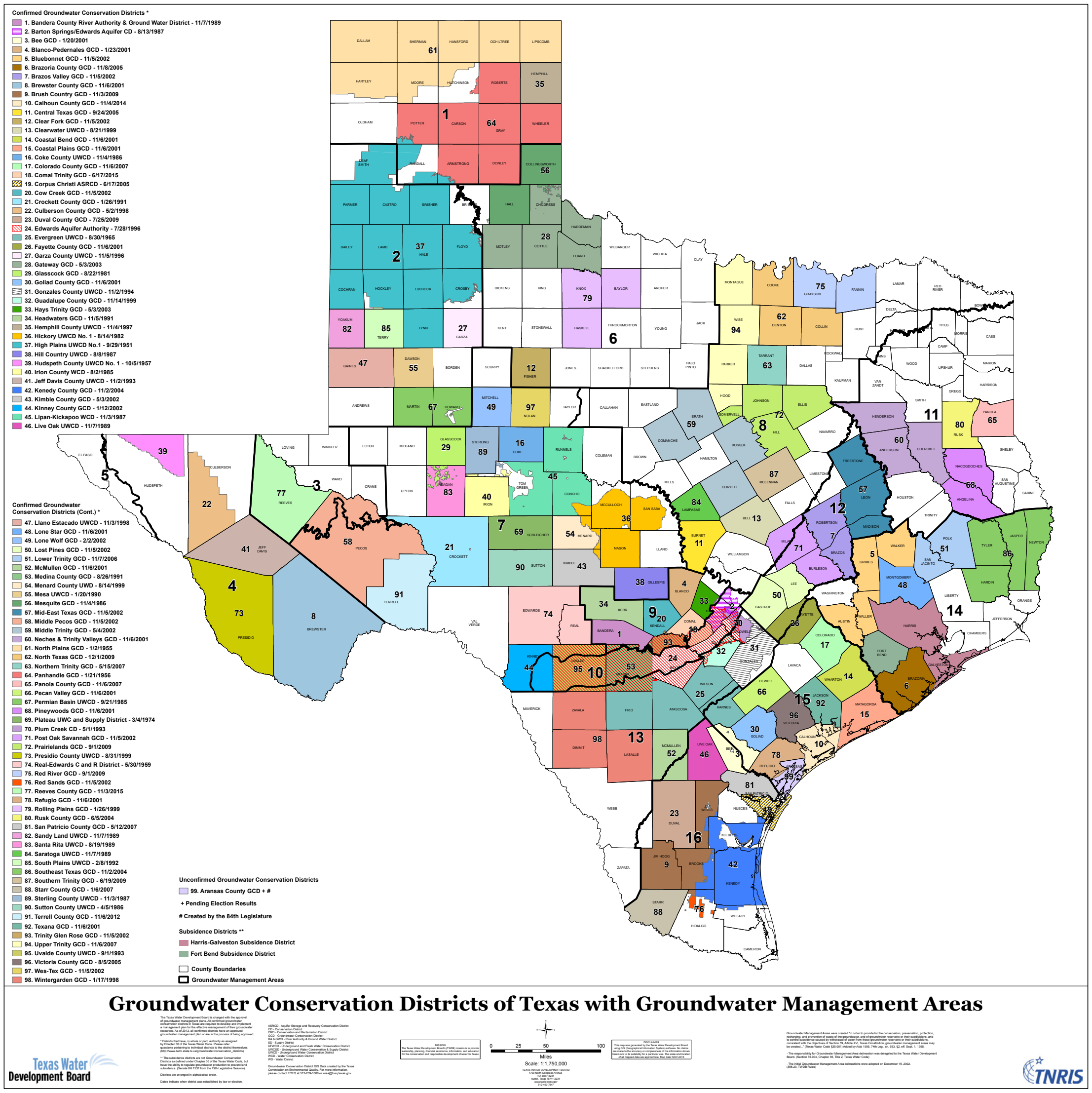

Figure 1. Texas groundwater conservation districts (GCDs) and groundwater management areas (GMAs). Map credit: Texas Water Development Board.

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.

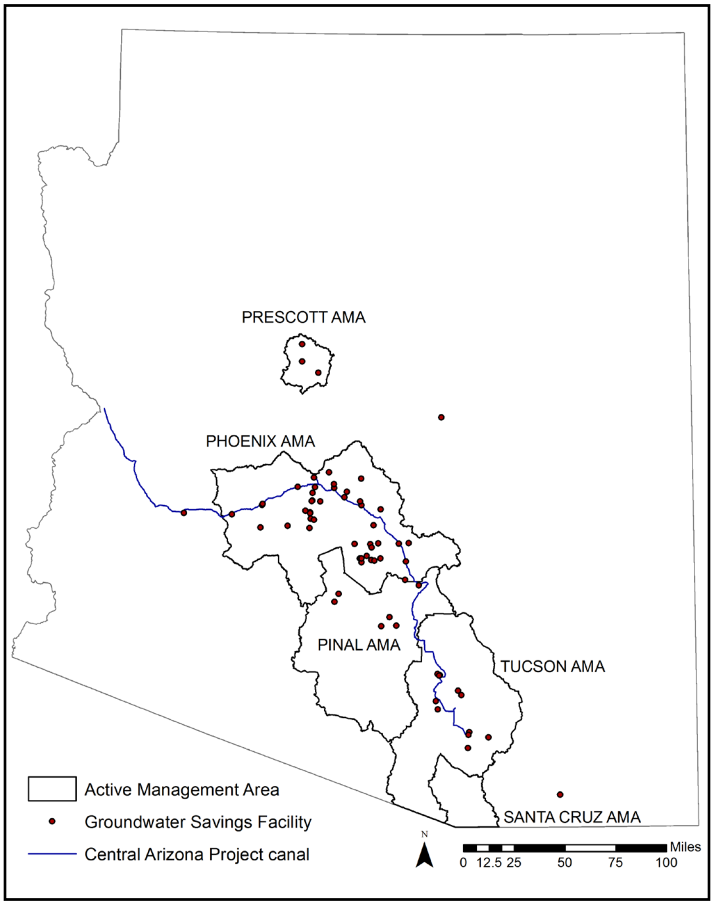

Figure 2. Arizona active management areas, groundwater savings facilities, and Central Arizona Project main canal. Map by authors with data obtained from Arizona Department of Water Resources.

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

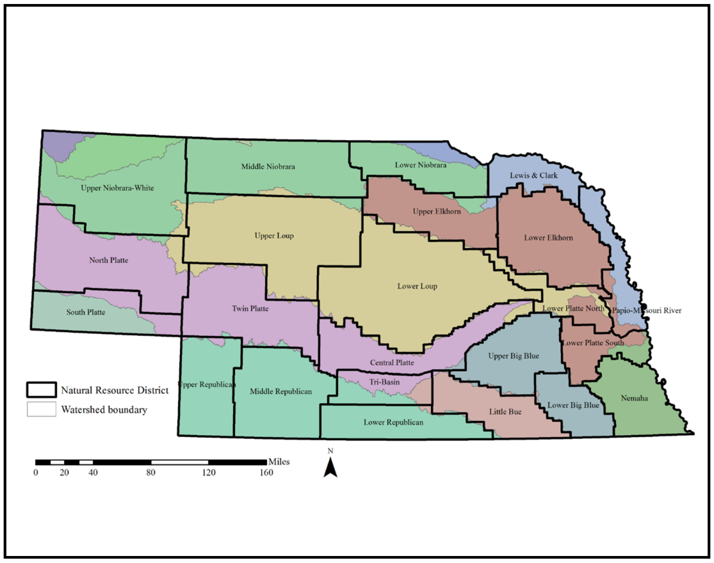

Figure 4. Nebraska natural resources districts (NRDs) and watershed boundaries. Map by authors with data obtained from Nebraska Department of Natural Resources.

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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Comparison of infiltration flux in playa lakes in grassland and cropland basins, Southern High Plains of Texas

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Abstract: Playas are the dominant wetland type on the Southern High Plains of Texas and capture runoff during periods of heavy rainfall. Observing the hydrologic functions of playas is important to evaluate their ecological services, which include encouragement of species biodiversity and recharge of the underlying High Plains (Ogallala) Aquifer. Ten pairs of playas were chosen in 10 counties on the Texas Southern High Plains. Each pair included 1 playa surrounded by natural grassland (not in the Natural Resources Conservation Service's Conservation Reserve Program) and 1 playa surrounded by cultivated cropland. Instrumentation at each playa allowed calculation of changes in free water evaporation and water stored over time during the hydroperiods, defined as continuous durations of surface water storage in the playa basins, caused by one or more rainfall events that generated sufficient runoff flows to reach and fill the playas. A water budget model calculated daily infiltration flux through the playa bottoms. Six cropland playas and 3 grassland playas had significant hydroperiods with associated consistent instrumentation operation during the 6-year study across the years 2005 to 2011. The average observed infiltration flux rates were approximately 10 millimeters/day (range 2 to 20 millimeters/day) and 3 millimeters/day (range 1 to 5 millimeters/day) for the cropland and grassland playas, respectively. The preliminary results may be influenced by the presence of eroded sediments from the surrounding cropland, but more runoff events are needed to differentiate between the impacts of playa floor soils and variations in rainfall and playa watershed characteristics that contribute to the hydroperiods.

Keywords: playas, infiltration, Ogallala Aquifer, evaporation

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Terms used in paper

Short name or acronym	Descriptive name
ARS	Agricultural Research Service
CRP	Conservation Reserve Program
NRCS	Natural Resources Conservation Service
SHP	Southern High Plains
USDA	U.S. Department of Agriculture

INTRODUCTION

Playas are the dominant wetland systems on the Southern High Plains (SHP) of Texas and New Mexico, which is one of the world's most intensely cultivated areas (Bolen et al. 1989). Playas are ephemeral depressional recharge basins that function as stormwater runoff catchments during periods of significant rainfall. Understanding the ecological factors that are shaping the playa's ecosystem is necessary for conservation of these wetlands because playas are becoming the only remaining sites of natural biodiversity within the SHP (Haukos and Smith 1994). These playas support wildlife and plant life species, as well as a variety of invertebrates (Bolen et al. 1989). These wetlands also function as areas of water storage, providing a principal flood control mechanism in the SHP. In addition, playas serve as the primary source of recharge to the underlying High Plains Aquifer system, which is a main source of water for irrigation, livestock, and many municipalities (Reeves 1996). Land use surrounding the playa, either grassland or cultivated land for crop production, controls quantity and quality of runoff and thereby recharge volume through the playas. Besides recharge, water stored in playas can be lost to either free water evaporation or evapotranspiration through vegetation.

Quantifying infiltration flux through playas is necessary to estimate the portion of surface runoff that potentially recharges the groundwater system. As part of the U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) Ogallala Aquifer Program and the Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program, a long-term study of infiltration flux observation began in 2005. This study focused on a pair of playas each surrounded by cropland and natural grassland in 10 selected Texas counties in the SHP. The natural grassland areas were sometimes used by the landowners for grazing cattle. The word "natural" primarily means that those grassland areas were not enrolled in the Conservation Reserve Program (CRP), which normally prevents grazing. All 20 playas were instrumented to measure required weather variables for calculation of free-water evaporation as well as changes in water stored in the playas when inundated. The primary objective of this study was to evaluate the hypothesis that playas surrounded by cropland have faster infiltration flux losses than playas surrounded by grassland. This objective was addressed through field data collection and application of a water budget model to estimate infiltration flux losses through playas surrounded by cropland or natural grassland based on the data collected.

BACKGROUND

High Plains Aquifer

The High Plains (Ogallala) Aquifer encompasses groundwater beneath 450,000 square kilometers in Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, Wyoming, and South Dakota (Opie 2000). The Ogallala Aquifer represents the principal source of domestic and irrigation for the region, which provides much of the nation's livestock, corn, cotton, sorghum, and wheat production (Reeves 1996). The SHP encompasses the southernmost part of the aquifer and includes over 77,700 square kilometers of West Texas and eastern New Mexico (Reeves 1996). Irrigation and other withdrawals exceed recharge in much of the SHP, causing declining water levels in many locations (Mulligan et al. 2005). The areas of the aquifer without withdrawal, however, show increasing groundwater storage.

Playas

More than 20,000 playas have been mapped in the High Plains of Texas based on the presence of hydric soils in historical soil surveys (Fish et al. 1998, PLJV 2009). Figure 1 displays the distribution of playas in Floyd County (PLJV 2009) as an example. A playa wetland is defined as a shallow depression with a relatively flat bottom, sometimes called the lakebed or

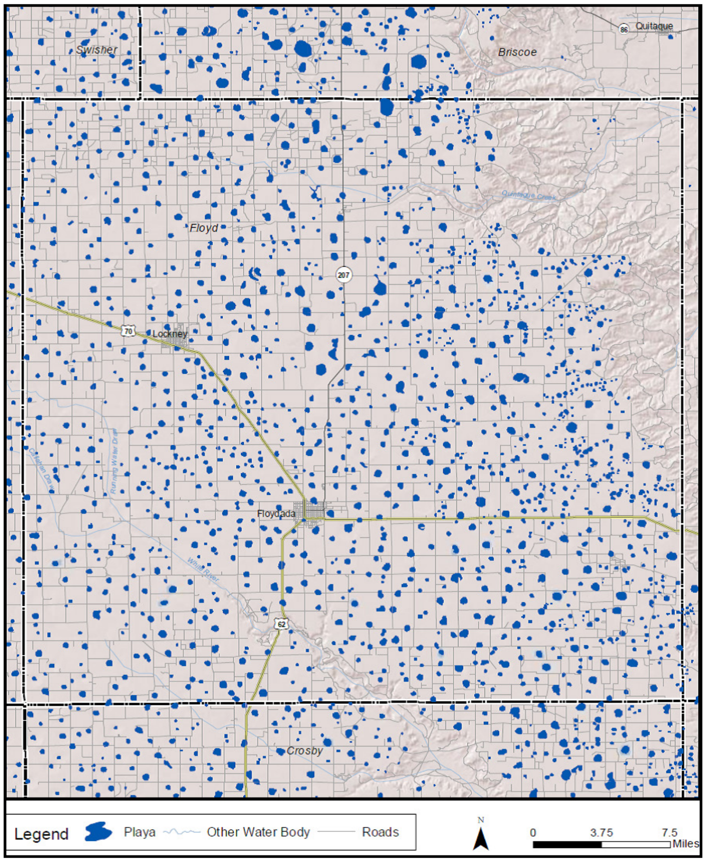

Figure 1. Playa wetlands in Floyd County, Texas (PLJV 2009).

playa floor. Playa bottoms are comprised of 0.3 to 1.5 meters of hydric soils and vertisol clays, usually Randall or Ranco clays (fine, smectitic, thermic Ustic Epiaquerts) in the SHP. Vertisol clays swell when wet and shrink when dry, forming large desiccation cracks (Hovorka 1997). The playa edge sloping upward from the lakebed is referred to as the annulus, which leads to the surrounding watershed, or upland region. The shallow soil texture in the annulus is typically coarser than the playa bottom clays. The Playa Lakes Joint Venture (2009) release notes for Figure 1 stated that the playas in Texas were mapped using the combination of SSURGO soils data, LANDSAT imagery to establish the "wettest image" from 1986 to 2000, and the National Agricultural Imagery Program of the USDA. This approach did not limit the playa shapes to the hydric soil boundaries but allowed for inundated areas in the playas beyond the hydric soils. As our project was also concerned with the water held within the basins, this representation was useful.

It was previously hypothesized by some observers that recharge through the playas was prevented by the playas' clay bottoms (Reddell 1994). Evidence suggests otherwise. First, playas are freshwater systems. If all the water loss within the playas occurred through evaporation, then all playas should be more saline than the rainfall and runoff. Only 40 to 50 large saline lake basins exist as local topographic lows correlated with bedrock highs in the southwestern portion of the SHP (Wood et al. 1992), and their high salinities are due to long-term evaporation of groundwater. Chaudhuri and Ale (2014) noted that the total dissolved solids levels in the SHP groundwater tend to be larger in the southern counties in the SHP, but their study did not tie the ephemeral playa lake water qualities to the aquifer beneath. Infiltrating water from the playas can dissolve materials during movement through the unsaturated and saturated zones. Second, calcrete or caliche layers that typically top the Ogallala formation generally are thin or missing beneath the playas (Reeves 1996). Calcrete is a hardened deposit of calcium carbonate and forms in arid regions when infiltrating rainfall dissolves minerals and redeposits them lower in the soil profile, forming a caliche layer. Since caliche layers are thin or missing beneath the playas, the dissolved minerals must be passing through the bottom of the playa. Finally, tritium in rainwater and runoff from above-ground nuclear testing has been detected at much greater depths beneath playas than in the surrounding upland areas (Nativ 1992; Wood and Sanford 1995; Wood et al. 1997).

Some researchers (Wood and Osterkamp 1984a, b; Claborn et al. 1985; Reed 1994) have proposed that infiltration flux through the annulus may exceed that through the playa bottoms. If the water depth is high enough to inundate the coarser soils along the edge of the playa, infiltration rates in those soils can be faster than those in the playa floor (Wood and Osterkamp 1984; Claborn et al. 1985). The behavior of the expansive clay soil in the playa bottom further complicates the infiltration process. When the playa has been dry for several weeks or longer, the bottom clays form large desiccation cracks (Figure 2a). Coarser sediments carried by runoff from the surrounding cropland can fill the cracks. Grassland playas receive less sediment because the vegetation limits soil erosion. Rainfall intensity must exceed 1.2 to 3 centimeters/day, depending on antecedent moisture conditions, to cause runoff events that inundate or flood the playa (Reed 1994).

Infiltration in the playa floor follows 3 distinct stages (Zartman et al. 1994.). Immediately after inundation, stage I flooding, or macropore infiltration, takes place, in which the cracks in the lakebed allow infiltration at a high rate (Figure 2b). As infiltration progresses, the clay swells and becomes less permeable, resulting in a sharp decrease of infiltration rate during Stage II, as micropore infiltration becomes dominant. Playas surrounded by cultivated cropland may receive coarse sediments in runoff that can fill the desiccation cracks and increase the overall permeability of the playa bottoms sediments. Stage III of infiltration occurs when the soil becomes saturated, resulting in a constant infiltration rate (Figure 2c). Zartman et al. (1994) performed 14 infil-

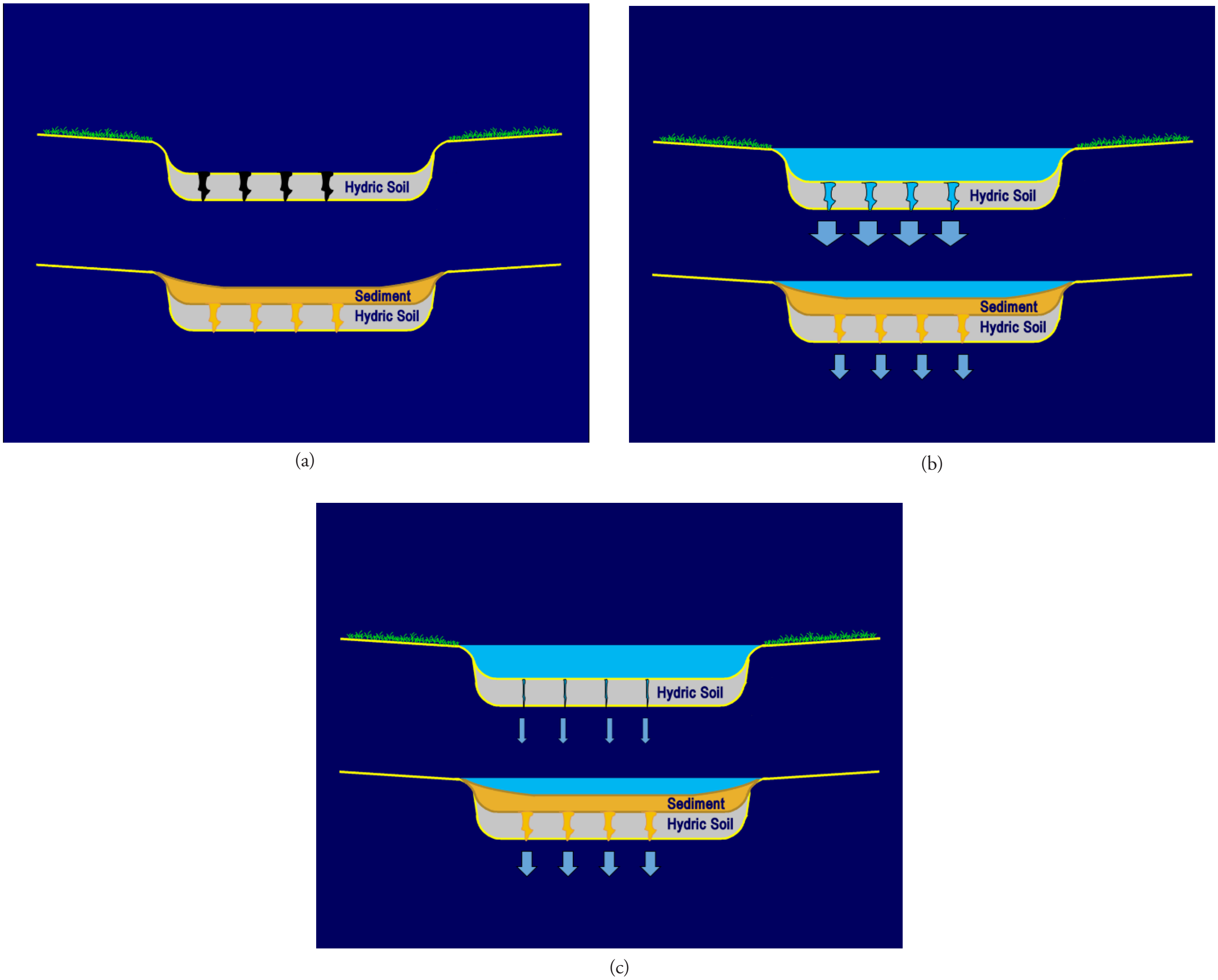

Figure 2. General schematic descriptions of hydrologic conditions near a playa lake, and comparison of conditions in grassland (upper) and cultivated (lower) playas (a) when dry, (b) during the first flush of early inundation, and (c) after days of inundation allowing floor clays to swell.

trometer tests at each of 3 different relative elevations in each of 3 playas. Large Stage I and Stage III rates were noted in infiltrometers that included desiccation cracks. Stage I infiltration rates ranged from 10 to 2490 millimeters/minute with average values between 100 and 200 millimeters/minute. Stage III infiltration rates ranged from 0.004 to 996 millimeters/minute, with average values near 5 millimeters/minute.

Water loss through evaporation from the free water surface occurs also during the hydroperiod, which is the duration when the playa wetland continuously holds water due to one or more sequential rainfall events (Tsai et al. 2007; Gaff et al. 2000), at rates controlled by the temperature, wind speed, and solar radiation. Vegetation can also transpire water from the root zone to the atmosphere at rates depending on the available water content and the growth stage of the individual plants.

Land use in playa watersheds

Land use adjacent to and surrounding a playa can influence its hydrologic function. Upland sites surrounding playas generally consist of cropland or native (or CRP) grassland. In a playa surrounded by grassland, the Randall clay is exposed as hydric soil. In playas surrounded by cropland, however, coarser sediments can accumulate in the basin during runoff events, thereby changing the shape of the basin and reducing the hydric soil-defined volume available for ponding. Luo et al. (1997) compared the effects of sediment accumulation between 20 cropland playas and 20 grassland playas in 11 SHP counties and reported that cropland playas contained 8.5 times more sediment than grassland playas. Their interpretation was that 18 of the 20 cropland playas had lost most of their original basin hydric soil-defined volumes, while grassland playas lost only about one-third of their volumes. Villarreal et al. (2012) compared the sediment depth and grain-size distributions above the hydric soils in pairs of cropland and grassland playa basins in Briscoe, Floyd, and Swisher counties that were also included in the field observations in our project. Their work noted non-uniform distributions of sediment depth and clay/sand fractions. Quantitative sediment depths for playas in Briscoe, Floyd, and Swisher counties from Villarreal et al. (2012) are presented with our results for interpretation of this project's findings.

Alteration of the playa basin due to sediment accumulation also leads to an increase in the amount of surface area per unit volume, thereby increasing the evaporative component of water loss from the playa. Increased evaporation also results in a shortened hydroperiod. Tsai et al. (2007) studied the influences of land use on water loss and hydroperiods of 40 SHP playas. They formulated a tilled index, which is the fraction of tilled or untilled area within a watershed. A tilled index value of 1 indicated that 100% of the land within the watershed was tilled, while an index value of -1 indicated that 100% of the land was untilled. Their results showed that higher tilled index values resulted in a greater water volume loss, demonstrating that a playa with more surrounding grassland will have longer hydroperiods. The ability of wetlands to store water has ecological, environmental, and economic implications (Luo et al. 1997). Maintaining natural and therefore longer hydroperiods is necessary for persistence of plants and animals that use the playa wetland. The CRP serves to replace cultivation with grasses to reduce erosive losses within the playa. These grasses may also benefit the playa hydrologic behaviors.

Field observations

Analysis of recharge from the playas began in the 1930s. It was originally believed that evaporation from the playas was more common than infiltration, as indicated by Schwiesow (1965), who estimated that less than 10% of runoff water reaches the aquifer by infiltration through the soil, and more than 90% of this water is lost through evaporation. Water budget studies in several master's thesis projects at Texas Tech University, however, demonstrated otherwise and have shown that more recharge takes place than previously thought. Koenig (1990) studied the effects of macropores on infiltration patterns in the basin soils of a cultivated playa in Lubbock County using a 7.6-meter diameter basin infiltrometer. Three trials were conducted at 3 sites in the playa during April and May of 1990. Results indicated that infiltration rates were 418, 225 and 349 millimeters/hour during the first 28 minutes. Initial soil moisture contents were 15.6%, 28.4%, and 18.8%, respectively, for the 3 trials, indicating that the higher initial soil moisture contents resulted in lower initial infiltration rates.

Evans (1990) investigated the bimodal infiltration patterns in 3 playas in Lubbock County. The 3 playa watersheds were in cropland, grassland, and CRP. For each playa, stage I and stage III infiltration rates were determined at 90 different sampling points via a double-ring infiltrometer method. The inner and outer rings were 128 and 205 millimeters in diameter, respectively. Stage III infiltration rates were 720, 900, and 2000 millimeters/hour for cropland, grassland, and CRP playas, respectively. Stage III determinations were made at the end of 3 days for 2 of the wetlands and at the end of 2 days for the third playa due to unexpected flooding. Stage III infiltration rates were high because steady-state flow had not yet been achieved in all infiltrometers within the 3-day test period — much shorter than natural playa hydroperiods of weeks to months.

Reed (1994) conducted a water budget study of 3 playas in Carson County at the Pantex Plant. Playa 1 received discharge from the site's wastewater treatment plant, and, as a result, retained water continuously, along with runoff from surrounding industrial and grassland areas. Playas 2 (cropland and grassland) and 3 (grassland only) only received storm runoff. A water budget model was developed specifically to calculate infiltration rates through Playas 2 and 3. Daily meteorological data from the National Weather Service station at the Amarillo airport were used to compute evapotranspiration rates by the Penman equation. Typical infiltration rates ranged from 3.1 to 7.5 millimeters/day (totaling 1930 millimeters/year) for Playa 2 and 2.1 to 4.4 millimeters/day (totaling 1185 millimeters/year) for Playa 3. Wood et al. (1997) later expanded the study to specifically relate recharge amounts of macropore recharge within the playa floors to micropore recharge in the upland areas surrounding the playas. Based on the combination of the water budget results with geochemical chloride and tritium tracer calculations, they estimated that macropore flow was 25 to 50 times faster than interstitial flow through the playa bottom sediments.

James (1998) reported a hydrologic budget analysis on 5 urban playa lakes that were permanently wet due to urban storm runoff from Lubbock, Texas, over a 2-month period in the summer of 1995. In urban settings, urban playas collect stormwater volumes that have been increased by land development and urbanization. During the residential and commercial development of these neighborhoods, these playas were deepened by removing some of the natural hydric soils to increase the storage volume for the increased runoff from the increased impervious areas, but the bulk of the playa floor soils were still the Randall clay found in the rural playas. Water surface elevations were measured using pressure transducers. Meteorological data were obtained from the National Climatic Data Center for evapotranspiration calculation, and topographic data were obtained from bathymetric and land surveys. The water budget analysis yielded infiltration fluxes that ranged from 3 to 48 millimeters/day and hydroperiods of 18 to 49 days. West (1998) performed a companion water budget analysis on 6 urban playa lakes in Lubbock, Texas, including 5 of the same lakes observed by James (1998). Six lakes were observed during the summer of 1995, and 2 lakes were also monitored during the summer and fall of 1997. West (1998) noted that the infiltration rates varied from 1.5 to 14 millimeters/day, with hydroperiods varying from 11 to 142 days.

METHODS

Study area

For this study, 10 pairs of playas, 1 surrounded by cultivated cropland and 1 by grassland, were chosen in 10 SHP counties as shown in Figure 3 and Table 1. The study sites were selected as pairs of similarly sized playas, each relatively close to the other to minimize differences in rainfall and surrounding soils. The watershed area contributing to each playa was carefully delineated considering both local topographic maps and the influence of roadways and ditches; the watershed areas are also listed in Table 1.

Table 1. Location and land use of playas.

Station	County	Land use	Latitude (decimal degrees)	Longitude (decimal degrees)	Watershed area (hectare)
1	Floyd	Grass	34.095	-101.117	145
2	Floyd	Crop	34.073	-101.315	244
3	Briscoe	Crop	34.487	-101.279	391
4	Briscoe	Grass	34.499	-101.398	161
5	Swisher	Crop	34.542	-101.571	125
6	Swisher	Grass	34.486	-101.548	83
7	Hockley	Grass	33.401	-102.485	129
8	Hockley	Crop	33.494	-102.408	109
9	Bailey	Grass	34.021	-103.018	244
10	Bailey	Crop	34.033	-102.676	103
12[1]	Lubbock	Grass	33.491	-101.591	18
13	Lubbock	Crop	33.807	-102.056	187
14	Crosby	Crop	33.541	-101.298	203
15	Crosby	Grass	33.512	-101.260	169
16	Castro	Crop	34.544	-102.231	557
17	Castro	Grass	34.665	-102.221	566
18	Carson	Crop	35.358	-101.321	586
19	Carson	Grass	35.461	-101.280	364
20	Gray	Crop	35.266	-100.951	51
21	Gray	Grass	35.268	-100.922	21

[1]Station 11 was assigned to the Lubbock data collection site.

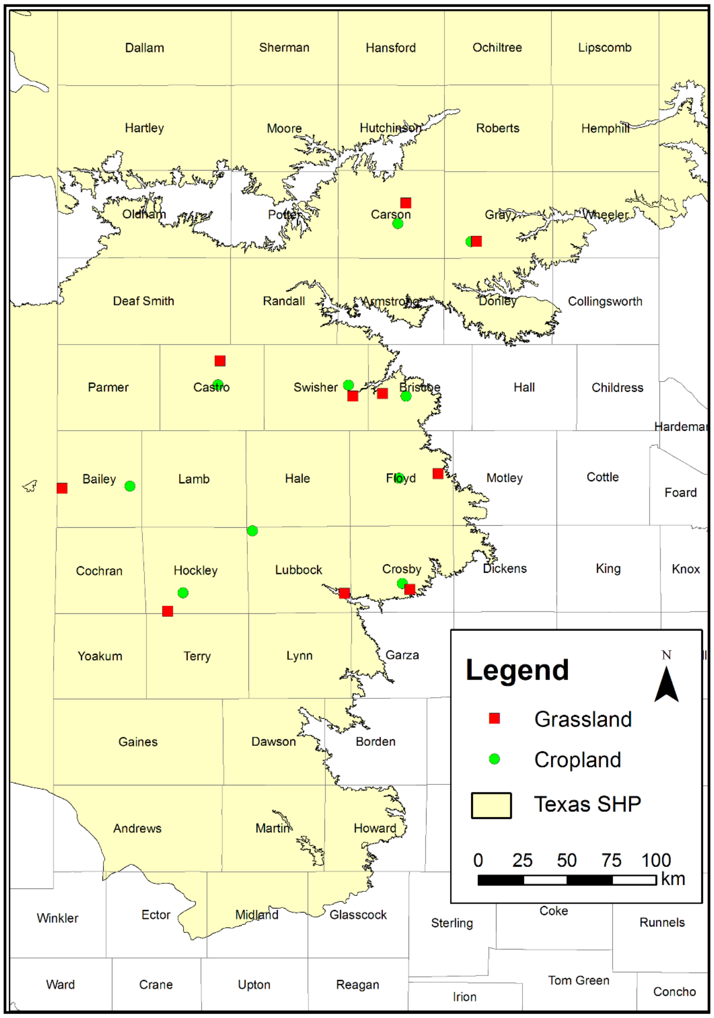

Figure 3. Study area showing playa locations in the Southern High Plains (SHP) in Texas.

Basic water budget

The hydrologic budget model is an application of the law of conservation of mass for the playa lake for a given time period, as expressed by the continuity equation denoted by equation 1

$$\Delta S = PA + R - EA - IA \tag{1}$$

where P = precipitation (meters), R = runoff into the playa (meters^3), E = free water evaporation (meters), A = free water surface area (meter^2), I = infiltration flux (meters), and ΔS = change in storage (meters^3). Transpiration losses by vegetation type and season within the inundated playa were not considered separately as collection of that data was beyond the scope and budget of the project. The research team chose to emphasize collecting similar data in as many playa locations and land uses as financially feasible, which limited the types of data that could be quantified. The free water evaporation loss from the playa water surface to the atmosphere was assumed to be much greater than transpiration because of the large water surface area of the playa relative to the coincident vegetation. Movement of runoff into the playas was primarily overland flow that could not be measured directly, and some playas were also influenced by roadway ditches or subtle flow channels that drained part of their watersheds.

The project team defined an inundation period as the time between consecutive significant precipitation events during which the playa held standing water. In dry periods of no rainfall, the water depth in the playa was constant at zero. Inundation began when runoff from rain events initially flooded the playa. Following significant rainfall events and subsequent inundation, the water depth in the playa increased due to runoff and then declined due to infiltration flux and evaporation.

Precipitation and runoff were considered inputs to the playa system, whereas evaporation and infiltration were considered outputs. Change in storage represented the quantity of water left in the playa after accounting for losses due to evaporation and infiltration. Between precipitation and runoff events, runoff and precipitation were zero, leaving

$$I = -\left(\frac{\Delta S}{A}\right) - E \tag{2}$$

for a given time period. Free water evaporation can only be estimated using calculations based on multiple weather data measurements as shown in the next section, each with its own uncertainty caused by instrument and maintenance limitations. The change in storage for the playa contains approximations based on the water level measurement approach and movement of the water surface caused by winds as well as the surveyed topography of the playa bottom. All of these uncertainties are then lumped into the overall estimate of infiltration through the playa floor as the final unknown in the water budget. The total error in the infiltration calculation could be similar in magnitude to the calculated values, which encouraged great care in all instrument maintenance, data processing, and evaluation of the numerical results.

Evaporation model

For this study, the Penman-Monteith equation was used to model evaporative losses from the playa basin and is denoted by equation 3 below (Maidment 1993).

$$E_p = \frac{\Delta}{(\Delta+\gamma)}\frac{R_n}{\rho_w \lambda} + \left(\frac{\gamma}{\Delta+\gamma}\right)\left(\frac{6.43(1+0.536U_2)D}{\lambda}\right) \tag{3}$$

where E_p = potential evaporation (millimeters/day), R_n = net radiation exchange for the free water surface (millimeters/day), U_2 = wind speed, measured at 2 meters (meters/day), D = vapor pressure deficit (kilopascals), λ= latent heat of vaporization (megajoules/kilogram, Δ = gradient of vapor pressure (kilopascals/degree Celsius), γ = psychrometric constant (kilopascals/degree Celsius, and ρ_w = density of water (kilogram/meter^3). The vapor pressure deficit (D) is calculated as

$$D = e_s - e \tag{4}$$

where e = vapor pressure (kilopascals) and

$$e_s = 0.6108\, exp\left(\frac{17.27T_a}{237.3+T_a}\right) \tag{5}$$

where T_a = observed air temperature (degree Celsius).The latent heat of vaporization (γ) is calculated by

$$\lambda = 2.501 - 0.00236T_s \tag{6}$$

where T_s = observed water surface temperature (degree Celsius). The gradient of vapor pressure is found as

$$\Delta = \frac{4098e_s}{(237.3+T_a)^2} \tag{7}$$

The psychrometric constant (γ) is calculated by

$$\gamma = 0.0016286\frac{P}{\lambda} \tag{8}$$

where P = atmospheric pressure (kilopascals). A wind speed correction factor of 1.0082 was recommended by the manufacturer for the instrumentation (Campbell Scientific, Logan Utah, 1998) to scale up the wind speed, U_2 (meters/second), observed at the sensor level.

It should be noted that true values of free water evaporation are not available, as all equations or field observations in evaporation pans or other devices are estimates at best. The Penman-Monteith equation was selected as a model to calculate evaporation rates because of its success in 2 previous regional studies. The complex nature of equations 3 through 8 makes it difficult to quantify the uncertainty in the daily evaporation calculations based on the uncertainties in the multiple observed weather data. Acceptance of the calculated estimates is typically supported by comparing them with other reported estimates from nearby locations. Dean (1993) confirmed that evaporation rate estimates from the Penman-Monteith equation agreed with corrected pan evaporation measurements from a local research station in Lynn County in 1990-91. The average daily evaporation rates for the Penman-Monteith and corrected pan evaporation methods were 5.5 and 5.6 millimeters/day, respectively. Rainwater et al. (2005) used a Penman-type equation to calculate evapotranspiration (ET) rates in a study dealing with septic tanks and their drainfield capacities. During the year 2000, the total ET was 1820 millimeters, which compared well to the average uptake of 1830 millimeters from the ET trenches. In the current study, the calculated free water evaporation estimates were measured to the Texas Water Development Board's monthly lake evaporation data reports for appropriate locations across the state (TWDB 2014). These data were provided as monthly totals in each year, so seasonality and precipitation impacts were included, even though the daily values were not provided. Weighted average evaporation rates were calculated for the hydroperiods.

Weather stations and device information

Instrumentation units were assembled and placed within the playa basins to track precipitation and water level, and provide variables for calculation of free water evaporation. Sensors for measuring wind speed (014A Anemometer*, Met One Instruments, Grants Pass, Oregon), air temperature and relative humidity (HMP50-L Temperature and Relative Humidity Sensor, Campbell Scientific Inc.), precipitation (TR-525M tipping bucket rainfall sensor, Texas Electronics Inc. Dallas, Texas), and water depth (260-700 Ultrasonic Snow Depth Sensor, NovaLynx Corp. Grass Valley, California) were mounted on a horizontal boom at 2 meters above the playa bottom. A 1 meter by 1 meter steel plate placed directly below the ultrasonic depth sensor prevented weed growth and provided a clean echo reflection surface. Radiation as both global down-welling solar radiation (LI-200 solid state pyranometer, LiCor Inc. Lincoln, Nebraska) and net solar radiation (NR-Lite2 thermopile radiometer, Kipp & Zonen USA Inc., Bohemia, New York) were measured with sensors placed on the primary tripod or on a remotely mounted 2-meter mast. A thermocouple mounted on the lower surface of an expanded Styrofoam float measured the water surface temperature. Another thermocouple placed at a depth of 5 centimeters below the soil surface measured the temperature of the playa basin. All data were recorded as 15-minute averages. With the exception of wind speed and precipitation, all variables were logged at 1-second intervals averaged over 15 minute and were recorded with a programmable datalogger (CR-1000, Campbell Scientific Inc.). Because precipitation and wind speed transducers deliver discrete pulses rather than continuous voltages, these data were

*Mention of this or other proprietary products is for the convenience of the readers only and does not constitute endorsement or preferential treatment of these products by USDA-ARS.

totaled over 15-min periods and recorded. A digital cellular modem provided internet connectivity to each datalogger so that data could be downloaded weekly for cursory inspection and plotted monthly for visual inspection and comparison in an attempt to ensure data integrity.

Equations 3 through 8 were used to calculate the evaporation for each 15-minute time interval in each day, then those values were summed to get a daily evaporation amount. The average water surface elevations for each day were used to estimate the water surface area and storage volume for each day.

Elevation-area and elevation-volume relationships

As shown in equation 2, the water budget components for this study, storage, evaporation, and infiltration flux were calculated on a volumetric basis. The Penman-Monteith procedure in equations 3 through 8 yielded potential evaporation rate in millimeters/day. Therefore, a method was required to determine the changes in playa water storage on a volumetric basis, as well as playa water surface area to convert the evaporation rates to a volumetric basis. Elevation-volume and elevation-area curves were developed from topographic data determined through GPS surveys and Surfer® (Golden Software 2009). Polynomial equations were fitted to the data points to calculate each elevation-volume and elevation-area curve. For some of the playas, single smooth trend lines sufficiently fit the data. In some instances, several polynomial lines were required for different segments of the data, thereby completely representing the surveyed topography. The playa bottom shapes varied from near circular to rectangular when viewed from above, the playa bottoms were not completely flat, and the upward slopes at the edge of the hydric soils into the coarser annulus upland soils were not consistent. The goal was to honor the data points calculated by Surfer® rather than produce smooth curves.

Water budget calculation

The water surface elevation values for the playas after each rainfall event were used as the independent variables in the volume and area curves. The volume of water stored and the surface area of water at the exact water surface elevation were computed using the polynomial equations from the volume and area curves. The change in storage was computed and the daily evaporation, multiplied by that day's surface area, resulted in evaporation values on a volumetric basis. Adhering to the water budget model in equation 2, subtraction of evaporation from storage resulted in the estimate of infiltration volume through the playa bottom, which was then divided by that day's water surface area to obtain the daily infiltration flux. Daily infiltration flux values were averaged for each inundation period. Sequential inundation periods were summed for the lengths of the hydroperiods.

Uncertainties in the free water evaporation calculations and the water level measurements were both lumped into the final estimate of the daily infiltration flux. Quantitative analysis of errors is possible for the results of simple equations that combine variables that can be assumed to be normally distributed, or at least have simple error distributions within the range of observed values. In our case, the observed weather variables varied both within each day as well as across seasons of the year, so comparison of mean or median values with associated variations about those values was problematic. The challenge of calculating small amounts of infiltration flux by comparing small changes in water levels and daily evaporation amounts was still well worth pursuing, but precise quantification of errors in infiltration flux was not pursued. The hypothesis considered the potential difference in infiltration fluxes between playas with different surrounding land use, so the means and standard deviations for the inundation events observed in each playa were compared.

RESULTS

Deployment of instrumentation began in 2005, and data collection continued into 2011. Occasional instrument problems were encountered and repaired, but unfortunately some rainfall and inundation events were not captured completely. During that time period (2005–2011), the Floyd grassland (station 1), Floyd cropland (2), Briscoe cropland (3), Swisher cropland (5), Hockley cropland (8), Bailey grassland (9), Bailey cropland (10), Castro grassland (17), and Gray cropland (20) playas received sufficient rainfall for significant inundation while all instruments were operational. Examples of the relationship between rainfall and water depth in playas during their hydroperiods are shown in Figures 4 to 10. The figures emphasize long-term observations while the playas were inundated, so the time scales differ between playas, and the infiltration conditions are Stage III.

Typical calculated daily evaporation rates are shown in Figure 11 for the Briscoe cropland playa (3). The evaporation rates adhered to normal seasonal weather patterns (higher in summer, lower in winter), as well as day and night diurnal variations. The relationship between infiltration rates across the playas varied over time based on the differences in rainfall/runoff events that affected the depth of water in the playas (providing hydraulic head for infiltration), the season of the year (higher evaporation during the summer and lower evaporation in the winter), and the land use differences. For example, both playas in Floyd County held water during 3/10/2007 to 1/20/2008. The grassland playa infiltration rates for different inundation periods varied from 0.2 millimeters/day during 6/12/2007 to 7/12/2007 (depth fell from 68 to 50 centimeters) to 2.4 millimeters/day during 12/27/2007 to

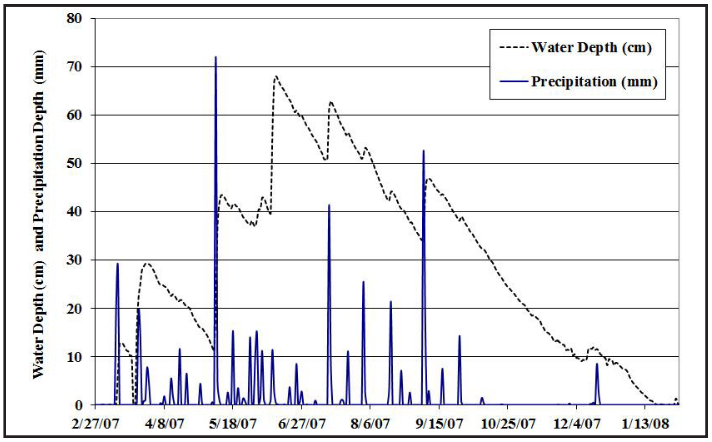

Figure 4. Water depth and precipitation during significant inundation periods at Station 1, Floyd grassland playa.

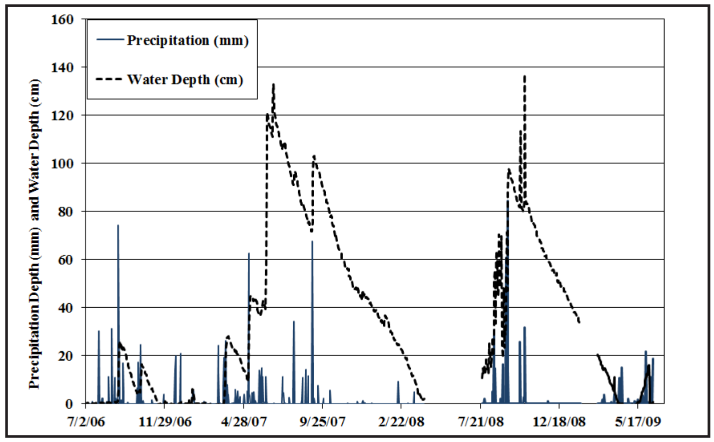

Figure 5. Water depth and precipitation during significant inundation periods at Station 2, Floyd cropland playa.

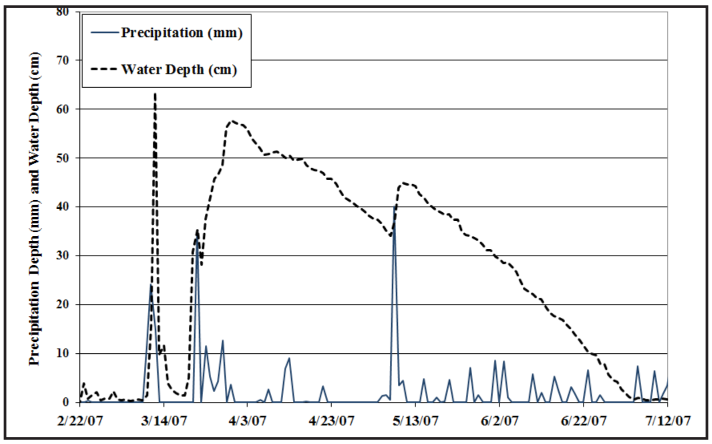

Figure 6. Water depth and precipitation during significant inundation periods at Station 3, Briscoe cropland playa.

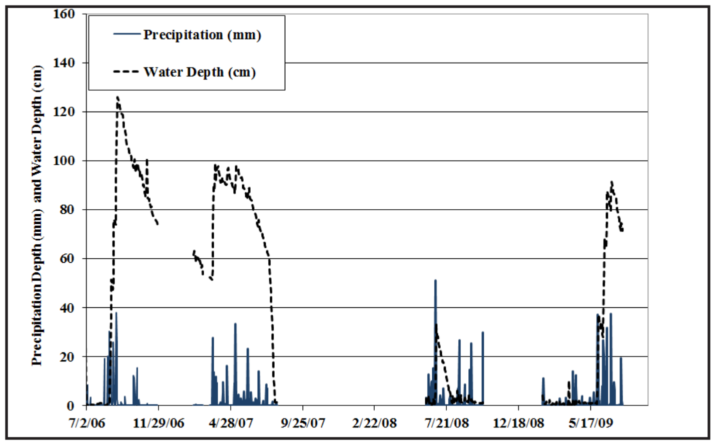

Figure 7. Water depth and precipitation during significant inundation periods at Station 5, Swisher cropland playa.

1/20/2008 (depth fell from 8 to 0 centimeters). The cropland playa infiltration rates for similar inundation periods were 7.0 millimeters/day during 6/24/2007 to 7/10/2007 (depth fell from 132 to 105 centimeters) and 1.7 millimeters/day during 12/11/2007 to 1/14/2008 (depth fell from 47 to 33 centimeters). These incremental values from Ganesan (2010) demonstrated the complexity of the comparisons.

An example of the elevation-volume and elevation-area curves is shown in Figure 12 for the Floyd grassland playa (1). The shape of the elevation-area curve shows that the area of the water surface increases by 100% within the first 10 centimeters of elevation change, then by another 50% over the next 70 centimeters. Complete sets of all observations and measurements are available from the corresponding author upon request.

Hydroperiods varied with location and rainfall amount (Table 2, Figure 13). Based on our definition of inundation period as time with water stored in the playa between rainfall events, it should be noted that multiple inundation periods were often included in 1 hydroperiod. The TWDB (2014) ranges of lake evaporation rates for the different counties and time periods are also listed for subsequent comparison to our calculated values. Seven of the 25 hydroperiods lasted through at least part of the winter months (Bailey grassland once, Floyd grassland once, Floyd cropland 3 times, and Swisher cropland twice), which were historically the months with the least rainfall and runoff. The prolonged hydroperiods were caused by sequential storm frequency and intensity, with the time between rainfall events insufficient for complete drainage. The other 18 hydroperiods ranged from less than 2 weeks to over 5 months. The shortest hydroperiods were associated with the cropland playas in Swisher, Hockley, Gray, and Bailey counties. The shortest hydroperiods were greatly affected by their relatively small amounts of rainfall. The 2 grassland playas with observed hydroperiods received relatively large amounts of rainfall during those hydroperiods. The relationship between hydroperiod length and precipitation is shown in Figure 13. The total hydroperiod in days, H, versus total rainfall in milli-

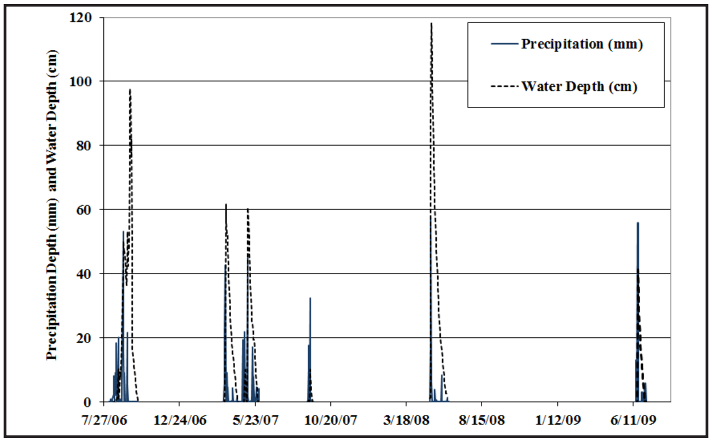

Figure 8. Water depth and precipitation during significant inundation periods at Station 8, Hockley cropland playa.

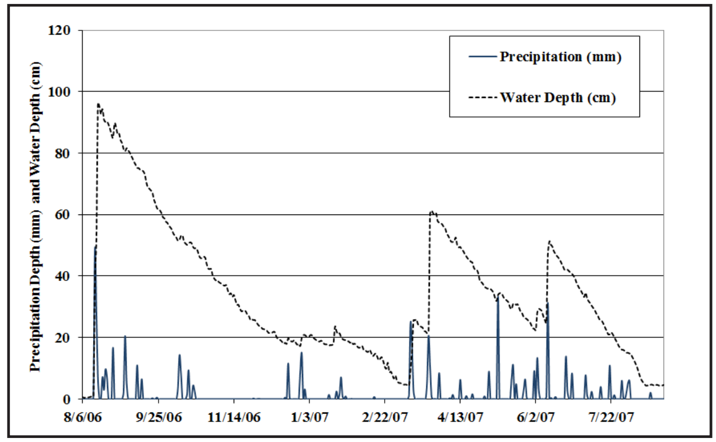

Figure 9. Water depth and precipitation during significant inundation periods at Station 9, Bailey grassland playa.

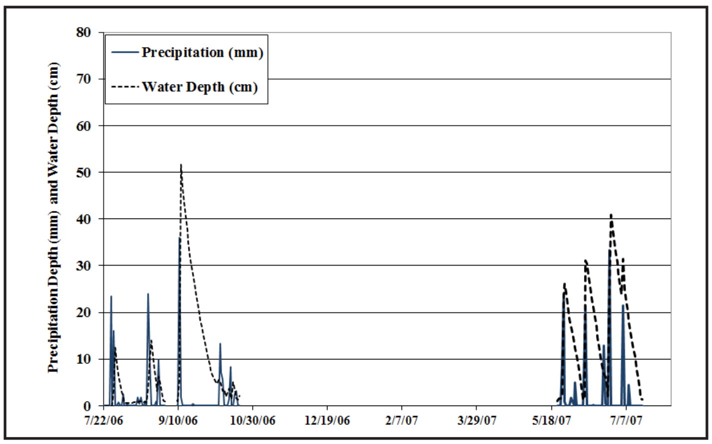

Figure 10. Water depth and precipitation during significant inundation periods at Station 10, Bailey cropland playa.

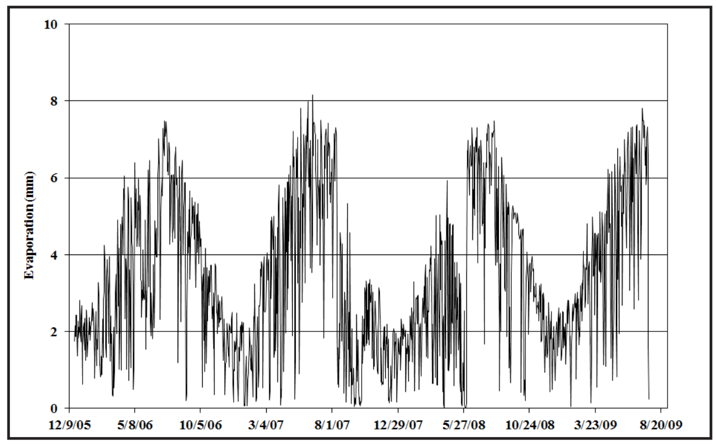

Figure 11. Daily evaporation values at Station 3, Briscoe cropland playa.

meters during the hydroperiods, P_H, was fitted with a power law equation as

$$H = 0.13\, P_H^{1.23} \quad (9)$$

with R^2 of 0.91. The fitted equation is interesting but simplistic, as it does not include any other variables that describe the rainfall events or hydrologic characteristics of the playas or their watersheds. It should also be noted that the smallest P_H value included in Table 2 was 43 millimeters in the Bailey cropland playa, of which almost 24 millimeters fell on the first day of inundation, similar to other observations of threshold precipitation amounts for runoff to playas (Reed 1994). Future progress by the research team with more observations in more playas should improve understanding of the characteristic behaviors of the playas in different locations and land use.

Water budget results are displayed in Table 3. Among the playas surrounded by cultivation, the number of inundation periods varied from only 1 for the Gray cropland playa to 42 for the Briscoe and Swisher cropland playas. The Floyd, Bailey, and Castro grassland playas had inundation periods of 12 , 15, and 5 days, respectively. Average inundation period lengths, which represented the time between significant rainfall events during hydroperiods, ranged from 12 days for the Bailey and Swisher cropland playas to 29 days for the Briscoe cropland playa. Of course, the frequency of rainfall events did not depend on the location or land use but was more subject to random meteorological conditions. The calculated average evaporation rates shown in Table 3 appeared reasonable as compared to the weighted average evaporation rates from the TWDB (2014) database for the hydroperiods. Daily evaporation and infiltration volumes were found by multiplying the daily evaporation rates by that day's average water surface area.

Figure 14 allows visual comparison of the average infiltration flux rates for each playa, along with their standard deviations. It is noted that these datasets may not be large enough for proof of normal distributions, but the mean and standard deviations are useful for this preliminary comparison. In Floyd and Bailey

Table 2. Summary of hydroperiod data.

Station	County	Land use	Hydroperiod dates	Hydroperiod duration (day)	Rainfall (millimeters)	TWDB evaporation (millimeters/day)
1	Floyd	Grass	3/10/07–1/20/08	254	557	4.6
2	Floyd	Crop	9/1/06–11/17/06	78	210	4.3
			3/21/07–4/3/08	378	472	4.5
			7/13/08–4/10/09	269	332	4.5
			4/16/10-1/5/11	254	520	5.6
3	Briscoe	Crop	3/18/07–7/4/07	109	216	4.0
5	Swisher	Crop	8/18/06–7/31/07	254	479	3.9
			6/22/08–8/2/08	42	93	7.4
			5/22/09–7/23/09	63	238	7.2
			6/5/09–11/17/09	166	378	6.3
			4/16/10–1/18/11	275	608	5.5
8	Hockley	Crop	8/19/06–10/3/06	45	197	4.7
			3/20/07–4/21/07	33	94	4.8
			4/28/07–5/30/07	33	124	3.7
			9/4/07–9/16/07	13	62	4.6
			5/4/08–6/13/08	41	97	6.9
			6/16/09–7/7/09	22	82	7.4
9	Bailey	Grass	8/12/06–3/9/07	210	273	3.5
			3/10/07–8/20/07	164	311	4.8
10	Bailey	Crop	7/26/06–8/8/06	15	43	6.4
			8/12/06–9/1/06	21	50	5.7
			9/9/06–10/20/06	32	80	4.1
			5/22/07–7/18/07	58	149	4.6
17	Castro	Grass	5/16/10–8/5/10	82	124	6.0
20	Gray	Crop	7/2/11–8/2/11	22	70	9.2

Table 3. Water budget results (rates in millimeters/day).

Station	County	Land use	Number of inundation Events	Average inundation duration (days)	Average daily evaporation (meters^3)	Average evaporation rate	Average infiltration flux volume (meters^3)	Average infiltration flux rate	Infiltration flux standard deviation
1	Floyd	Grass	12	20	651	4.9	114	0.9	1.0
2	Floyd	Crop	36	21	613	5.7	345	2.8	1.5
3	Briscoe	Crop	42	29	490	5.1	199	2.0	0.3
5	Swisher	Crop	42	12	517	5.3	453	4.7	2.6
8	Hockley	Crop	6	17	74	5.2	342	19.8	4.7
9	Bailey	Grass	15	15	431	5.2	221	2.6	1.5
10	Bailey	Crop	7	12	91	6.0	271	17.4	3.2
17	Castro	Grass	5	13	95	6.2	99	4.7	1.5
20	Gray	Crop	1	13	260	8.9	106	3.8	na

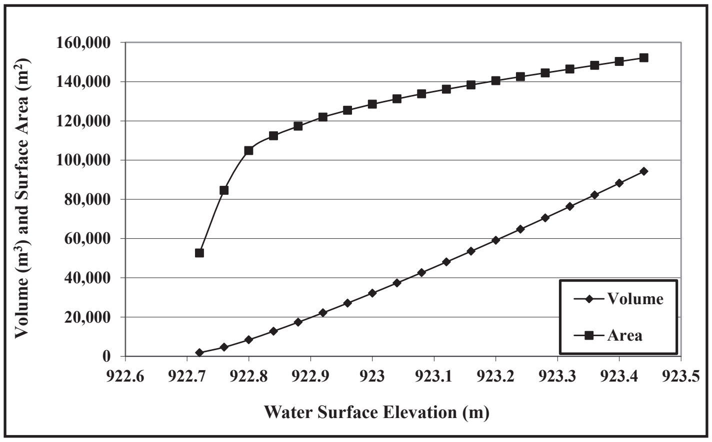

Figure 12. Playa volume and area versus elevation for Station 1, Floyd grassland playa.

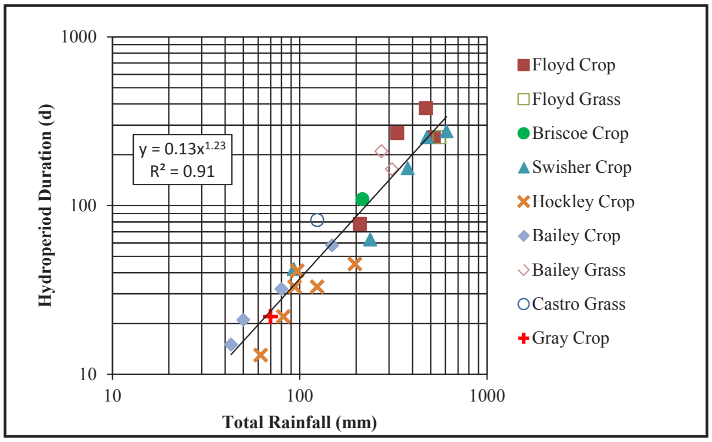

Figure 13. Hydroperiod length versus total rainfall during hydroperiod.

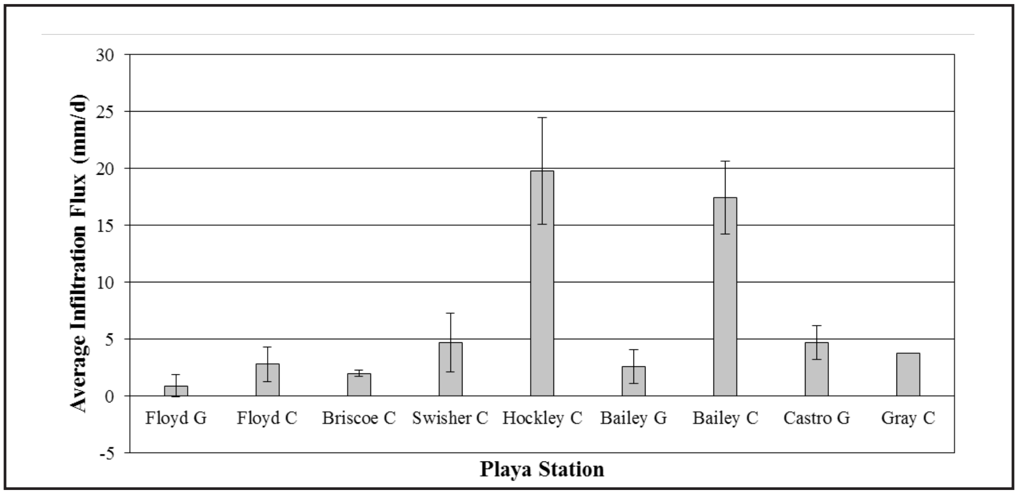

Figure 14. Comparison of average infiltration flux rates across playas.

counties, we were able to compare the average infiltration flux rates estimated for both the cropland and grassland playas. The Floyd cropland playa average infiltration flux rate was 2.8 ± 1.5 millimeters/day, while the Floyd grassland playa average infiltration flux rate was 0.9 millimeters/day ± 1.0 millimeters/day, indicating more infiltration on average in the cropland playa, but the difference between the 2 land uses was not large as both flux rates were relatively small. The Bailey cropland playa average infiltration flux rate was 17.4 ± 3.2 millimeters/day, while the Bailey grassland playa average infiltration flux rate was 2.6 ± 1.5 millimeters/day, which appeared to be a significant difference. Comparison of the 7 cropland playa results showed large differences in the average infiltration flux rates. The Bailey and Hockley cropland playa infiltration flux rates were significantly higher than those for the other 5.

The findings by Villarreal et al. (2012) provided useful insights for the playas in Briscoe, Floyd, and Swisher counties. In all 6 playas, they found non-uniform distributions of the erosional sediments across the hydric soils in the playa bottoms, affected by both the runoff inflow systems and windblown movement of sediments. The average sediment depths in the Floyd cropland and grassland playas were both 18 centimeters. The clay and sand fractions were 61±12% and 17±13%, respectively, in the cropland playa and 65±11% and 11±8% in the grassland playa, which appeared to relate to the greater infiltration flux in the cropland playa. The Briscoe cropland playa had average sediment depth of 23 centimeters, with 57±10% and 6±6% clay and sand fractions, respectively. The Swisher cropland playa had a much higher average sediment depth of 29 centimeters, with 60±10% and 9±5% clay and sand fractions, respectively. These 2 playas had relatively low infiltration flux rates among the cropland playas, but they exceeded average rates for 2 of the 3 grassland playas. Overall, these analyses do not cause rejection of the study's hypothesis, but the hypothesis is not yet confirmed. Complete determination of the mechanisms of the potentially enhanced infiltration and the associated reduction in hydroperiods length in playas filling with cropland sediments has not yet been achieved, but the research team is continuing the monitoring of these 10 and additional SHP playas in pursuit of that understanding.

Our preliminary average infiltration flux rates did follow other published results. James (1998) reported infiltration rates of 5 urban playas in Lubbock County ranging from 3.0-48 millimeters/day, while West (1998) observed infiltration rates ranging from 1.5-14 millimeters/day in the same playas. Hydroperiods in the 2 studies lasted from 18 to 49 days and 11 to 142 days, respectively. Their infiltration rates were similar to the results of this study, although the period of observation in this study was much longer. Reed (1994) found typical infiltration flux rates in more rural playas at the Pantex Plant that ranged from 3.1 to 7.5 millimeters/day for Playa 2 and 2.1 to 4.4 millimeters/day for Playa 3.

CONCLUSIONS

This study incorporated a water budget model to calculate infiltration rates through pairs of playas in 10 northwest Texas counties during 5 years of observations. Inundation periods with consistent data collection were observed in 9 of the playas. Two cropland playas had mean infiltration fluxes 3 to 6 times higher than their grassland counterparts in the same counties, tending towards shorter hydroperiods of 3 months or less if rainfall events were widely distributed in time. The presence of sediments in the cropland playa clays may contribute to the higher infiltration flux rates. The timing and intensity of rainfall events appeared to have great control over which playas caught and held runoff, and those conditions can vary greatly over short distances in the SHP, even within a county. The ongoing plan for this long-term project is to observe the hydroperiod behaviors at each playa over many years. A longer dataset will hopefully allow more statistical significance to determining land use effects on playa hydroperiods and infiltration losses as, they might be separated from other hydrologic factors.

Sustainability of the Ogallala Aquifer is an open question because of a declining water table in locations of groundwater withdrawal. It is known that recharge to the aquifer occurs via infiltration of water through playas, though the actual amount has rarely been quantified. Playa watershed land use affects the structure of and recharge through playas. Therefore, understanding recharge and the conditions that affect recharge to the playas is imperative in preserving the Ogallala Aquifer that serves so many important needs. Conservation of these important wetlands is necessary for future replenishment of the Ogallala, as well as for maintenance of the region's vital ecosystems.

ACKNOWLEDGMENTS

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A literature review: developing an information feedback interface to encourage water conservation behavior among utility customers

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Abstract: Water conservation behavior among water utility customers can be encouraged by engaging and educating customers about their consumption habits. To be successful, the information used to engage and educate must (1) be comprehensive, including both broad and narrow information, so that individuals understand where they fit into water management and how their actions impact water management and their community, and (2) help them make decisions about their use.

This article is a literature review of elements that can be incorporated into a customer-friendly information feedback interface. Some elements discussed are billing features, information about the water cycle, and local water sources, and local partnerships. The use of data is also addressed, and to that end, benefits of advanced metering infrastructure systems are mentioned. The details of these systems are not addressed. The intent of this research is to provide types and styles of information that can be combined to create an effective and meaningful information feedback system for water utility customers to encourage conservation.

Keywords: information customer feedback, water conservation interface

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Terms used in paper

Short name or acronym	Descriptive name
AMI	advanced metering infrastructure
EPA	U.S. Environmental Protection Agency
JEA	Jacksonville Electric Authority
SAWS	San Antonio Water System

INTRODUCTION

Providing customers meaningful water use information can encourage conservation behavior and can help customers become more educated about their consumption habits and the impacts of these habits (Aitken 1994). To be successful, the information used to engage and educate customers should (1) be broad and comprehensive so that individual customers understand where they fit into water management and how their actions impact water management and their community, and (2) help them make decisions about their use.

This article is a literature review of elements that can be incorporated to create a customer-friendly information feedback interface. Some elements discussed are billing features, information about the water cycle and local water sources, and local partnerships. The use of data is also addressed, and to that end, benefits of advanced metering infrastructure (AMI) systems are mentioned in conjunction with data feedback and in other ways, though the details of AMI systems are not addressed. Although these and other elements are discussed, this literature review aims only to provide types and styles of information that be combined to create an effective and meaningful information feedback system for water utility customers that will encourage conservation. This research does not propose that every element is required for success. Ultimately, utility managers interested in a feedback system should rely on their sense of what will resonate with their customer base in selecting elements.

The mechanism for sharing data and information is generally through an interface such as a unique webpage, landing pages for billing for each customer, and applications or other features for cell phones.[1] This review sets out types of information and features that are most useful in the interface for the target purpose of changing consumptive behavior. The interface elements discussed here may be mixed and matched to develop an impactful interface. Appendix A offers some examples of elements and features that may be included in an interface; however, there are more elements that may be included. A customer base, utility needs, and the service area should be profiled thoroughly before developing an interface in order to ensure its success.

[1] See *Appendix A* for images of a currently used interface.

ELEMENTS OF INTERFACES

Marketing Campaigns

In 2001, the United Kingdom's Environment Agency and the Thames Water Company conducted a £73,000 ($113,668 USD) joint research project evaluating "The Effectiveness of Marketing Campaigns in Achieving Water Efficiency Savings" (Howarth et al. 2004). The project's primary goal was to assess the effectiveness of a water efficiency campaign on 8,000 residences in a specific area (Howarth et al. 2004). The research was conducted for just over 1 month (Howarth et al. 2004). The research project used newspaper and radio advertisements and sent mailers to the homes in the target area (Howarth et al. 2004).

After the campaign, a survey was conducted to assess the extent of the campaign message's reach. Responses to the survey questions showed that only 5% of the residents noticed any of the campaign communications, even though 25% of residents claimed to read the newspaper and/or listen to the radio (Howarth et al. 2004). Overall, the results indicated that the campaign had no impact on decreasing water use among residences. The research also noted case studies in Phoenix, Arizona; Copenhagen, Denmark; and Singapore, in which broad media campaigns did little to impact water consumption behavior (Collins et al. 2003). Ultimately, the 2001 study concluded that while an important first step in changing behavior, communication alone, through media or literature, does not have meaningful impact on water conservation behaviors (Howarth et al. 2004).

However, the Silva 2010 study that assessed media campaigns conducted over longer periods of time and with a consistent message had more promising, although inconclusive, results (Silva et al. 2010). The Silva 2010 study reviewed Tempe, Arizona's cooperative media program called *Water – Use It Wisely.* The program has been in place since the early 1990s and includes messages from 20 other water providers in the same region. Social media, along with standard media (TV, radio, etc.), was most heavily used in drought conditions, based on the conservation department's belief that "the media is our best avenue for getting information to the public." (Silva et al. 2010). Surveys from the Silva 2010 study reflect that 75% of respondents were familiar with Tempe's main water conservation slogan and had seen it more than 10 times.[2] Overall, the report found that some of Tempe's media approaches were statistically significant in influencing water conservation, though the study made no projections as to how much water was saved by the media efforts alone (Silva et al. 2010).

Another subject in the Silva 2010 study is the Jacksonville Electric Authority (JEA)[3] in Jacksonville, Florida, which has an on-going media campaign that includes TV sponsorships, Public Service Announcements, print, and radio. Using a survey, the study found that more than 80% of respondents were familiar with 1 of JEA's primary conservation messages, but again there was no quantitative information about the impact of the media campaign on volume of water saved.[4] Examples from Durham, North Carolina, and Orange, Florida, yielded the same results.[5]

A study of Phoenix, Arizona, for the same Silva report found a decrease in water consumption and an increase in customers self-reporting their conservation activity from the period of 1996–2007, but could not establish whether the decrease had a direct relationship to a media and messaging program that occurred during the same time frame.[6] The same was found for a study of Seattle, Washington.[7]

At the time of this review, the authors could not find any publicly available or peer-reviewed data that shows the correlation between a media campaign in isolation and volumes of water saved. This point is made only to emphasize the need for a feedback interface that is more than just the arm of a media campaign. It is not made to undermine the role or value of a serious media campaign. (Media campaigns on their own serve a very distinct and critical purpose.) As the above case studies indicate, a sustained media campaign becomes recognizable to the public and is an important step in changing behavior due to its raising awareness (Silva et al. 2010), and is necessary to on-going efforts in calling attention to the importance of water conservation.

Moreover, media campaigns may become increasingly impactful as more avenues for communication with customers emerge. For example, social media outlets are the latest opportunity for utilities to communicate conservation messages. A recent study that surveyed Texans across all age ranges shows that 51% of respondents have a Facebook account and 17% have a Twitter account (Baselice 2015). For these reasons, incorporating a media campaign, with links to social media platforms, into a feedback interface is still strategically important.

Additionally, a critical relationship can exist between a media campaign and an effective interface, as media campaigns can help develop awareness among a customer base that, in turn, helps create customers that would actually use a feedback interface. Therefore, media campaigns and media messaging should be carried out in conjunction with other information feedback options, all of which can be incorporated into a singular feedback interface.[8]

Water and Natural Cycles

Actively engaging customers so they develop both an interest and understanding regarding hydrological, seasonal, and climactic cycles; local water sources; and the necessity of conservation are the most important parts of changing behaviors to promote conservation (United Nations 2002; Hassel et al. 2007). Feedback data available to customers is often specific to their location, and their use can have the effect of undermining the need to conserve. Additionally, many people do not know what their local water source(s) is/are (The Nature Conservancy 2011). In fact, a survey conducted in Texas revealed that in 2014 only 28% of those surveyed were confident they knew where their water came from; this was the same percentage achieved in the same survey when it was conducted in 2004 (Baselice 2015). Failing to illustrate how the water cycle works or to educate customers about the source of their water is a missed opportunity to emphasize the need to conserve. This oversight is significant because a lack of understanding of natural cycles and the interaction between natural water cycles and infrastructure creates a significant hurdle in successfully promoting conservation efforts (Department of Sustainability and Environment 2005).

In fact, the market research conducted after a 2001 study and survey suggested that customer response to a conservation project was poor because water-related matters ranked

[2] The total number of customers surveyed was not stated.

[3] JEA is responsible for electric, water, and sewer services.

[4] The total number of customers surveyed was not stated.

[5] The total number of customers surveyed was not stated.

[6] The total number of customers surveyed was not stated.

[7] The total number of customers surveyed was not stated.

[8] Incorporation of various forms of feedback into a singular interface is important in creating an effective interface. However, this literature review does not suggest that the interface should be the only way to interact with customers.

lowest of all environmental concerns held by the public. Furthermore, feelings of insignificance about independent actions contributed to non-action (Howarth et al. 2004). This attitude is common, especially in water-rich areas of the world. However, importantly another study found that "participants who understood the environmental impact of their water consumption were much more motivated than others to reduce their water consumption and saved as much as 23% relative to normal levels" (Jeong 2014). It can be inferred from these 2 studies that an increase in knowledge and awareness of water issues could have a positive impact on willingness to conserve and support of conservation efforts.

In Roseville, California, the water department had a difficult time getting residents to conserve water. The historical abundance of water in the area dampened awareness efforts, and most customers were unaware of their own consumptive habits and the impact of those habits to their community (West Governor's Drought Forum 2015). However, the record-breaking drought in California in recent years reduced the community's water supply drastically, compelling the water utility to implement a customer education plan quickly in order to force the issue of awareness as a means to reduce residential water consumption. The water department implemented a feedback interface that allowed it to push highly customized and tailored information to its customers (West Governor's Drought Forum 2015).

The information used by Roseville in its interface emphasized the dynamics between how the change in climate conditions and other factors were impacting the amount of available water and, in turn, impacting the cost of water supply in the future (West Governor's Drought Forum 2015). The interface also included future projections of water supply and the likelihood of drought; these proved to be powerful motivators[9] for water conservation activities among Roseville's customer base[10] (West Governor's Drought Forum 2015). Getting customers to understand the cost associated with supplying water as it relates to natural systems is a major challenge, but Roseville found that drought and the threat of drought are very strong motivators relating to natural cycles and systems (West Governor's Drought Forum 2015).

Partnerships

Demonstrating partnerships with relevant and well-respected organizations in customer feedback information can be effective because it signifies third-party independent approval with a utility's promotion of conservation (Hassel 2007). Demonstration of a partnership could be as minor as a logo appearing on an interface or as major as a public endorsement or the development of a jointly promoted conservation program. Such an announcement could be included in the interface, as could an advertisement for a partnership event. Organizations that seem to lend the most credibility are niche organizations, specialty institutes, and governmental authorities. Some examples of these types of partnerships are:

- The San Antonio Water System (SAWS) and Master Naturalists and/or Master Gardeners. SAWS and these organizations have a successful history of promoting native landscapes, DIY efforts, and a deeper understanding of water issues in South Central Texas. They garner more public engagement and reinforce the idea that the community must work together to conserve.
- The Texas Water Resources Institute is working with the cities of Round Rock and Arlington, Texas, to develop a customer interface that helps both utilities and customers understand volumetric usage and communicate conservation messages (Kalisek 2015).
- DC Water partnered with the U.S. Environmental Protection Agency (EPA) to promote its WaterSense program and encourage the replacement of high use fixtures as well as other conservation behavior (DC Water Authority 2016). Because of the EPA's strong base in the capital city, this program resonates strongly with the residents of Washington D.C. and encourages changes in fixtures since the message to change is coming from the highest environmental governing body in the country.

These kinds of joint efforts should be touted on an interface.

Billing Features

Customers appreciate direct access to billing and use information (Moore et al. 2008; National Energy Technology Laboratory 2008). Largely, with enough data included in the interface in easy-to-understand formats, customers can answer their own questions and spot problems that may be affecting their bill (National Energy Technology Laboratory 2008). Additional features, such as prepayment programs and select time of month billing, provide flexibility to the customer (National Energy Technology Laboratory 2008). Many of these billing features can be included in an interface.

The Silva 2010 survey reflected that only 64% of customers tracked their usage over time from their water bill (Silva et al. 2010). However, many customers said that bill tracking would be useful if there was an easier way to do it (Silva et al. 2010). Including a tool in the interface that helps customers manage and track their billing information would be a great way to encourage awareness and, in turn, conservation behav-

[9] This type of information was also found to be motivating in the Silva 2010 Study.

[10] Additionally, this information can also relate to the expenses of supplying of water as reduced supply can increase the cost to the customer.

ior. Adding interactive elements to the interface also increases the likelihood of continued use of the interface.

One way to allow for tracking is to include a graphic feature that will track both billing and use over time simultaneously. Another option might be comparison displays of billing and use for periods of time the customer can select. Allowing them some control over what they view may interest them more than just reviewing a chart.

Incorporating a bill pay option in the interface that would provide graphical or informational displays adjacent to the actual amount owed would also be a welcome addition. Though this is sometimes a challenge because of utility billing systems, it is an important consideration because it reinforces the connection between volumetric use and billing and would force customers to see their use when paying their bill.

One challenge with billing in general is a tendency for customers to set up automatic bill payments so that they are not obligated to even look at their bill or consumption if they do not want to. However, there may be some creative work-arounds. For example, a utility might elect to send an email notification to customers informing them that their bill is ready but without stating the amount up front. Instead, to find out the billed amount and volumetric use, the customer may have to check the interface. Of course customers with relatively steady bills may be less inclined, but many people want to know what they are paying and what they are paying for. Another option may be providing a discount or credit for every month they review the data or answer a question through their interface.

Related Programs

Including a pre-developed campaign or program within the interface (such as Texas' Water IQ or the Seattle 1% Program) helps to maximize information sharing with interface users (Silva et al. 2010). This allows a utility to send specific messages or establish priorities among its customer base (Silva et al. 2010). For example, if the utility is focusing its efforts on outdoor water use, the interface could be a place to explain why outdoor water use is important and to tie in links for native landscapes, landscape workshops, irrigator licensing programs, or applications for rebates and information for other incentive programs.

Including this variety of relevant information also helps the customer to view the interface as a well-rounded resource, which is important since in some communities many customers do not view their utility website or utility emails as a worthwhile resource (Silva et al. 2010). The Silva 2010 study made this finding but did not provide any suppositions as to the reasons for this. It may be because customers find the information to be too broad to be useful to them individually. It may also be because of uncertainty as to the origins of the information and therefore its usefulness (for example, if it is a press release it may have outdated or inaccurate data), or it may simply be that the customers do not have the time to read the email or visit the website and would prefer a more succinct presentation of information.

New Technology

Advertising new products or upgrades to commonly used products and services is another great way to promote water conservation (Deni Greene Consulting Services 1996; Hassel et al. 2007). Of course, utilities cannot tell customers which appliances or fixtures to buy or exactly when they should, but there is an opportunity to promote the benefits of water efficient fixtures and appliances. Most importantly, this is one of the easiest ways to help a customer make a decision that will leave them feeling vested in water conservation. For example, they can learn whether it is time to replace a low efficiency washing machine and how it will benefit them and their community. In making this purchase, they are now participants in conserving water in their community. Promotion of the EPA's WaterSense program would be useful here or similar product reviews and reports that most customers do not have the time or interest to find on their own. Moreover, those customers who do will certainly appreciate the resource.

Dynamism

Utilities are chronically trying to keep up with their customer base by developing rapport, engaging them, and keeping up with the service area demographics and customer needs and concerns. Developing information fields in which customers can send direct emails to their billing departments or conservation staff from the billing portion of their interface can help create a sense of more personalized service and recognition. In addition, depending on the format of the fields, there is potential to capture common questions and problems with bills or other information in the interface and get ahead of them, i.e. find patterns of concern among the customer base and head them off.

A related tool might survey what household appliances customers have. If a customer indicates they have an older washing machine, then a pop-up message connecting them to rebates or incentives could encourage them to make a change. Information on how much of their water bill is associated with the older washing machine might also be useful, though it requires additional questions such as how frequently they wash their clothes and possibly some back-end calculations the interface must be set up to perform.

Similarly, tools that may help customers determine information such as the appropriate amount of water use for their household size could include fields that capture household demographics, water features (pools, fountains), and square footage. Adding inputs to the interface to account for demographic elements such as the number of people in the household, the number of bathrooms (specifically the number of toilets), and whether there is an irrigation system present in the home may help customers understand their consumptive habits and identify areas of improvement (McKenzie-Mohr et al. 1999; Faruqui et al. 2010; Silva et al. 2010).

Dynamic features such as these require a mutually beneficial exchange of data but are ideal for managing customer needs and expectations, and for planning. With household demographic information, utilities can start to develop a sense of how much water children versus adults use or how transient the service area is. Another way to capture this kind of information for utility use only might be a local water census issued every few years by the utility in exchange for billing discounts or other financial incentives (though it is always best to develop a tool that the customer benefits from as well because participation occurs more easily).

Using Consumption Data

Uses

Consumption data can be used in 2 ways (though sometimes it can serve both purposes): 1) to enable the customer to make data-driven use decisions and 2) to enable the utility to make data-driven management decisions. Either way, the availability of individualized consumption data has been linked to a reduction in use. This was the case in the Sacramento County Water Agency where 2 water conservation programs were proven effective, but where the Data Logger Program resulted in greater water conservation (Tom et al. 2011). This difference in results was attributed to the Data Logger Program providing more detailed information about customer use, thereby enabling the customer to make more educated decisions about their use (Tom 2011). Notably, success with data feedback in particular comes from the data being relatable and easy to navigate and interpret.

Another example is Roseville, California, which experienced a 4.6% reduction in water use. This reduction was largely attributed to a combination of the municipal utility being able to drill down to single-customer use patterns and then using that information to focus on broad education efforts for its 36,000 customers, and tailoring information for the 18,000 residents receiving Home Water Reports and information about their consumptive habits (West Governor's Drought Forum 2015). Although 4.6% seems low, it is a strong beginning for the utility as it continues to refine its interface.

Efficacy

Much like media campaigns, the exact efficacy of data sharing as it relates to volumetric savings is unknown. Additionally, research has not yet identified the exact amounts of data required to trigger water conservation behavior. However, 1 energy conservation study did find a connection between AMI data feedback and a reduction in energy use (Faruqui et al. 2010). Although energy and water utilities are very different, water managers can benefit from the research conducted by the energy industry since similar challenges and technologies exist. Also, at least 1 water utility is studying the same connection (Faruqui et al. 2010).

The energy study conducted in 2010 by Ahmad Faruqui reviewed how direct feedback of real-time information influenced energy consumption (Faruqui et al. 2010). Faruqui specifically explored energy saving behaviors and customer attitudes about the direct feedback of information provided to them (Faruqui et al. 2010). The feedback instrument for all of the subject studies was an in-home display device. These devices are roughly the size of a residential thermostat screen, and are registered to a smart meter and can be placed virtually anywhere in the home.

Depending on the make and model, the in-home display devices can perform functions such as showing real-time energy use, day-to-day comparisons of energy use, use trends over time, and in some cases, they can be used to pinpoint what rooms or appliances in the home use the most energy. The study concluded that consumers who actively engaged with the feedback interface reduced their energy consumption by 7%, on average (Faruqui et al. 2010). Where time-of-use rates were used, the presence of rates and what customers will pay based on real-time data caused a reduction in energy consumption (Faruqui et al. 2010).

In 2014, the water utility in Duluth, Minnesota, deployed AMI to approximately 5,000 distinct customers in a pilot program to test its effectiveness. Officials at the utility evaluated whether customers viewed the AMI-enhanced consumption information and other information promoted on the interface more than they would review a standard monthly bill that was available to them online (Bensch et al. 2014).

The Duluth study is on-going in that participants are still being monitored to ascertain any long-term trends in data views and long-term changes in behavior and consumption. Interestingly, not long after the pilot study was underway, some participants in the pilot revealed that the enhanced feedback prompted them to examine their own behavior and heightened their awareness of other ways in which they waste water, such as through inefficient home appliances (Bensch et al. 2014). Self-reports from pilot participants showed that those already taking small measures were motivated toward more efficient behaviors and those who were simply preparing to take efficiency measures were pushed to carry out their plans (Bensch et al. 2014). The direct relationship between AMI data and changes in behavior is still being evaluated in this study. However, based on the responses of the participants, the data is raising awareness about personal consumption habits, an important first step in promoting conservation behavior.

A note on AMI

Data is collected in a variety of ways, but this review notices that much of the data used in feedback interfaces is derived from AMI systems. If set up correctly, AMI systems provide one of the most efficient methods of collecting data in a way that makes data easy to analyze. The largest benefit of an AMI system is that it collects data in real-time and can collect data in increments as small as 15 minutes. This creates a rapid precision not yet experienced by data collectors. It also provides utilities an opportunity to communicate data to their customers much more quickly and accurately through a variety of interface features such as prompts and reminders, high-use alerts, leak alerts, and other types of near-instant notifications. Also, many other technologies can now be connected to AMI systems such as leak loggers, which help a utility discover leaks and their locations.

Presently, the energy industries have led the way in making changes or conversions to meter systems so data can be collected more efficiently and expeditiously. In fact, the number of these types of changes, particularly the implementation of AMI systems, within the gas and electric industries is constantly increasing around the United States (Federal Energy Regulatory Commission 2014). Between 2011 and 2012, some 5.9 million AMI systems were installed and operated, amounting to nearly 30% of all gas and electric meters in the United States. Because of the usefulness of AMI systems in those industries, water utilities are increasingly considering implementing AMI systems (or systems with similar features) in the model of the gas and electric industries (Moore et al. 2008). Although AMI is not for every water utility (Hawkins et al. 2015),[11] the current interest renders it a worthwhile subject for review in the context of providing data for a customer interface.

One benefit that highlights the speed and efficiency of AMI is leak detection.[12] In Park City, Utah, the water department invested in an AMI system with leak detection features; however, after installation, some problems with the leak detection features frustrated customers. In response, the utility remedied the problems and improved on the leak detection feature by adding a notification pane in the interface through which it could more directly reach customers with consumptive use information and notifications of customer-side leaks (West Governor's Drought Forum 2015). In some cases the leak detection feature not only lets the customer know there may be a problem but also the type of leak based on volume and other factors. These efforts in Park City seem to have gotten customers more interested in their water use habits and supportive of the system; the overall response to this feature was very positive after all of the related concerns were resolved (West Governor's Drought Forum 2015).

Reminders and Prompts

One of the most useful determinations made from the 2010 Duluth study was that continuous engagement with a feedback interface is critical because even those customers genuinely interested in reducing their consumption may need reminders and prompts to encourage continuous engagement with the interface (Bensch et al. 2014). Reminders and prompts help guide people to the correct course of action (McKenzie-Mohr et al. 1999; Silva et al. 2010). Frequently, customers will learn of useful information and develop an intention to take action, but over time they forget or lose motivation (Bensch et al. 2014). Including a prompt or reminder feature in the interface can help customers maintain motivation and eventually take action where they otherwise would not (Bensch et al. 2014). For example, a customer could log in to the interface and become interested in an incentive program. While the customer might not be able to take immediate action, they can request an email reminder to be sent in the future, set a reminder the next time they log on to the interface, or download information into their calendar system (likely Outlook, iCal or Google Calendar).

Similarly, customers interested in rebate programs for high-efficiency washing machines may set a notice to remind them of a deadline if they are not purchasing the washing machine immediately. Another example might be a push notification to email or a notice when the customer signs into the interface letting them know they are close to meeting a pre-set billing goal. A utility in Duluth, Minnesota, found that frequent prompts and reminders like these examples are effective for changing behavior and are valued by the customers (Bensch et al. 2014).

[11] AMI is not for every utility, and it is important for utilities to perform a cost-benefit analysis and consider how AMI may help them and their customers before investing in it. See Hawkins et al. 2015.

[12] Leak detection is not part of every AMI system, but is increasingly common.

Personal Motivators

Self-interests or personal commitments motivate people to action and can be presented in an interface. For example:

Money

Behavioral changes are more likely to occur if incentives are offered. This is especially so with regard to water conservation; because the environment and hydrological systems are so large and complex, it is difficult to convince customers that individual actions have any significant consequences (Hassel 2007). Results from a 2010 survey showed that 78% of respondents said saving money was a primary reason for taking proactive measures to conserve water (Silva et al. 2010). Only 10% of respondents had ever participated in a utility rebate program (Silva et al. 2010). A full 61% said they would have participated in a rebate program if one had been available (Silva et al. 2010).

Since money is a major motivator, it is especially important to include incentive programs in the interface (Grizzell 2003). Adding incentive information, especially financial incentives such as rebates and billing discounts associated with conservation behavior, gives customers an additional reason to interact with the interface (Deni Greene Consulting Services 1996; Hassel et al. 2007). For example, using the interface as another means to convey information about cash-for-grass type rebate programs is ideal since not every customer will come across that information through another route. Customers may be more inclined to visit the interface if the incentives change or are rotated on a regular basis. Checking in to see what benefit they may receive may keep them motivated to use the interface. Additionally, if the interface also includes billing information, there may be a significant benefit in presenting rebate or discount information for conservation efforts simultaneously with the bill.

Pre-payment for electricity also influences energy consumption when available in conjunction with real-time use information. Under pre-payment plans, customers avoid a singular large monthly bill by paying for their electric service in advance in weekly increments, or otherwise as needed (Hatch 2012). Generally, customers are motivated to stay within whatever energy budgets their pre-payment buys and the availability of real-time data enables them to do that; as a result, energy consumption could be reduced by 14% (Faruqui et al. 2010).

Commitments

Getting customers to make personal commitments to water conservation efforts or goals makes them more likely to work toward larger commitments or goals in the future and more likely to make changes in water consumption behavior when asked (McKenzie-Mohr et al. 1999; Silva et al. 2010). This may even take the form of a pre-payment plan in which customers make personal commitments to use water until a certain price cap is reached.

Societal Norms and Peer Pressure

Establishing societal norms gives customers a frame of reference and renders them more likely to change their behaviors when asked to in the future. Societal norms may be established via an interface so long as a unified message is conveyed to all those who signed up for access to it (McKenzie-Mohr et al. 1999; Silva et al. 2010; West Governor's Drought Forum 2015).

Though only 2% of respondents in the Silva et al. 2010 surveys stated that peer pressure motivated them to conserve, other studies have found peer pressure and comparison to the usage incurred by neighbors to be more effective than appealing to people's sense of social responsibility, safe guarding the earth for the future, and even saving money (Silva et al. 2010). In fact, market strategy research for energy indicates that using social norms as a motivational tool can increase household energy savings by 5.7% to 10% (Ehrhardt-Martinez et al. 2010).

One example of imposing peer pressure is providing information that compares 1 household's consumption to another of similar value, square footage, year built, and number of inhabitants. These kinds of comparisons may greatly influence conservation behaviors. Including this comparative information is increasingly popular as more individualized data becomes available. Additionally, this specific type of comparative norming has been found to be effective in getting customers to embrace conservationist behaviors, though more research is needed (Hastings et al. 2015).

A great example of societal norms at work is the Report Water Waste system used by SAWS. Through this system, customers can (and do) actively report instances of water waste. Once the report is received by SAWS staff, an alert letter is sent to whomever is responsible for the property where the instance occurred (usually the owner or property manager) requiring that they resolve any water waste at their property.[13] Additionally, local police officers working in conjunction with SAWS may issue citations for water waste they encounter. These citations have associated fines and are referred to the Municipal Court system where they may be disputed. Across the city, customers take water conservation very seriously, no doubt in large part because of the reporting system and the message that it sends about water use in the community.

[13] Sometimes staff will make phone calls to the responsible party instead of, or in addition to, an alert letter being issued.

Personal Benefits

Although peer pressure and societal norms are effective, the need for individuals to believe their actions will truly have an impact is another hurdle to changing conservation behavior. For this reason, emphasizing the personal benefits of signing up for interfaces and interface notifications is useful in getting customers to return to the interface once they have signed up (U.S. Department of Energy 2014). For example, if leak detection notices are only offered to those who sign up for the interface service, then more people are likely to sign up since leak detection can save them money. In extremely well-equipped communities that may have separate irrigation meters for commercial and Home Owners Association properties, irrigation-specific leak detection notices could lead to significant financial savings and could also be tied to enrollment. Offering billing date options for those who enroll in the interface program may also be a way to garner interest because it may be beneficial to the customer. Bill credits or discounts may also be a tool to interest people in using an interface.

PRESENTING INFORMATION

Data

The Duluth study found a disparity between the information customers wanted and needed, and the information delivered by AMI systems; specifically, the data presentation suffered from lack of clarity and the interface was not user-friendly (Bensch et al. 2014). The participants in the Duluth study said the data was the most helpful part of the pilot, but they also tended to look at the data only once because of its overwhelming presentation (Bensch et al. 2014). Additionally, customers reported high rates of interest in data feedback, but their interest was dwarfed by their time or/and willingness to actually engage with and make sense of the data (Bensch et al. 2014). Essentially, complexity of the data presentation may undermine its usefulness, particularly when utilities are seeking voluntary actions from consumers. More easily understood treatments of the data, such as comparative formats, are more useful in achieving conservation behavior and, importantly, in sustaining customer interest (Bensch et al. 2014). While simplifying the data is important for customer understanding, it is also important to have staff in at least 1 department (billing, conservation, customer service) trained to knowledgeably answer questions about the bill and the meter technology.

Credibility

Information credibility is important to successfully changing consumptive behaviors. In a survey conducted among homeowners and home renters, water supply officials were considered the most credible source for water conservation information. Officials with a financial interest in water conservation (e.g. plumbers, manufacturers, contractors) were seen as less credible, with the exception of landscapers and nursery owners and workers (Silva et al. 2010). Therefore, it may be important to enhance information in the customer feedback to reflect the perspective of water conservation officials, as opposed to the utility broadly. It may also be useful to incorporate information and suggestions from other credible sources (local leaders, respected organizations, known professionals external to the utility, etc.).

Cost Breakdowns

In an energy study, different treatments of feedback information for electricity consumption were analyzed to determine what information and what presentation of that information resulted in maximum electricity savings (Karjalainen 2011). The study results indicated that customers were most responsive to cost breakdowns over time as it related to their monetary savings (Karjalainen 2011). Customers also found savings breakdowns concerning specific appliances or services (including brand names) very helpful in demonstrating what the value of making a change would be (Karjalainen 2011).

The study also indicated that:

- people can interpret tables, charts, and graphs if they are well-designed;
- many people are overwhelmed by highly technical information and scientific units; and
- many people do not have comprehensive understanding about the electric industry (Karjalainen 2011).

Customers most appreciated:

- presentations of costs (over a period of time);
- appliance-specific breakdown, i.e. information on how much each appliance consumes proportionally; and
- historical comparison, i.e. comparison with a customer's own prior consumption (Karjalainen 2011).

Relative Information

People learn and analyze in different ways, which is why it is useful to present complex information in relative forms. For example, the Sacramento County Water Agency ran 2 water conservation programs simultaneously to discern customer preferences and response rates to data feedback (Tom et al. 2011). The first program was the Data Logger Program, in which a Meter-Master Model 100 EL data logger was attached to the customer's water meter for 1 week and provided a detailed report of water use from each fixture (Tom et al. 2011). In the second program, the Water Wise House Call Program, a water efficiency staff person spent an hour with customers issuing assessments and recommendations (Tom et al. 2011). In a sample of 100 households, both programs were found to be effective[14] (Tom et al. 2011).

In another study, 2 different treatments of feedback presentation were compared and evaluated for 4,700 residents (Jeong 2014). The results of the study suggest that providing water consumption in gallons alongside water consumption in energy units required to deliver the volume in gallons led to a statistically significant reduction in water consumption, while providing water consumption only in gallons did not (Jeong 2014). The authors of this study provide some speculation as to the findings. First, they suggest that energy data may be presented in simpler terms and in more familiar units than water consumption data usually is (Jeong 2014). This is very possible since energy conservation is an older and more established concept in the United States. The authors also note that previous research in energy conservation demonstrated recognition of energy units and an easier time in achieving conservation by sharing data with customers (Jeong 2014). Second, the authors suggest that "By providing feedback at the intersection between water and energy consumption, the feedback appealed to both those individuals interested on water conservation and those interested in conserving energy" (Jeong 2014).

Feedback Frequency

Regarding feedback frequency, it has been found that daily or weekly feedback information generated the highest electricity savings per household at 11% to 14%, while providing real-time feedback resulted in 7% savings (Ehrhardt-Martinez et al. 2010). Although drill-down features are likely to be of interest to the customer, it is definitely a useful presentation for utilities to analyze because they offer multiple planes on which the utility can perform an analysis of consumptive use patterns. Most drill-down features present as monthly or weekly data that give the customer a sense of their use for a broad period of time. The customer can then select the data (usually by clicking or touching the icon or graph that reflects the data) to see weekly or daily information, and then again to see daily or hourly information, etc. If a drill-down feature is included because the AMI system records data at small intervals, it is important to help the customer interpret the results of the drill-down feature so they are not overwhelmed or uncertain how to improve on their consumption.

[14] While both programs were effective, the Data Logger Program resulted in greater water conservation. The difference in results was attributed to the Data Logger Program providing more information about customer use and in greater detail, thereby enabling the customer to make more educated decisions about their use (Tom 2011).

CONCLUSION

The Silva 2010 survey reflects that many customers already believe they engage in water conservation practices (Silva et al. 2010). In fact, many reported changes in their activities such as a new tendency to run the dishwasher or clothes washer only when full (Silva et al. 2010). These responses suggest a high level of awareness (Silva et al. 2010). Utilities can and should exploit this awareness by developing customer interfaces that promote increased conservation, since providing water consumption feedback for customers has proven effective in promoting conservation (Jeong 2014). In 2010, a comprehensive meta-review was conducted of 57 residential energy-feedback studies spanning 36 years and 9 countries, including the United States, Canada, Europe, Australia, and Japan (Ehrhardt-Martinez et al. 2010). The study found that across countries, feedback programs resulted in average savings of 4% to 12%, demonstrating that with the right presentation of information, people are willing to modify consumptive habits and other behaviors (Zelezny 1999; Ehrhardt-Martinez et al. 2010).

To be impactful, these interfaces must be robust and contain data, motivational materials, educational information, and content that can help the customer make decisions about their water use habits and become vested in conserving water in their community (Syme et al. 2000; Hassel et al. 2007; Ehrhardt-Martinez et al. 2010; Faruqui et al. 2010; Karjalainen 2011; Silva et al. 2010). This well-rounded approach has been proven more useful and meaningful to customers than interfaces that only use certain types of information such as education-only or data-only, which are much more typical of utility communication to customers (Hassel et al. 2007). The Silva 2010 study supports this as it revealed that feedback mechanisms are unlikely to encourage more significant household energy savings without being accompanied by additional products and services that actually help the customer make decisions about changing their consumption habits (Zelezny 1999; Ehrhardt-Martinez et al. 2010).

Examples of this comprehensive interface may be broad, such as information about conservation efforts in the customer's home region. Other examples may be more specific such as individualized consumption data, comparative information such as consumption volume of households of similar square footage and number of persons, and customizable interactive features such as pre-payment goals and do more to engage the customer (Syme et al. 2000; Hassel et al. 2007; Faruqui et al. 2010; Karjalainen 2011).

This research highly encourages the development of a feedback interface. However, consideration of development costs for these interfaces is an important element in design. Design and implementation expenses will vary depending on utility-specific qualities such as the scale of deployment (size of customer base), ease of deployment, likelihood of engagement as compared to engagement experienced under current programs, the number of features, and development partners such as private consultants versus public or research entities. As a result, the relative value of water savings compared to the cost of implementation is an important consideration, but one that is not made here. It is too variable and there are not enough case studies on these points to make any firm conclusions. Utilities considering information and feedback systems are encouraged to perform these evaluations before making decisions. Talking to system developers, relevant utility departments (billing, customer service, metering, conservation, etc.), and other utilities is the best way to start. Talking to customers and asking what would help them or assessing what they do not know is another great first step.

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APPENDIX A

The following images are taken from the Meter Study Project being conducted by the Texas Water Resources Institute. The images have been used with permission to provide a visual reference for some of the elements addressed in this review. This interface is a web portal for customers to access.

Figure A, below, is a copy of the landing page. The chart and tabular information can change if the customer elects to drill down in a monthly data set. Additionally, the data may change altogether if the customer elects to use data from an irrigation meter, or additional meters tied to the account. Also, the information in the bar chart can be changed from volume to dollar amount by clicking the yellow "View Cost" button at the top of the screen.

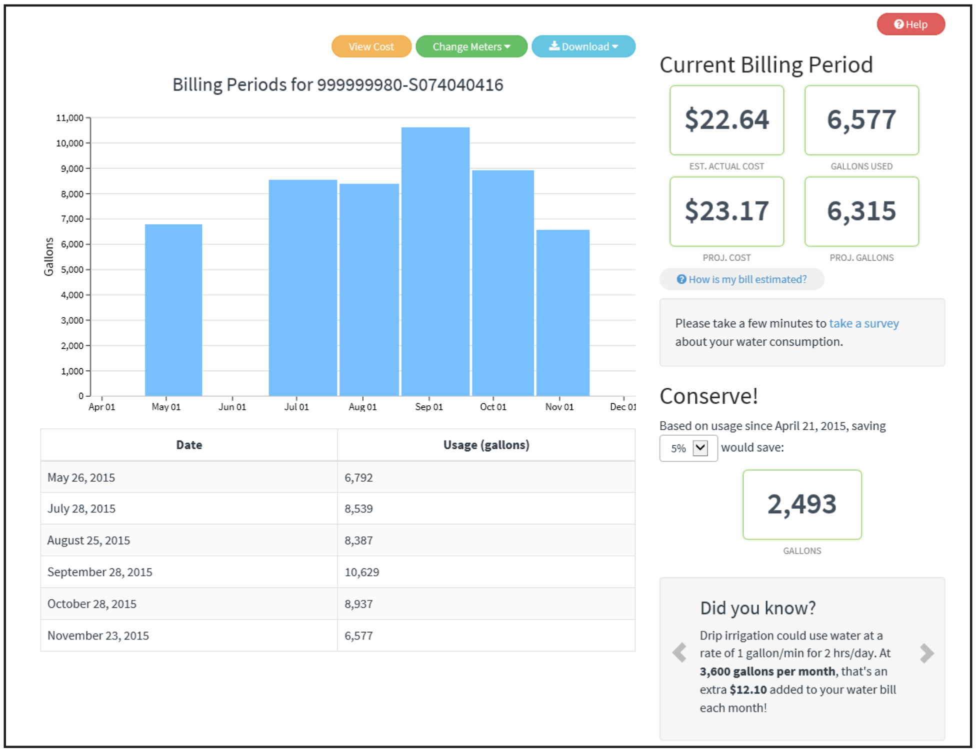

Figure A. Layout from the landing page of the web portal.

The Drill Down feature lets customers go from a broad month-to-month view of their usage as shown in Figure B to daily usage shown in Figure C to hourly usage for a given day as shown in Figure D. The customer needs only to click any bar in the bar chart to drill down to more detailed data.

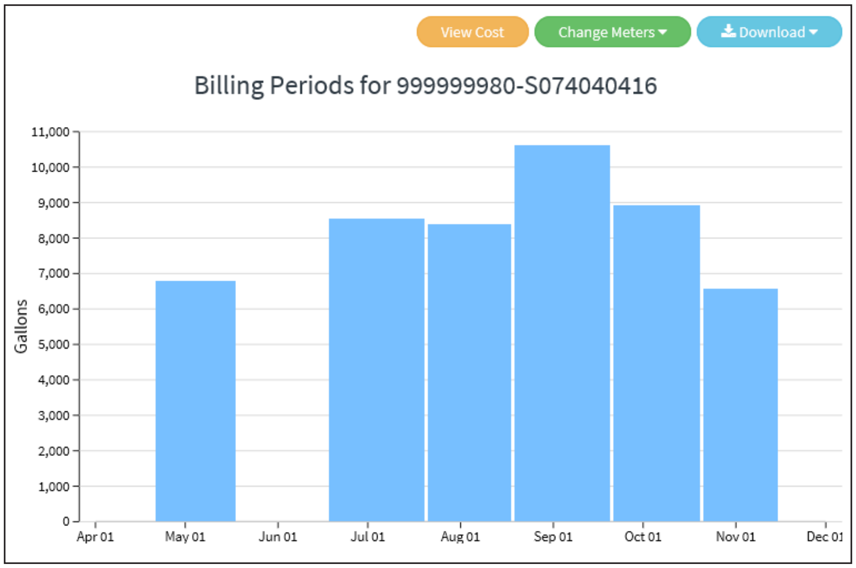

Figure B. Month by month usage for 2015 (begins in April when customer enrolled).

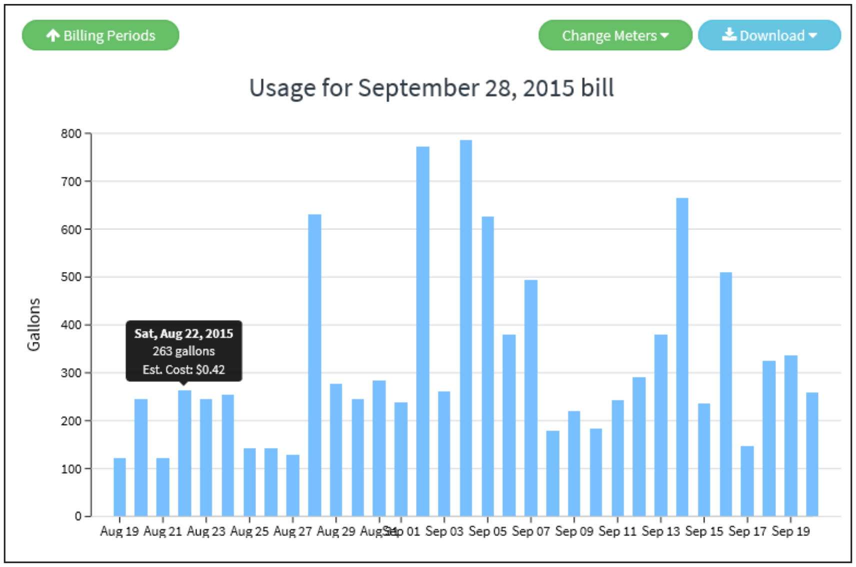

Figure C. Daily usage for the month of August 2015.

Figure E shows an informational prompt that rotates through different messages. The information in each message connects a common activity with both waste and dollar amounts.

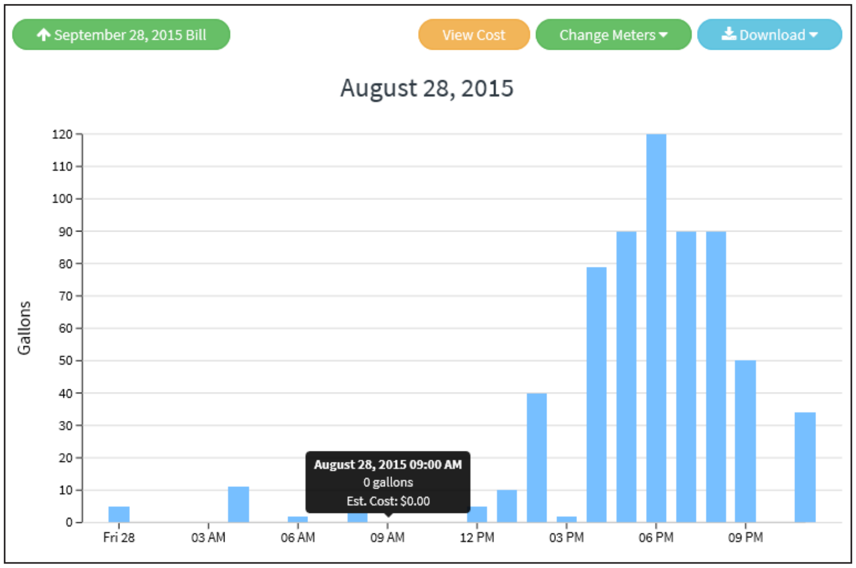

Figure D. Hourly usage for August 28, 2015.

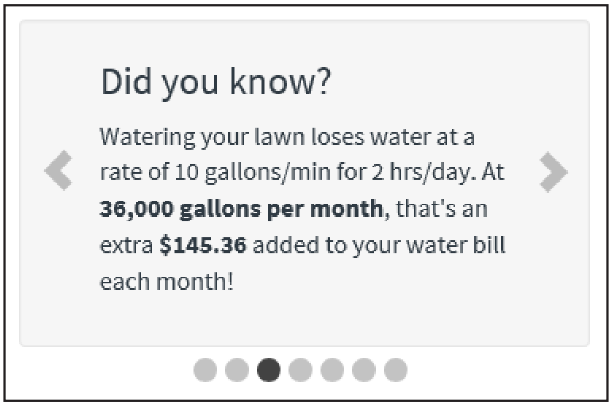

Figure E. Informational prompt.

Figure F, below, is an interactive feature that shows the customers how many gallons of water are saved based on a percentage savings of their usage. The percentages can be changed and have correlating gallon volumes based on the customer's use.

Figure G, below, is a relative and comparative information item that presents use in terms of dollars and volume and simultaneously tracks the customers use information.

Figure H, below, is a survey prompt that collects information for the utility and makes the customer reflect on their consumptive behavior.

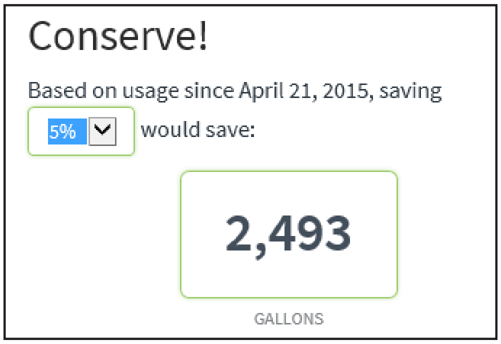

Figure F. Conserve! prompt.

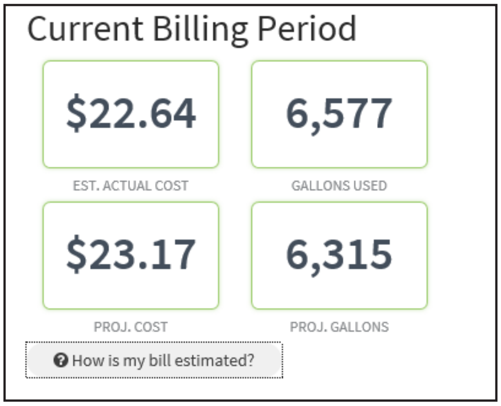

Figure G: Relative and comparative consumption prompt.

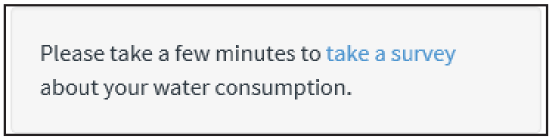

Figure H. Survey prompt.

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Program note: An introduction to the NWS West Gulf River Forecast Center

Gregory J. Story[1]

Abstract: The National Weather Service (NWS) West Gulf River Forecast Center (WGRFC), in cooperation with numerous federal, state, and local government entities, uses the latest science and technology to provide timely and accurate river forecasts in an effort to protect life and property for most of the river drainages in Texas. Disaster preparedness decreases property damage by an estimated $1 billion annually nationwide. The mission is to provide basic hydrologic forecast information for the economic and environmental well-being for the nation. The WGRFC is 1 of 13 river forecast centers within the United States and is located in Fort Worth, Texas. The WGRFC's area of responsibility stretches from the Rio Grande in southern Colorado, New Mexico and south Texas eastward to the Sabine River along the Texas-Louisiana border. Other rivers in the center's area of responsibility include the Pecos, Nueces, San Antonio, Guadalupe, Colorado, Brazos, Trinity, and Neches rivers. This article will describe the variety of hydrologic forecasting services routinely provided by the WGRFC. Although flood forecasts are its most well-known product, the WGRFC also generates river and water information used for recreation, reservoir operations, and water supply plans. Additionally, the WGRFC produces estimates of hourly precipitation. To achieve this, the WGRFC has 2 primary functions; a hydrometeorological function and a hydrologic function. This article will describe each function and discuss how each function serves as steps in the preparation and the issuing of hydrologic forecasts.

Key words: flood, precipitation, forecasts

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Terms used in paper

Short name or acronym	Descriptive name
AHPS	Advanced Hydrologic Prediction Service
CoCoRaHS	Community Collaborative Rain, Hail and Snow
CHPS	Community Hydrologic Prediction System
DOH	development and operations hydrologist
HAS	hydrometeorological analysis and support
HIC	hydrologist-in-charge
MPE	Multisensor Precipitation Estimator
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
QPF	quantitative precipitation forecast
RFC	river forecast center
SCH	service coordination hydrologist
SHEF	Standard Hydrological Exchange Format
WFO	weather forecast office
WGRFC	West Gulf River Forecast Center

INTRODUCTION

The West Gulf River Forecast Center's (WGRFC) area of responsibility includes the drainage area of most rivers in Texas. The WGRFC (Figure 1) gets its name because all the rivers it is responsible for drain directly into the western Gulf of Mexico. The easternmost river is the Sabine River, which comprises the border between Texas and Louisiana, thus the center is responsible for a small part of western Louisiana. The western and southernmost river is also the longest river in the center's area, the Rio Grande. The headwaters of the Rio Grande are located between 2 mountain ranges in south central Colorado. The Rio Grande drains south through the heart of New Mexico, thus the center is responsible for much of that state. Downstream, the Rio Grande forms the international boundary between Mexico and the United States from El Paso to Brownsville, Texas. The WGRFC's area of responsibility includes portions of 4 states and comprises over 402,000 square miles (1,040,000 square kilometers), of which 87,000 square miles (225,000 square kilometers) is in Mexico. It has roughly 320 forecast points on 15 major river systems. Figure 2 illustrates the area of responsibility of the WGRFC.

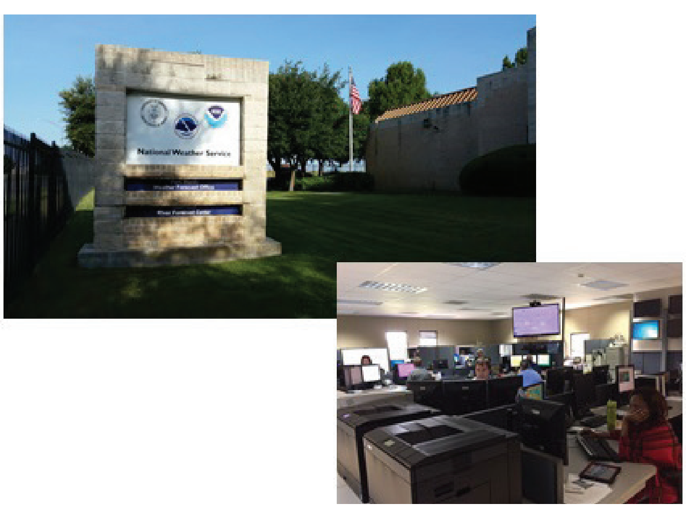


Figure 1. The NWS Office in Fort Worth and the WGRFC operations area.

The River Forecast Center (RFC)'s authority as the U.S. government entity responsible for providing flood forecast services was established in Article 1 of the Constitution, the "Organic Act" of 1890 (15 USC 313), and the "Flood Control Act" of 1938 (33 USC 706). The National Weather Service (NWS)'s River and Flood Program traces its origins back to the start of the NWS itself. In 1870, Congress authorized the Army Signal Service Corps to create a river and stream gauge program as well as a weather observation and forecasting program. Then, Congress passed the "Organic Act" of 1890, which transferred all weather and related river services into the Department of Agriculture and created a civilian U.S. Weather Bureau, which would later become the NWS. The NWS is now a part of the National Oceanic and Atmospheric Administration (NOAA) in the U.S. Department of Commerce.

The WGRFC maintains a staff of more than 15 personnel. WGRFC management consists of the hydrologist-in-charge (HIC) who provides managerial and technical oversight of all WGRFC activities, the development and operations hydrolo-

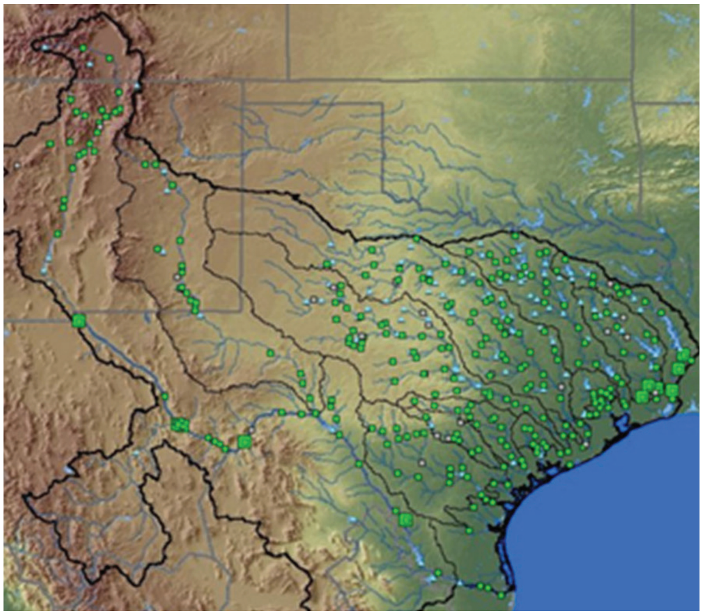


Figure 2. The WGRFC area of responsibility.

gist (DOH) who provides the technical direction to support operational requirements, and the service coordination hydrologist (SCH) who leads the WGRFC efforts to identify and meet customer hydrologic requirements. There is 1 administrative support assistant on the staff. The bulk of the staff is comprised of professional hydrologists and meteorologists. The WGRFC provides for a nominal staffing of 16 hours per day, 7 days per week. Normal business hours are 6 AM until 10 PM Central Time. WGRFC operational policy dictates 24-hour coverage when current or expected hydrometeorological conditions warrant.

Primary operational duties include hydrologic forecasting, hydrometeorological analysis and support (HAS), and the monitoring (quality control) of associated data sets that are input to (or the output from) operational computer models.

The HAS forecaster is responsible for assimilating the observed and forecast precipitation and temperature input for the river forecast model and preparing the Hydrometeorological Discussion product and the Flood Outlook Potential product. The HAS forecaster is also responsible for coordinating with and supporting the lead duty hydrologic forecaster. The hydrologic forecaster is responsible for the daily river forecasts, flash flood guidance, data discussion products, social media postings, executing the river forecast computer model and coordinating river forecasts as required. Each RFC provides its forecasts as hydrologic guidance to a network of NWS weather forecast offices (WFOs) located within each RFC's area of hydrologic responsibility. An RFC's area of responsibility is defined by river basin boundaries, while a WFO's area of responsibility is generally defined by political boundaries.

Other operational functions are performed on a seasonal or as needed basis. These functions include producing water supply forecasts for Colorado and New Mexico, spring flood outlooks, and drought summaries.

NWS's hydrology program has capitalized on new technologies by incorporating improved data sets to make more accurate, site specific, and timely hydrologic forecast products. This modernization has also included implementing new hydrologic software. The latest software, called the Community Hydrologic Prediction System (CHPS), was implemented at all the RFCs in early 2012.

Meteorological features of the WGRFC region vary greatly, with high temperatures in the summer consistently over 100 °F (38 °C), to lows in the winter of less than -30 °F (-34 °C) over northern New Mexico and southern Colorado. Average annual rainfall varies from 8 inches (203 millimeters) over parts of New Mexico to more than 60 inches (1524 millimeters) over extreme southeast Texas. Average snowfall ranges from 20 (508 millimeters) to more than 100 inches (2540 millimeters) over the southern Rocky Mountains, which influences the upper Rio Grande. Streamflow characteristics also vary greatly. Rapidly responding creeks and rivers due to rocky terrain dominate the Texas Hill Country, making this 1 of the most flash flood prone areas in the country; while flat terrain creates more sluggish streams over the lower reaches of the rivers in the coastal plain. Complex reservoir operations are common on river systems over northern and eastern Texas where prolonged flooding can occur.

Drought can dominate the region at times, limiting surface runoff. In wet years though, the combination of high soil moisture and widespread heavy precipitation can result in frequent flooding almost any time of the year. Flash flooding on smaller streams and in urban areas generally results from heavy localized thunderstorms. Tropical systems from the Gulf of Mexico can move onshore in Texas and have produced some of the highest rainfall rates in the world.

In addition to providing forecast guidance NWS offices, the RFC coordinates and provides forecasts to other government agencies and river authorities. These agencies include the division and district offices of the U.S. Army Corps of Engineers, river authorities, the Texas Department of Emergency Management, the International Boundary and Water Commission, and the U.S. Geological Survey.

OPERATIONS

The WGRFC is divided into 2 primary functions: the hydrometeorological analysis and support (HAS) function and the hydrologic function. Figure 3 illustrates the flow of information from these 2 functions that leads to the creation of a river forecast at the WGRFC.

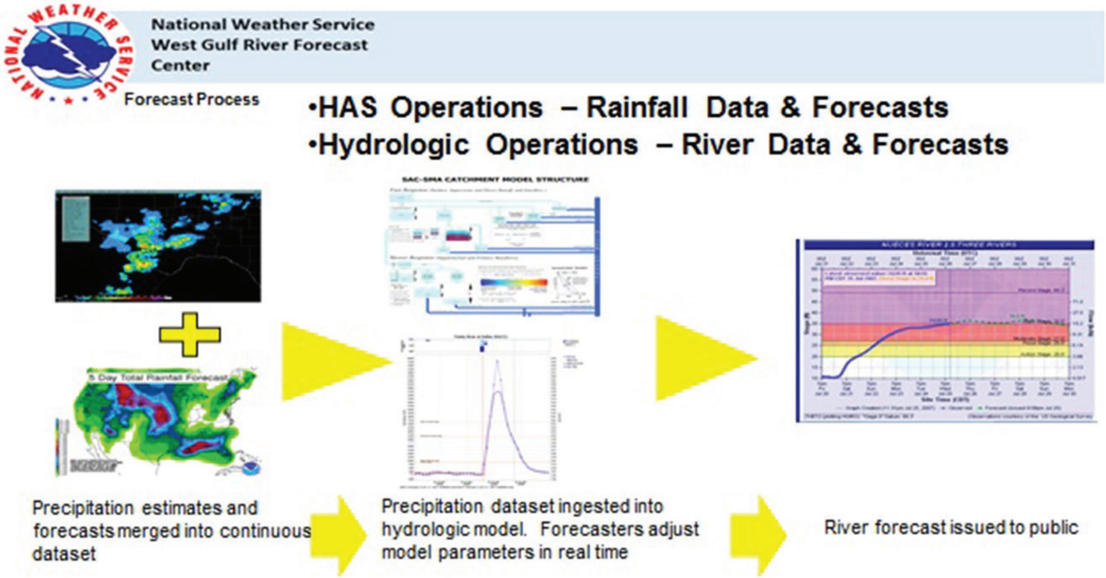


Figure 3. The flow of data from past and future rainfall to river forecasts for the public.

The HAS function

HAS forecasters monitor rainfall estimates from multiple sources, including radar and satellite. One of 2 significant changes to RFC operations in the modernized NWS is the use of radar precipitation estimates in generating river forecasts. Precipitation estimates from the WSR-88D radars from the 24 sites have allowed for better temporal and areal distribution of precipitation than if rain gauge data were solely used. Rainfall estimates from these sources are adjusted based on comparisons to rain gauge reports. The final "best estimate" of precipitation is input into the river forecasts models. This data is also available to external users (graphically or by downloading) through the Advanced Hydrologic Prediction Service (AHPS) website (http://water.weather.gov/precip). An example of what is available on the AHPS website is shown in Figure 4.

The WGRFC staff uses a Multisensor Precipitation Estimator (MPE) to ingest precipitation data from a variety of sources (most of which is radar-based) to input into the hydrologic models. This program has the ability to view raw radar-estimated precipitation, gauge reports, computerized radar precipitation estimates from the National Severe Storms Lab and satellite precipitation estimates to give HAS forecasters multiple options to blend together the best possible fields. Using their experience, they arrive at the optimum precipitation estimates that will be ingested into the river models. After the precipitation has been tabulated, the mean areal distribution is determined for all river subbasins of concern. The basin average precipitation is obtained by computing an arithmetical average of the gridded fields from the MPE. Figure 5 shows how the WGRFC uses a multisensor approach to derive areal averaged precipitation estimates.

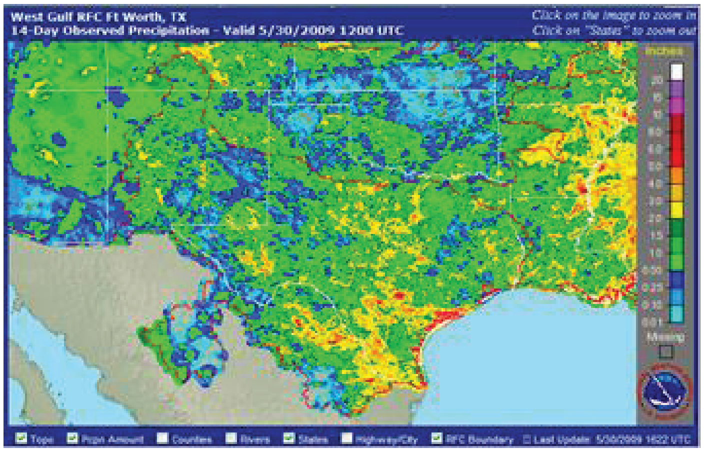


Figure 4. Precipitation accumulation from the WGRFC on the AHPS website.

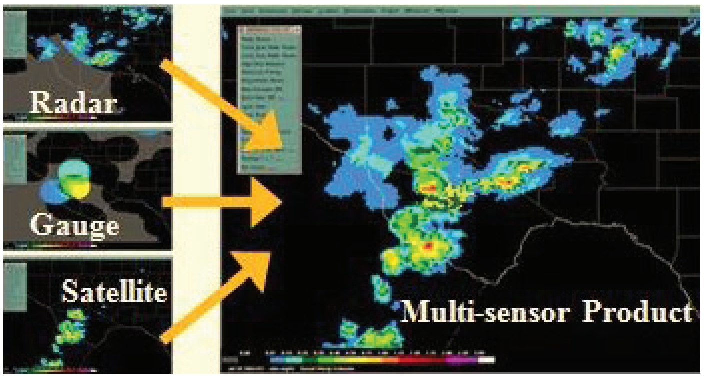


Figure 5. Example of blending radar, satellite, and gauge data in MPE to arrive at a best estimate field based on all sensors.

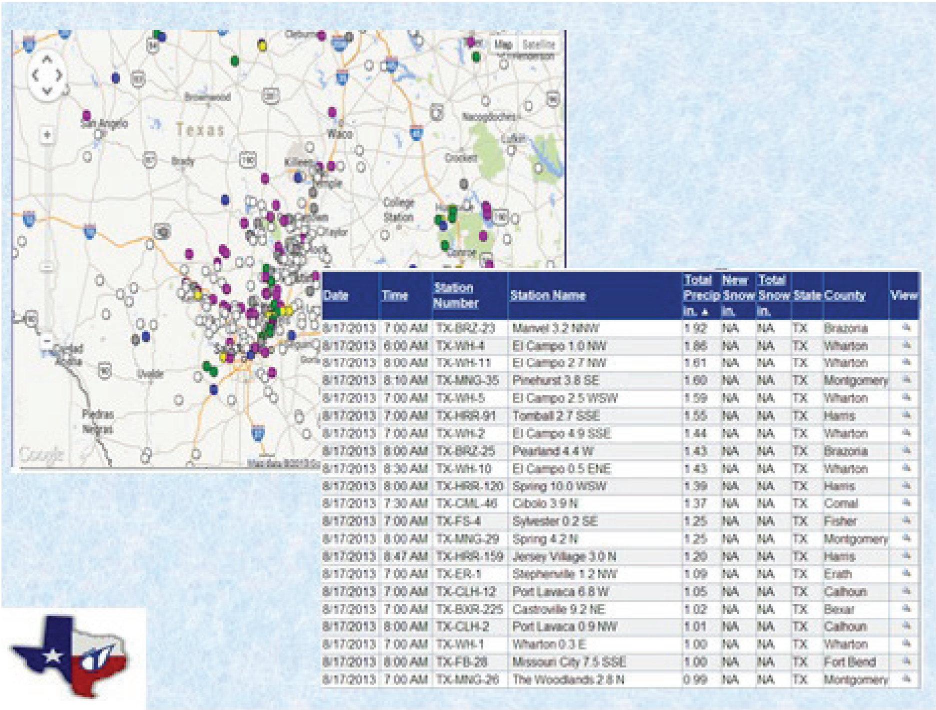
HAS forecasters also analyze meteorological model data to generate a quantitative precipitation forecast (QPF). QPF is a specific forecast detailing the amount, timing, and location of basin averaged future precipitation. Using QPF provides more lead time for forecasts of rising rivers when heavy rainfall is expected in the area. The RFC can also provide a contingency river forecast based on QPF. A user may want to know how different amounts of forecast precipitation will affect the river stages when a major storm is impending. Basing their decisions, actions, and forecasts on up-to-date science and technology (along with experience), the HAS forecasters perform a vital function in the river forecast process.

A big part of the HAS function is data quality control. The NWS collects hydrologic data from many sources. An important source of data comes from paid or volunteer cooperative observers. Many of these observers report daily river and rainfall amounts, while others send reports based on the current hydrologic situation. Other data sources include the U.S. Army Corps of Engineers, U.S. Geological Survey, and city, county, and state alert networks. Much of the data is collected by automated gauges such as Automated Surface Observation System (ASOS), mesonet, and satellite gauges called data collection platforms (DCPs). Manually read, non-automated rain gauge data continues to be of great value to the WGRFC. There are now more than 5,200 stations in Texas of the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network. During 2015 there were instances when more than 1,000 rain gauge readings measured over a 24 hour period that were 0.01 of an inch or more were received from this volunteer network. The WGRFC HAS forecasters continue to benefit from this growing network and encourage everyone to join. For more information about CoCoRaHS, go to http://www.cocorahs.org. An example of a CoCoRaHS rainfall map and data display for central Texas is shown in Figure 6.

The local WFO still collects the majority of hydrologic data and transmits it to the RFC in Standard Hydrological Exchange Format (SHEF). SHEF was developed to standardize the format of the data sent to the RFCs. This has allowed computer programs to be written that automatically read and input the data into a database, which is accessed by computers at the RFC. Automated data collection systems such as the NWS Hydrometeorological Automated Data System and Automated Surface Observing System also transmit data in SHEF format.

The hydrologic function

After obtaining the latest and most accurate rainfall datasets, WGRFC hydrologists begin the process of generating river forecasts for the area. The RFC decodes and processes the data to determine runoff from these rainfall amounts. The result is a stage and flow forecast at a specific point along a river. Using river gauge data and streamflow measurements and estimates, the hydrologists look at the combinations of rainfall, runoff, and routed river flows to issue river forecasts. When action



Date	Time	Station Number	Station Name	Total Precip in. ▲	New Snow in.	Total Snow in.	State	County	View
8/17/2013	7:00 AM	TX-BRZ-23	Manvel 3.2 NNW	1.92	NA	NA	TX	Brazoria	
8/17/2013	6:00 AM	TX-WH-4	El Campo 1.0 NW	1.86	NA	NA	TX	Wharton	
8/17/2013	8:00 AM	TX-WH-11	El Campo 2.7 NW	1.61	NA	NA	TX	Wharton	
8/17/2013	8:10 AM	TX-MNG-35	Pinehurst 3.8 SE	1.60	NA	NA	TX	Montgomery	
8/17/2013	7:00 AM	TX-WH-5	El Campo 2.5 WSW	1.59	NA	NA	TX	Wharton	
8/17/2013	7:00 AM	TX-HRR-91	Tomball 2.7 SSE	1.55	NA	NA	TX	Harris	
8/17/2013	7:00 AM	TX-WH-2	El Campo 4.9 SSE	1.44	NA	NA	TX	Wharton	
8/17/2013	8:00 AM	TX-BRZ-25	Pearland 4.4 W	1.43	NA	NA	TX	Brazoria	
8/17/2013	8:30 AM	TX-WH-10	El Campo 0.5 ENE	1.43	NA	NA	TX	Wharton	
8/17/2013	8:00 AM	TX-HRR-120	Spring 10.0 WSW	1.39	NA	NA	TX	Harris	
8/17/2013	7:30 AM	TX-CML-46	Cibolo 3.9 N	1.37	NA	NA	TX	Comal	
8/17/2013	7:00 AM	TX-FS-4	Sylvester 0.2 SE	1.25	NA	NA	TX	Fisher	
8/17/2013	8:00 AM	TX-MNG-29	Spring 4.2 N	1.25	NA	NA	TX	Montgomery	
8/17/2013	8:47 AM	TX-HRR-159	Jersey Village 3.0 N	1.20	NA	NA	TX	Harris	
8/17/2013	7:00 AM	TX-ER-1	Stephenville 1.2 NW	1.09	NA	NA	TX	Erath	
8/17/2013	7:00 AM	TX-CLH-12	Port Lavaca 6.8 W	1.05	NA	NA	TX	Calhoun	
8/17/2013	7:00 AM	TX-BXR-225	Castroville 9.2 NE	1.02	NA	NA	TX	Bexar	
8/17/2013	8:00 AM	TX-CLH-2	Port Lavaca 0.9 NW	1.01	NA	NA	TX	Calhoun	
8/17/2013	7:00 AM	TX-WH-1	Wharton 0.3 E	1.00	NA	NA	TX	Wharton	
8/17/2013	8:00 AM	TX-FB-28	Missouri City 7.5 SSE	1.00	NA	NA	TX	Fort Bend	
8/17/2013	7:00 AM	TX-MNG-26	The Woodlands 2.8 N	0.99	NA	NA	TX	Montgomery	

Figure 6. Central Texas rainfall map and data display from CoCoRaHS observers.

stage or flood stage criteria will be exceeded, the river forecasts are used as guidance to create public river flood warnings and statements and help authorities prepare for the impacts associated with the expected river conditions. Forecasts are accessible via the NWS AHPS at: http://water.weather.gov. An example of a forecast hydrograph from the WGRFC on the AHPS website is shown in Figure 7.

Currently, the WGRFC uses the Sacramento Soil Moisture Accounting Model to determine proper runoff calculations. Unit hydrographs are used to associate runoff over a specified time to a streamflow amount. Wherever possible, unit hydrographs are developed from existing streamflow gauge records. However, synthetic methods have been used in ungauged areas. At the WGRFC, synthetic unit hydrographs are generally developed by using a variation of the Soil Conservation Service method. This method requires only minimum data, namely: length of storm, slope, size of drainage area, and the desired duration. The flows generated from unitgraphs are then routed downstream using 1 of 3 routing methods, i.e., Lag and K, Tatum or Muskingum.

The accuracy and timeliness of the river forecasts, especially for floods, are of the utmost importance to the safety of lives and property throughout Texas. Evacuating people, livestock, and goods, and protective measures for fixed installations can be accomplished only if sufficient warning time is available. If accuracy is not maintained, warnings may not be issued, and protective measures or evacuations may not be taken when they are required. In turn, organized plans of action would not be taken because of lack of confidence in the forecasts. The decision to issue WGRFC-prepared flood forecasts is an initial "trigger" for numerous and costly operations to prevent loss of life and damage to property. The return to normal operations after the flood waters recede is also an important phase of forecasting. This allows businesses and residents to plan recovery operations at the earliest possible time. Even in non-flood periods, efficient operation of water control structures and riverside industry depends on the accurate and timely forecasts of changes in river stages, and thus has considerable economic impact.

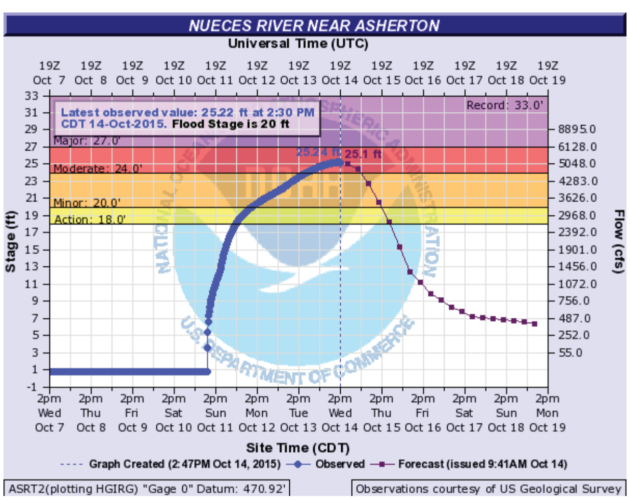


Figure 7. Forecast hydrograph from the AHPS website.

Forecasting is complicated by the wide variations in runoff characteristics among tributaries. These variables include: variable rainfall intensities, watershed basin characteristics, soil types, changing soil moisture conditions, vegetation types, land-use practices, and shifting river channels. Other variables include artificial controls from numerous dams flood control structures, environmental pollution abatement, and energy and municipal water supply operations.

All forecasts and guidance are issued to NWS WFOs in the WGRFC area of responsibility, as well as certain Corps of Engineers offices, river authorities, water districts, and emergency management offices when applicable. RFCs generally do not deal directly with the public since their primary mission is to provide support to other governmental offices.

The WGRFC issues annual spring outlooks during January to March. These outlooks discuss in qualitative and quantitative terms the potential for spring snowmelt flooding. Ground snow data, flight line and satellite snow information as well as existing ground and river conditions are all taken into consideration.

Snowmelt outlooks are produced using 2 major scenarios: (1) melt based on future probable temperatures and "normal" future precipitation for the season; and (2) melt based on future probable temperatures and no additional precipitation (rain or snow). In addition to these outlooks, unscheduled advisories and/or forecasts are issued as hydro-meteorological conditions warrant.

Presently, water supply forecasting is a multistep process. The WGRFC provides water supply guidance for the Upper Rio Grande Basin and its tributaries in New Mexico and southern Colorado. The WGRFC issues a variety of products relating to water supply forecasting, including a joint publication by the Natural Resources Conservation Service (NRCS) and NWS: "Water Supply Outlook for the Western United States." This publication is available on the NRCS and the Colorado Basin River Forecast Center websites. Water supply flow volume forecasts issued in terms of annual and seasonal runoff are used in the long range planning by water users for operating multipurpose reservoirs to accomplish optimum flood control and to minimize the waste of valuable water resources. The initial water supply forecasts are issued in early January to give an early outlook for the planting plans for irrigated crops, possible rationing of short water supplies for agricultural and municipal users, and early release of upstream reservoir water to increase capacities to reduce anticipated flood crests.

In 2012, a modern, hydrologic forecast architecture, the CHPS was implemented at the WGRFC. CHPS replaces

NOAA's previous software for water forecasting—the NWS River Forecasting System, which was not flexible enough to support the burgeoning needs of the hydrometeorological community of the 21st century.

CHPS is built on standard software packages and protocols, and open data modeling standards, and provides the basis from which new hydraulic and hydrologic models and data can be shared within a broader hydrologic community. Developed using a "service-oriented architecture," an emerging standard for large-scale system design, CHPS enables scientists and programmers to work together and rapidly transition new innovative analyses and forecast techniques (e.g., water quality models) from the drawing board to operational deployment. Figure 8 shows a sample of some of the graphics available to WGRFC hydrologists within CHPS.

The WGRFC is also responsible for issuing guidance in a catastrophic dam failure. The WGRFC uses the best practices available to provide the best information possible to its customers. Often this information can be obtained from Emergency Action Plans (EAPs), which were prepared for various dams and reservoirs and are kept on file at the WGRFC. If an EAP does not exist for the dam in question, the WGRFC uses information about the dam from the National Inventory of Dams database from the US Army Corps of Engineers to assist in providing flood guidance.

The WGRFC also participates in tabletop planning exercises with its stakeholders. These include dam owners and operators, local emergency managers, the Texas Department of Emergency Management, Federal Emergency Management Agency, river authorities and other state and federal government entities involved in flood warning, mitigation, and public safety.

Summary

Periodically, the impacts from river flooding can be extreme. (Figures 9 and 10). However, with accurate and timely forecasts, precautions can be taken to help minimize the damage associated with river flooding. The WGRFC's mission is to provide those forecasts. Officials can then determine the best course to protect all interests involved during river flood events.

Information about the WGRFC's current operations is available through social media — Facebook (https://www.facebook.com/NWSWestGulf) and Twitter (https://twitter.com/NWSWGRFC) — and on its website (http://www.srh.noaa.gov/wgrfc).

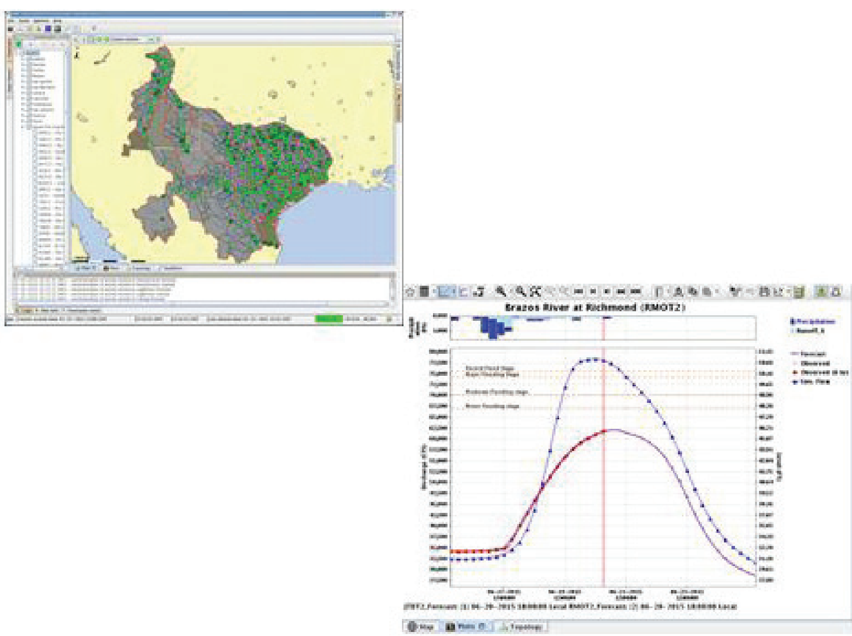


Figure 8. Sample output from the CHPS software.

Figure 9. Emergency spillway in use at Canyon Lake July 2002.

Figure 10. Downstream flooding on the Guadalupe River at New Braunfels.

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Book review: Bitter Waters: The Struggles of the Pecos River

Dearen, P. 2016. Bitter Waters: The Struggles of the Pecos River. Norman (Oklahoma): University of Oklahoma Press. ISBN: 9780806152011. 256 p. $17.97.

Reviewed by Colin McDonald[1*]

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The most basic assumption about a river is that it will dilute salts and carry them away to sea. The Pecos River of West Texas has never lived up to such expectations, despite what the land speculators and politicians say.

As it cuts across the Chihuahuan Desert, the twisting river is lined with 4 centuries of stories describing decade-long droughts and water so salty it kills livestock and sterilizes farmlands.

The looming river has become a popular setting for Western novels and films. Now someone has taken on the stranger than fiction story of the river itself.

In his book, Bitter Waters: the Struggles of the Pecos River, Western novelist Patrick Dearen walks readers through the geology, hydrology, climate, history, and politics that make the Pecos one of the most misunderstood and mistreated rivers in the Lone Star State.

The legal battles of the Pecos were well documented in 2002 by G. Emlen Hall in High and Dry: The Texas-New Mexico Struggle for the Pecos River, but Dearen is the first to tackle the entire story from a West Texas perspective.

He writes about the Pecos' headwaters in the 13,000-foot-high Sangre de Cristo Mountains, where climate change and a century of fire suppression have left dwindling snow packs and catastrophic-fire-prone forests of dying pine trees. He writes about how underground nuclear explosions are suspected in altering and enhancing the pathways of the salty springs that have always been the bane of anyone looking to get a drink from the Pecos. He writes about how the increasing salt load of the river is presenting a threat to everything downstream, including the Rio Grande Valley.

None of these subjects are new. In the first chapter, he includes a quote attributed to a 1942 report by the National Resources Planning Board: "For its' size, the basin of the Pecos River probably presents a greater aggregation of problems associated with land and water use than any other irrigated basin in the Western U.S."

The strength of Dearen's work is the perspective he brings to a subject that is usually dominated by lawyers, scientists, academics, and bureaucrats.

Dearen's expertise lies with the particular personality and character of the West. His previous work includes being a reporter at local newspapers, collecting the oral histories of cowboys, and trying his hand at science fiction writing. He was born in West Texas in 1951 and has spent his career there. He has a flare for introducing each chapter's subject—invasive plants, water compacts, endangered species—as if they were characters walking into a dusty saloon and sparking an unexpected plot twist.

"Again, the long struggle between states seemed over, but now the river offered up new threats to plague the very waters that would come Texas' way," he writes to introduce golden alga, the latest and possibly most horrific result of the outdated water policy of the Pecos.

With this twist, Dearen introduces a creature stranger than science fiction that is perpetuated by the classic western theme of neighbors not getting along to the detriment of all.

The single-cell organism made its first appearance in the Western Hemisphere on the Pecos in the 1980s. It's a mystery how golden alga got there or what triggers its sudden random exponential growths in population, but the results are not.

The blooms of alga are thick and turn the water a golden color. They also dissolve the cells of fishes' gills and internal organs, causing them to slowly die. The blooms can be controlled, or at least drastically reduced, by freshwater inflows. But on the Pecos in Texas, freshwater flows are rare. It is now common to see tens of thousands of dead fish floating on any reach of the Pecos, all the way to the confluence with the Rio Grande.

The stronghold for this invasive foreigner is Red Bluff Reservoir, which was created by a federally subsidized dam in 1936.

The water of the shallow and leaky reservoir is controlled by the Red Bluff Water Power Control District. Its authority was granted by federal and state governments that were desperate to create jobs during the Great Depression and when little was known about the flows of the Pecos.

Although the nearby fields of cotton, alfalfa, and melons were already switching to wells when the dam was built and often cannot use the water held by the reservoir, the district resists change. The power plants have been abandoned. There was rarely enough water for them to operate.

With the aid of the desert sun, the water in the reservoir becomes ever saltier and warmer, enabling the golden alga to multiply ever faster. The lake is now so hostile to fish that the state of Texas has given up stocking it or even conducting fish surveys. When the water is released downstream, it can spark fish kills all the way to the confluence with the Rio Grande.

It would seem that such a menace to the Texas reach of the Pecos would be enough to spur a unifying movement to find a way to stop the alga. But that would be the naive reaction of someone who does not understand the history of the Pecos and the deep divisions and pride that keep people from working together.

Dearen, on the other hand, knows who to interview. He boils the story down to its most basic elements with quotes from those who actually live and work with the river.

"We may be obsolete someday," conceded Robin Prewit, a longtime employee of Red Bluff District. "Maybe this isn't the best use of the water… But at least give some credit for what it is and how it came to be and what it means to some people."

Dearen's book was commissioned by the Pecos River Resolution Corporation, which was founded by oilman P. Lourcey Sams and dedicated to recording the facts of the river that will lead to a "comprehensive understanding of the best overall use of the Pecos River and what would be involved in accomplishing this mission," according to the corporation's website.

The project was made possible by the underwriting of the Nita Stewart Haley Memorial Library in Midland, Texas, and by contributions from oil and gas companies and foundations, including the Apache Corporation, Concho Resources, and the Permian Basin Area Foundation.

While this backing may have limited Dearen's scrutiny of the oil and gas industry, it did not stop him from a telling a history that needs to be shared.

His book is not the complete story of the Pecos. No book ever could be. But it is a start to understanding why the Pecos is such a great place for a Western novel and lousy place to be a fish.

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Book review:
Water is for fighting over: a compilation of articles on water resource management in Texas

Roper CO, Linton T. 2015. Water is for fighting over: a compilation of articles on water resource management in Texas. Self-published. 176 p.

Reviewed by Robert E. Mace[1*]

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Future generations will surely look back at the drought that plagued Texas from 2010–2015 as historic. Not only was it the second longest statewide drought, but it resulted in record agriculture losses, record wildfires, and some harrowing months for communities struggling to meet water demands. It also sparked the long-desired creation of a funding mechanism to implement the state water plan (ironically from what is popularly called the Rainy Day Fund), a holy grail pursued since the birth of stakeholder-driven Texas water planning in 1997.

The drought also produced this little gem of a book: *Water is for fighting over: a compilation of articles on water resource management in Texas,* a highly readable collection of 64 chronologically presented short articles written by Ms. Chris O'Shea Roper and Dr. Tom Linton for the *Galveston County Daily News* and reprinted in 8 small-town newspapers across the state. Roper is a freelance writer who often writes about coastal ecological issues, and Linton is a marine biologist at Texas A&M University-Galveston.

The writer-scientist collaboration works well. The authors state that "[t]he book is intended to present both water management issues and potential solutions." That's an overly dry and underserving description of the book—it's much more than that. What's so enjoyable and fascinating about this tiny tome is its real-time diaristic nature. Little did the authors know when they began the series that the drought would continue for another 4 years, and they followed it to the bitter end, experiencing and writing about the various ups and downs of weather and water policy. Just like the movie *Titanic*, we already know the ending; the fun and fascination is experiencing the event through someone else's eyes.

The book's stated purpose and title suggest you may be lectured about what to do about water (especially when you see "Ph.D." on the cover). In it I didn't find solutions so much as discussions on the latest water conservation techniques or non-traditional water technology, such as desalination, reuse, and waterless fracking. The book is eminently friendly. It's a one-sitting read or, if you prefer, its short essays lend it to leaving on top of the Reader's Digest next to your dual-flush toilet.

The authors begin, in November 2011, at a Texas Water Development Board meeting to approve the 2012 State Water Plan. And the story unfolds from there. Some of the topics covered include the cost of water, subsidence, conservation, the Edwards Aquifer, the Trinity River, water planning, legislation, ownership of water, hydraulic fracturing, desalination, reuse, the Brazos River watermaster, El Paso, funding the water plan, and environmental flows. In other words, almost everything in Texas water.

Being from and writing for Galveston, the authors emphasize Galveston-area water issues; however, the authors travel the state, check out water issues in Las Vegas, and even wind up at an international water conference in Scotland to talk about Texas water. Water issues tend to be global, so even Galveston-specific discussions are relevant to other parts of the state.

There's some unavoidable repetition of facts, but that's forgivable given the original format of the writings.

Interesting tidbits pepper the book's essays, such as:

- Rice is known as the "king of the coastal prairie."
- In 1925, the Texas Department of Health called the Trinity River a "mythological river of death."
- Pat Mulroy allegedly said that her friends in New Orleans told her: "You are welcome to our floodwaters."
- "Due to subsidence, erosion, and/or development, we have lost 25% of our wetlands in the last forty years. Sea grass loss is put at 80%."

The book's biggest failings are its financial discussions. The authors write that all federal Water Resource Development Act funding for Texas passes through the Texas Water Development Board (none of it does), that the Board has managed an evergreen bond fund since 1987 (it's actually a bonding authority that was given to the agency in 2011), and that funding more than \$50 billion in infrastructure needs with the \$2 billion entrusted with the Board is a "mission impossible" (the \$2 billion was only intended to fund \$27 billion in infrastructure needs [those needs identified in the state water plan as needing state financing] and is being used as a reserve fund to achieve that level of financing over the next 50 years). However, the authors are certainly not the only ones thoroughly confused by what looks like a Rube Goldberg machine to non-financiers, as the State Water Implementation Fund for Texas sometimes does.

The authors attended the Texas Water Foundation's Rainmaker Award ceremony on May 8, 2014 to honor former Texas Rep. Allan Ritter for his efforts as the chairman of the Texas House Committee on Natural Resources in funding the implementation of the state water plan. Attending and writing about this event is poetically perfect, providing one of several satisfying endpoints to the story arc of drought, its impacts, and its outcomes.

The narrative ends August 1, 2015, after the end of the statewide drought, after the 84th Texas Legislative Session, and after the authors spoke at the World Water Conference in Scotland, completing their journey of documenting for future generations one perspective on what happened during this terrible drought. Appropriately enough, the authors conclude with these words: "We are all in this together."

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Implementing three-dimensional groundwater management in a Texas groundwater conservation district

Hilmar Blumberg[1] and Gabriel Collins[2*]

Abstract: The Guadalupe County Groundwater Conservation District has implemented a 3-dimensional water management solution that allocates pumping rights based on actual volumes in place under a tract. This new regime treats the aquifer as a "constant level lake" where rights holders are awarded the right to a percentage of the inflow (recharge) based on the volume of saturated sands underneath their property.

Three-dimensional management can improve Texas groundwater governance by strengthening property rights, promoting conservation, and unlocking economic value by promoting water trading and collateralization. It is also cost-effective and can be rapidly implemented: the Guadalupe County Groundwater Conservation District created its initial 3-dimensional ruleset in approximately 4 months at a cost of roughly $15,000. Larger districts or districts that could not benefit from an existing property parcel map created by an appraisal district would face higher costs. Creating the type of property ownership maps used by local tax appraisal districts can cost as much as $100,000. Yet the intensive property tax regime in Texas means that even the least-populous counties typically already have such information available in digital form.

Quantifying the available water volume beneath each property and making pumping rights transferrable between wells profoundly transforms groundwater management and confers clear vested rights to water in place. As such, it can provide economic recourse to smaller water holders even in areas where municipalities and other large pumpers enter the district. In short, this forward-looking, conservation-oriented new ruleset provides a way for Texas groundwater stewards to move past flat surface acreage-based allocations and move into an era where a handful of large pumpers in a district do not erode the property rights of smaller holders. Quantifying water in place involves averaging and making certain approximations and generalizations because of the inevitably complex nature of geologic formations. Over time, groundwater conservation districts and their constituent members will determine how deeply to engage that complexity. The bottom line is that 3-dimensional management offers an exponential degree of improvement over existing Texas groundwater management models. The Guadalupe County Groundwater Conservation District's ruleset embraces a philosophy of iterative learning and improvement and acknowledges that employing models as tools of governance always involves approximations. It handles this by including the capacity to rapidly update and revise its approach as the district obtains additional data points and insights through operational implementation of its rules.

Keywords: rule of capture, groundwater governance, conservation, dormant rights, collateralization, water market, cap and trade

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Please note that in this analysis, Mr. Blumberg and Mr. Collins are expressing their respective personal ideas and opinions and that these do not necessarily reflect the views of the Guadalupe County Groundwater Conservation District or the Baker Institute for Public Policy.

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The Texas Supreme Court's landmark *Day* decision in 2012 held that surface owners have the right of absolute ownership to groundwater underlying their tracts.[1] Yet *Day* only establishes the ownership right to groundwater; it does not set forth guidelines on how to practically allocate and manage groundwater resources in a rapidly growing state with volatile weather conditions.

As such, the challenge moving forward is to find a way of maximizing groundwater's value to the predominantly rural property owners under whose tracts it lies while also helping that water flow to thirsty urban areas that are the engines of Texas' demographic and economic growth.

Groundwater conservation districts should seek to create fully developed systems of property management for their constituents, aiming to maximize and preserve property value while supporting a right to exclude. For groundwater, unlimited, perfect exclusion is presently impossible, as water molecules flow in response to changing pressure gradients. Yet with a developed free market with broad and predictable participation, like that which 3-dimensional groundwater management seeks to catalyze, a reasonable facsimile is possible that protects property rights, preserves precious water resources for future generations, and unlocks collateralization and other new forms of value-accretive economic activity. This is a key underpinning of the property right and an important shortcoming of the *Day* opinion, which in many ways gives groundwater owners an absolute ownership right but no practical remedy to enforce it.

"GOING 3-D"

Groundwater offers a dependable water source that is less rapidly affected by drought than surface water and buys municipalities and other non-agricultural users time to adjust to a long-term dry cycle, such as the one Texas experienced in the 1950s. A 3-dimensional groundwater management system that strengthens property rights and increases water's value while it still sits in an aquifer would offer a strong tool for inducing conservation of the resource and would benefit future generations of Texans.

For its portion of the Carrizo Aquifer, the Guadalupe County Groundwater Conservation District has created a transparent and cost-effective management solution that empowers local water owners. This solution entailed mapping the resource and equitably dividing it based not on flat surface acreage but rather on the available volume of saturated Carrizo Aquifer sand under each tract. By adopting this approach, the District has found a clear and powerful way potentially to transform Texas groundwater governance, moving from the old 2-dimensional regime of surface-based flat extraction limits to a new 3-dimensional model that visualizes the geological arrangement of groundwater in-place under a surface tract, quantifies its volume, and grants extraction rights accordingly, pro rata.

Each groundwater conservation district faces unique local hydrological, economic, and political conditions. The changes the Guadalupe Groundwater Conservation District made to its ruleset might not, without further suitable adjustment or alteration, be universally applicable across other groundwater conservation districts. Yet this solution offers a working model that leverages existing legal precedent and statutory powers to create a better way to manage groundwater resources for the benefit of both private owners and the consuming public. In brief, the Guadalupe County Groundwater Conservation District operationalized the *Day* decision, which affirmed surface owners' absolute ownership rights to the groundwater underlying their tracts. Its method of doing so focuses on meeting 3 core criteria essential for reshaping groundwater management in a fair, sustainable, and value-maximizing manner.

First, **legal and political feasibility.** The need for a better groundwater governance system is a "here and now" issue in Texas, and potential solutions must reflect this reality. The desire for perfection cannot be allowed to prevent something clearly forward-looking from being created. To that point, there is a need for a system that can be timely built and implemented in the state's current legal and political climate. Because inclusivity enhances feasibility, delineating the resource and using a transparent, market-based allocation system protects rural property owners who control much of the access to Texas groundwater supplies and positions them to monetize their water resources in a market-based system that favors the highest-value uses.

Second, **flexibility and scalability**. In Texas, underground water governance needs a system that can react nimbly to climate changes, water demand imposed by a fast-growing economy, and population growth, which is among the highest in the nation in both rate and scale. To give a sense of how profoundly and rapidly a drought can affect water demand in Texas, groundwater use rose by more than 2.7 million acre-feet year-on-year in 2011, according to Texas Water Development Board data.

A mapping and volumetric rights allocation system offers a strong and actionable solution among the currently available alternatives for managing increasingly scarce groundwater resources. Each of Texas' dozens of underground water-bearing formations is geologically and hydrologically different. Likewise, the politics of each groundwater conservation district and groundwater management authority differ as well. In that spirit, this case study is not intended to offer a "one size fits all" solution. Rather, it acknowledges that to succeed in the long run, groundwater management regimes need to be rooted in and reflect local conditions—the same reality that under-

[1] *Edwards Aquifer Auth. v. Day,* 369 S.W.3d 814 (Tex. 2012)

pinned the Groundwater District Act of 1949 (discussed in greater detail below).

Third, **fairness and protection of private property rights.** Under more familiar rules, especially those with overly generous, flat, surface-based correlative rights, groundwater resource development typically only benefits a handful of owners whose tracts overlie the thickest section of a water-bearing formation. Once a developer comes in, drills a well field, and begins pumping, a relatively small surface holding can absorb a significant portion of the allowable water extraction for the entire district. This ultimately means that many landowners who sit atop thinner sections of the aquifer, but have a property right in the water nonetheless, are effectively precluded from ever developing or monetizing the water assets underlying their land.

In contrast, the Guadalupe County Groundwater Conservation District's approach aims to make rights from throughout the district—even those over thinner saturated sands—to be marketable. The District provides significant information about the local groundwater resource and ownership characteristics, including saturated sand thickness on a tract-by-tract basis, which accrues to the benefit of local water owners.[2] Providing owners a solid base of information to inform their decisions helps protect private property rights. Along these lines, a groundwater conservation district that has mapped and subdivided its resource base is operating at a high standard of stewardship in full compliance with Chapter 36 of the Texas Water Code, which, among other things, demands that groundwater conservation districts "use the best available science in the conservation and development of groundwater through rules developed, adopted, and promulgated by a district in accordance with the provisions of this chapter."[3]

While some of the District directors may not have intended to create a water market when they adopted a new ruleset in 2004, those who authored the rules understood their deeper implications. The greater availability of information, combined with the fact that each water rights owner now possesses a protected slice of the Carrizo Aquifer pie in the District, sets the stage for a functional commodity market in water rights. As a robust market develops, better information availability will enable the market to function more efficiently and fairly—especially from the perspective of landowners atop valuable groundwater assets whose political buy-in is essential to the long-term legitimacy of new water resource governance models.[4]

Information transparency maximizes the total net economic value of the resource under the District's jurisdiction, while safeguarding against disproportionate rent transfers driven by the information asymmetry between sophisticated, well-capitalized buyers and sellers who might lack the means to ascertain what their resource is truly worth. This in turn helps create a fairer market, which generally helps cement local buy-in and drive grassroots political support that ultimately reduces risk to the big capital interests needed to finance large-scale water supply projects. Market-oriented groundwater conservation district rulesets also help promote conservation by shifting users' views from being purely extraction-based to being self-sustaining, commerce-based. In essence, owners have a fully vested property right that can be bought, sold, inherited, and used in other value-accretive ways. Marketable water rights can become a long-term asset that motivates owners of these rights to evince ever-greater interest in the election of forward-looking, conservation-minded groundwater conservation district directors.

For these reasons, the Guadalupe County Groundwater Conservation District's new ruleset closely adheres to the Texas Legislature's stated purposes behind the creation and empowerment of groundwater conservation districts, as outlined in Chapter 36 of the Texas Water Code. The District formed the new ruleset to protect property rights.[5] It is also balancing the conservation and development of groundwater resources to meet the state's interest in future, sustainable development.[6] Finally, the District's innovative use of the saturated volume model and commensurate division of water rights represents an application of "the best available science" to help find a proper balance between the conservation and development of groundwater.[7]

[2] Guadalupe County Groundwater Conservation District, "Water Rights," http://www.gcgcd.org/water-rights.html

[3] Texas Water Code, Chapter 36.0015(b). In this statute, "best available science" means "conclusions that are logically and reasonably derived using statistical or quantitative data, techniques, analyses, and studies that are publicly available to reviewing scientists and can be employed to address a specific scientific question." We firmly believe the Guadalupe County Groundwater Conservation District's creation of a saturated sands volumetric model and subsequent allocation of rights based on a recharge-driven annual production cap clearly meets the Water Code's standard.

[4] See, for instance: Damodaran, Aswath. "The value of transparency and the cost of complexity." Available at SSRN 886836 (2006).

[5] "Groundwater conservation districts created as provided by this chapter are the state's preferred method of groundwater management in order to protect property rights, balance the conservation and development of groundwater to meet the needs of this state, and use the best available science in the conservation and development of groundwater through rules developed, adopted, and promulgated by a district in accordance with the provisions of this chapter." Tex. Water Code Ann. § 36.0015 (West)

[6] Id.

[7] Id.

HOW AND WHY THE DISTRICT CHOSE TO CREATE A 3-DIMENSIONAL MODEL

The Guadalupe County Groundwater Conservation District was created in 1997 by Chapter 1066, Acts of the 75th Texas Legislature and was then amended in 1999 by House Bill 3817.[8] House Bill 3817 created the District in its present form with 7 directors elected from 7 single member districts and limited the District geographically to the portion of Guadalupe County that lies outside the boundaries of the Edwards Aquifer Authority.[9] Guadalupe County Groundwater Conservation District lacks taxing authority and raises all of its income from fees imposed on municipal and commercial groundwater transactions in the district.[10]

The District oversees groundwater extraction in an area with a population of more than 140,000 people and lies on the periphery of the rapidly growing San Antonio metropolitan area. Guadalupe County has grown from 89,000 residents in 2000, to more than 131,500 in 2010, and an estimated 147,250 in 2014, according to the U.S. Census Bureau. Approximately a third of these people live within the District boundaries.[11] Groundwater from the Carrizo Aquifer provides the baseline groundwater supply in the District. The Wilcox Aquifer also underlies the District, but there is no reported production from that layer to date in the portion of Guadalupe County under the District's jurisdiction. Upon its creation, the Guadalupe County Groundwater Conservation District board initially adopted rules directly derived from other, pre-existing groundwater conservation districts atop the Carrizo and Wilcox aquifers that also underlie Guadalupe County. Specifically, these rules relied upon (1) overly generous surface acreage-based production limits bound by a District-wide upper production limit set purposely low relative to the amount of water rights distributed; (2) wells being spaced far apart; and (3) water rights contiguity, meaning that rights had to be around the wells and connected.[12]

[8] "Groundwater Management Plan," Guadalupe County Groundwater Conservation District, 8 November 2012.

[9] Id.

[10] Id.

[11] Allison, Bass & Associates, LLP report Dec. 2011 GCGCD Voting Rights Submission/Election boundaries

[12] Id. The general rules enumerated above these rules were designed for an environment of very low demand and very large supply, with a few local users using water for irrigation, livestock, and other limited volume domestic supply. They were not designed to handle the issues that arise when nearby municipalities seek to extract and export tens of thousands of acre-feet per year of water from the area.

THE CALL TO ACTION

Certain Guadalupe County Groundwater Conservation District board members began to reconsider their rule structure as they watched several large municipal water suppliers—the San Antonio Water System, Schertz-Seguin Local Government Corporation, and Canyon Regional Water Authority—begin industrial-scale water rights acquisition and extraction in neighboring Gonzales County. Of particular concern, the Board saw that the Gonzales County Underground Water Conservation District's outdated ruleset led to a small handful of surface owners atop the thickest aquifer sections striking deals with the municipal suppliers, at which point the district essentially hit its annual production ceiling. As such, the few landowners who owned tracts atop the thick sections of the Carrizo Aquifer in Gonzales County effectively locked up the resource and locked out other groundwater holders. The latter's water lost much of its economic value because the District had reached its annual production cap and owners who had not yet entered the market were thus precluded from leasing their water.

Surface acreage-based correlative water rights, combined with contiguity requirements and caps on production imposed by groundwater conservation districts, break down when municipal-scale water extraction projects enter the picture.

Two primary factors drive this reality. First, just as the subsurface geology does not correspond with the surface topography, neither does the subsurface hydrogeology generally correspond with the distribution of surface holdings. Some tracts lie atop thin spots of saturated sand, while others sit atop the down-dip "sweet spots" in the aquifer where there may be several hundred feet or more of accessible water. The natural, extreme variations of saturated sand thickness and productivity within a connected aquifer system illustrate a critical flaw in the correlative, flat, surface acreage-based withdrawal regulation system used by many groundwater conservation districts in Texas.

Second, water migrates in response to pressure changes. When a developer sinks large-bore wells into the sweet spots and begins extracting large volumes of water, migration in the aquifer favors the down-dip holders at the expense of those owners atop thinner sands, who may find their property completely pumped away. Under Texas case law, such owners generally have no legal recourse to prevent neighbors from pumping the same groundwater that those same cases also clearly—and ironically—state is their "real property."[13]

Motivated by the events in Gonzales County, Guadalupe

[13] Gabe Collins, Blue Gold: Commoditize Groundwater and Use Correlative Management to Balance City, Farm, and Frac Water Use in Texas, 55 Nat. Resources J. 441, 448 (2015); See also *Sipriano v. Great Spring Waters of Am., Inc.*, 1 S.W.3d 75, 76 (Tex. 1999)

County Groundwater Conservation District has moved to rectify this inconsistency through exercise of the substantial powers conferred upon groundwater conservation districts under the Texas Water Code. The legal authority for the District's action is examined in greater detail later in the paper.

The Guadalupe County Groundwater Conservation District faced the same concentrated water rights ownership situation that had created such an inequitable outcome in Gonzales County, as only 25% of the District's acreage sits atop the thickest water-bearing strata: 350 feet thickness or greater (Figure 1). In the thickest intervals—350 feet to 662 feet—the ownership concentration level is very high. The 10 largest surface acreage holders account for 55% of total surface acreage atop water that is thicker than 350 feet, and the 5 largest surface owners in this group account for nearly 42% of all acreage atop the water layer that is 350 feet or thicker.[14]

The uneven distribution of water-bearing strata is precisely what makes the Guadalupe County Groundwater Conservation District's 3-dimensional management system so necessary. The thick aquifer sections are exactly the sweet spots that a water developer seeking to supply a municipality will want to drill into. Under the traditional management model based on flat correlative rights and district-wide production caps based on desired future conditions, these are the parties who would stand to reap most, if not all, of the economic returns, albeit in a shape-shifted version of the old, unadulterated "rule of capture," while the well field inexorably dries up their neighbors' groundwater holdings.

Yet, if a large water exporter comes into the Guadalupe County Groundwater Conservation District, the outcome will be very different. Each landowner sitting over various sections of the aquifer possesses a monetizable interest. Because water rights are transferrable without restriction to any well, the specific distribution of each cubic foot of saturated sand matters less than it would in a simple surface acreage-based allocation system. Money from water sales will flow to the owners of that cubic foot so long as they choose to participate in the market. Owners who sit atop thicker sections of the aquifer will still make more money if they lease. Unlike under a uniform surface-acreage system, where the thick water owners receive everything, under the 3-dimensional management model, owners of thinner sections now also have rights that allow them to participate in the marketplace.

[14]Data on water rights holders sourced from the Guadalupe County Groundwater Conservation District. Guadalupe County Groundwater Conservation District, "Water Rights," http://www.gcgcd.org/water-rights.html. (last accessed on 9 August 2016)

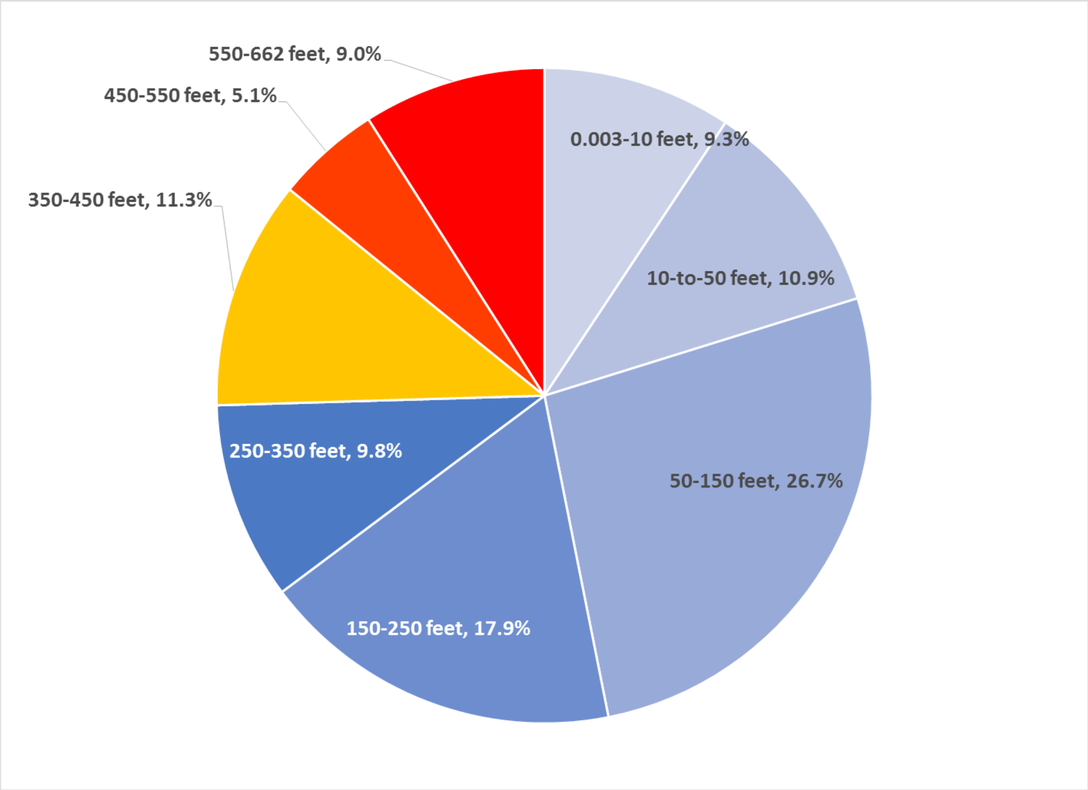

Figure 1. Guadalupe County Groundwater Conservation District acreage holdings classified by the thickness of water-bearing layer. Source: Guadalupe County Groundwater Conservation District, Authors' Analysis.

HOW THE DISTRICT REFORMED ITS RULESET

Guadalupe County Groundwater Conservation District board members moved rapidly in the wake of the Gonzales County water deals to restructure their management system so that future water commercialization would be fairer to property owners in the District. In contrast to legal and legislative solutions that often require years to craft and implement, the District needed a much shorter time—approximately 6 months—to develop its policy proposal, map the resource, and have the idea ready for public presentation and adoption. The proposal's sponsors operated under the philosophy that "the perfect should not be the enemy of the good" and sought to craft a system that would work immediately, but also could be improved as the District's demographic and hydrological characteristics evolved. Some of the District's directors ultimately voted for the new ruleset not to create a water market but rather to ensure that they were fully discharging their duties as groundwater resource stewards, as prescribed by Chapter 36 of the Texas Water Code.

Step one involved crafting the intellectual framework. First, the District recognized that a flat correlative rights system based solely on surface acreage fails to account for the reality that some property owners over an aquifer lie atop deeper, thicker saturated cross-sections of the aquifer, and can thus access more water and enjoy greater market functionality. In accounting for this, the District was in line with the Texas Supreme Court's analysis in *Day*, specifically the Court's position that "regulation that affords an owner a fair share of subsurface water must take into account factors other than surface area."[15]

Developing a more sophisticated allocation approach that goes beyond simple surface area divisions takes into account that deeper, thicker water is easier to produce. Someone who owns property over 10 feet of saturated sand generally cannot pump as much water as someone who owns property over 800 feet of saturated sand. Hence, in the aquifer situation, the thickness of saturated sand beneath a property does have a market implication to be reckoned with in the general water rights equation. For up-dip water holders, the key difference between the 3-dimensional management system and traditional management systems is that water molecules are treated as a vested property right before they are ever pumped. In addition, owners know with certainty how large their share of the District's total allowable water extraction volume is. This paves the way for up-dip owners to be compensated for water pumping that may not involve wellbores on their tract but drains water in place that would have never been monetizable in a non-3-dimensional system.

Moving beyond the old correlative rights system and the "rule of capture" ideas it was paired with democratizes groundwater assets and allows even small holders to monetize what they own rather than following the traditional development model. In the traditional model, a minority of landowners atop thick sections of the aquifer make a lot of money while others' water is effectively cut off from potential sales opportunities because the deep-dip holders have occupied the entire annual production quota. In such a worst case scenario, some water holders up dip would receive no compensation at all while their remaining water is drawn away by large extraction projects.

In essence, the District's new ruleset makes all groundwater rights under its jurisdiction into something akin to royalty interests in a pooled oil and gas lease. In both cases, leased rights owners—even if the wells are not on their tract—still receive a share of production proportional to their acreage holdings.[16] In both cases, land owners with export-oriented well fields on their tracts can also negotiate additional payments for damages, right of way access, and other matters. But the underlying groundwater resource is monetizable in a way that allows all groundwater owners to lease their rights and proportionally earn income from industrial-scale water sales.

From a resource conservation perspective, the most important difference between pooling of water interests and pooling of oil and gas interests is that oil and gas production expressly seeks to extract as much of the resource as economically possible. To the contrary, the 3-dimensional groundwater management philosophy is predicated upon setting an annual withdrawal limit based on recharge and then allocating this inflow volume based on the amount of saturated sand underneath each tract and allowing trading of rights within the volume parameters established by the annual production cap.

Step two required the District to map its groundwater resources. District members began working on the project in early 2004. To improve its ability to allocate the resource, the District modeled the saturated sands beneath every property located above the Carrizo Aquifer. It did so by cross-vectoring, that is, blending together, an extant digital property surface map from the Guadalupe County Appraisal District with a computer-generated saturated section thickness (isopachous) map, which, after integration, can easily assign every property over the aquifer a certain percentage of the entire saturated section volume in the district (Figure 2).

The Carrizo and the Wilcox aquifers under the Guadalupe County Groundwater Conservation District's jurisdiction feature major bands of more transmissive sands interlaced with less transmissive bands of sandy clays, but the entire aquifer,

[15] *Edwards Aquifer Auth. v. Day*, 369 S.W.3d 814, 841 (Tex. 2012)

[16] A central tenet of pooling for oil and gas development is that "production anywhere on a pooled unit is treated as production on every tract in the unit." *Key Operating & Equip., Inc. v. Hegar*, 435 S.W.3d 794, 799 (Tex. 2014)

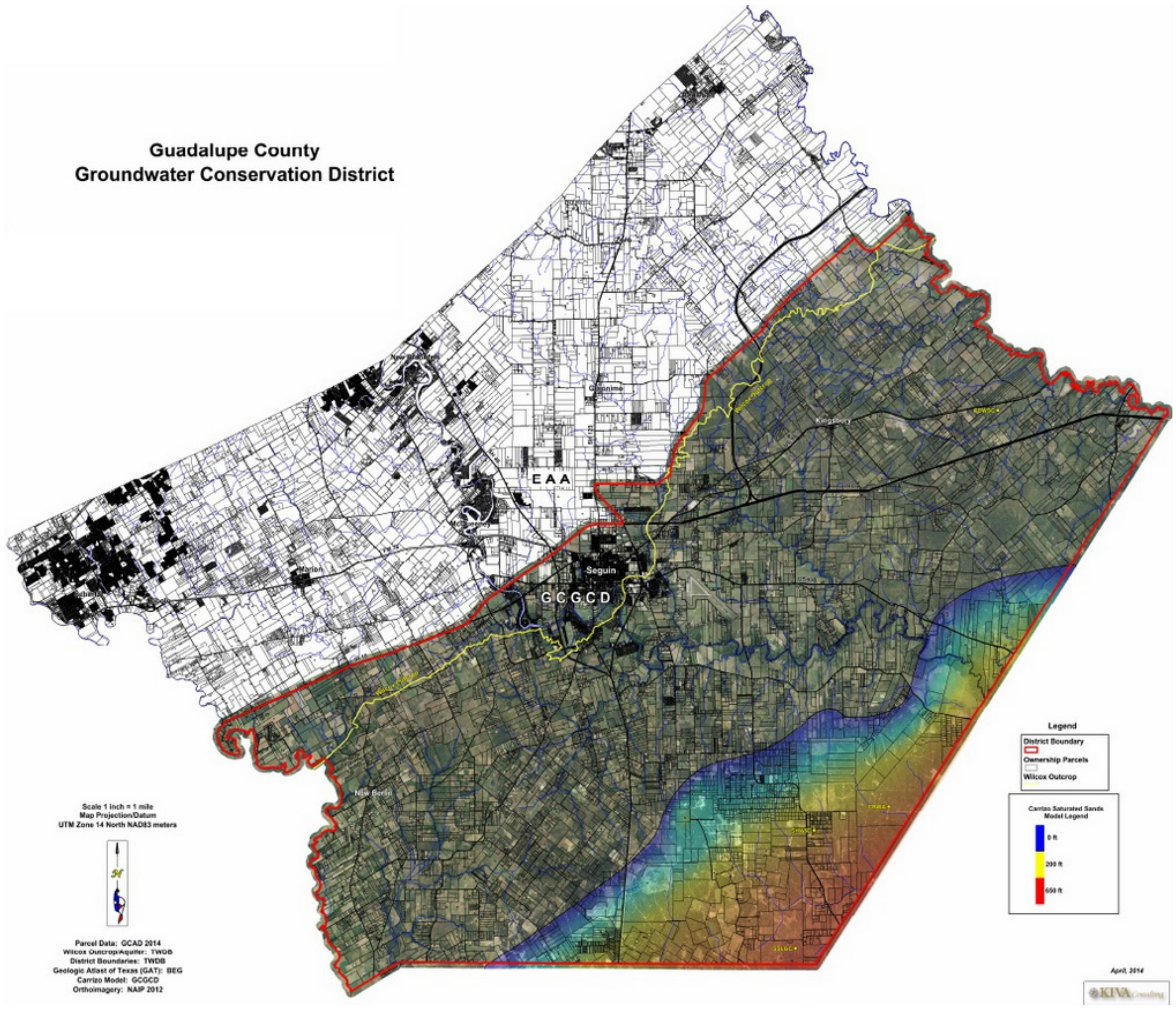

Figure 2. Guadalupe County property tracts superimposed on Carrizo Aquifer saturated sands depth. Source: Guadalupe County Groundwater Conservation District.

all of the Carrizo and all of the Wilcox, is really a connected, saturated collection of sands and clays. The District based its model on the thickness of the saturated sections, assuming that everyone with any saturated Carrizo had about the same amount of water per cubic foot of saturated matrix. This assumption was predicated on the reality that the aquifer is heterogeneous within fairly predictable limits; therefore, the model would yield useful results that far more closely mirror reality than 2-dimensional, flat surface acreage-based allocation models ever could.

The GIS database and 3-dimensional model of the saturated thickness were created using contour data, water level measurements and other relevant data provided by the District's hydrologist.[17] The computer-generated saturated sands model became part of the District's rule set on August 12, 2004.

The saturated sand volume was modeled using 16 feet by 16 feet square surface cells projected down through the saturated section exactly below, yielding the total estimated saturated section volume correlated to a given property. The District

[17] As currently conceived, the model does not account for artesian pressure in the aquifer. Under 3-dimensional management as implemented by the District, the aquifer may be thought of as a static-level lake with a certain inflow (recharge) that is divided fairly to all property owners "on the bank of the lake." The constant-level lake is owned by no one, only the inflow (recharge). The inflow is distributed *pro rata*, depending on how many feet of bank each owner owns and the "lake" (i.e. the aquifer) is only a temporary holding tank for the inflow. With the 3-dimensional model, the recharge (or some percentage of it) is distributed to every property owner *pro rata*, depending how many water molecules are under each property owner's property, not how deep those water molecules are, or how much pressure they are under. Awarding value (extra rights) because of artesian pressure is really part of the old order that is rooted in rulesets that award the deepest water most, if not all, of the selling rights.

then calculated the total volume of the saturated section under its jurisdiction by summing up the saturated volume total of all properties and assigned each individual property owner a percentage of the total. Subsequently, the District determined its total annual allowed production should equal 62.5% of the Carrizo Aquifer's assumed annual recharge in the District boundaries, yielding a maximum annual extraction volume of 12,600 acre-feet (62.5% x 20,000 acre-feet/year = 12,600 acre-feet/year). Note: This production limit was a politically determined and therefore malleable amount that generally tracks the desired future conditions that are reviewed at least annually as a result of the District's meetings with other members of Groundwater Management Area 13, which spans 17 counties and multiple aquifers in South-Central Texas between Austin and Laredo.[18]

Accordingly, from the leading edge of the saturated section under the recharge zone to the deepest, thickest sections in the confined zone, the properties gradually get more water rights per given surface area. However, once the thickness of the saturated section becomes constant moving down the dip (i.e., the sandstone beds cease to get thicker as they get deeper), the amount awarded per unit of surface area also stops increasing.[19]

MAPPING COSTS

While each aquifer exhibits different local characteristics, a core point of the Guadalupe County Groundwater Conservation District's methods is that its cost is surprisingly modest and lies within the budgetary means of most Texas groundwater conservation districts (Table 1). Digitized property maps are the most expensive component required for creating a 3-dimensional groundwater management system, but these costs have often already been borne by the local appraisal district. In the Guadalupe County Groundwater Conservation District's case, the local appraisal district spent approximately $100,000 to create its digital properties map but allowed the groundwater conservation district to use the property map for a nominal fee.

Appraisal districts across Texas are increasingly moving toward digitized parcel mapping and are likely to share their assets with the local groundwater conservation district if it chooses to create a property-based saturated volume model.[20]

Indeed, if the implications of the *Day* decision percolate further and local tax authorities began to view groundwater as a form of taxable property, local appraisal districts may become enthusiastic allies of groundwater conservation district boards who seek to map and delineate local groundwater resources.[21]

A hydrologist charged approximately $4,000 for creating the saturated thickness map of the Carrizo Aquifer in the relevant portion of Guadalupe County. A mapper then charged approximately $7,000 to integrate the appraisal district property map with the aquifer thickness data and create an actual picture of saturated volume by tract.

Structuring the Marketplace

Essentially free transferability of water rights is a central premise of the District's contemporary ruleset. Under this ruleset, water rights are initially tied to surface tract ownership. Water rights become "producible" when they are linked to a well for which the District has authorized a production permit.[22] This has resulted in setting the stage for a largely unfettered water marketplace in which every water rights owner in the district may participate. Because a groundwater conservation district acting totally within the bounds of established statutes and case law can create a defined pool of fully transferrable water rights, it profoundly transforms traditional Texas groundwater management.

Under the old regime, it was possible for a small number of landowners above the deeper, more water-laden portion of an aquifer to "lock up" nearly the entire annual permitted productive capacity of the aquifer in a particular district—akin to what transpired in Gonzales County and motivated the Guadalupe County Groundwater Conservation District to adopt its novel approach. Under the Guadalupe County Groundwater

[18] "Groundwater Management Area 13," Texas Water Development Board, http://www.twdb.texas.gov/groundwater/management_areas/gma13.asp

[19] The authors note that in more complex aquifers with variable confined units and other heterogeneous structures, groundwater volume models must also account for hydraulic conductivity.

[20] For an illustration of the digitization trend, see "Parcel Mapping," Texas Tech University Center for Geospatial Mapping, http://www.depts.ttu.edu/geospatial/center/cadastral.html as well as "County Appraisal Districts Maps Online," OGIGov, http://www.ogigov.com/onlinemaps.html (including a large number of rural Texas counties with substantial groundwater resources).

[21] We raise this point because the Texas Legislature has affirmed that it "recognizes that a landowner owns the groundwater below the surface of the landowner's land as real property." *Tex. Water Code Ann. § 36.002 (West*). Texas law also recognizes a severable groundwater estate. *City of Del Rio v. Clayton Sam Colt Hamilton Trust*, 269 S.W.3d 613, 617 (Tex. App.—San Antonio 2008) ("the Trust was entitled to sever the groundwater from the surface estate by reservation when it conveyed the surface estate to the City of Del Rio."). In turn, if the groundwater is "real property" and can be treated as a severable estate and the Texas Constitution and/or Legislature makes no exemption, then it is very likely subject to taxation. See for instance, *City of Beaumont v. Fertitta*, 415 S.W.2d 902, 912 (Tex. 1967) ("Our Constitution requires all private property to be taxed except that which must be specifically exempt by the Constitution and that which the Legislature may or may not exempt."). See also *Matagorda County Appraisal Dist. v. Coastal Liquids Partners, L.P.*, 165 S.W.3d 329, 332 (Tex. 2005) (severable real property estates can be taxed separately even though all are part of the same surface tract.)

[22] The District Rules, 5.3, provide a detailed explanation of the permitting requirements and process for issuing a production permit.

Table 1: Key tasks and their cost.

Task	Provider	Estimated Cost	Notes
Mapping property tracts in the groundwater conservation district	Local appraisal district	$100,000	Cost likely to have already been borne by the County and/or local appraisal district
Creating the saturated thickness dataset for the local aquifer(s) in question	Hydrologist	$4,000 to $15,000	
Integrating the datasets to create a saturated volume model	GIS specialist	$7,000 to $15,000	
Miscellaneous administrative costs, meetings, etc.	Groundwater conservation district board members	$3,000	
Total cost (high case)		$133,000	
Total cost (most likely case)		**$14,000 to $20,000**	

Conservation District system, the only way the District can hit its annual production limit is for every property owner over the saturated section of the aquifer in the district to participate in the marketplace.

The system offers 2 distinct benefits for more effective resource management. First, the system has high local legitimacy because it was developed by directors elected by District landowners. Second, it fosters preservation of the District's water resources because water rights unsold become water preserved—at least until the price of water climbs sufficiently to induce reluctant sellers to enter the market.

The 3-dimensional management system does not place the entire volume of water contained in the regulated portion of the Carrizo Aquifer up for sale. Rather, the volume that could potentially be traded cannot exceed the annual recharge-based production cap imposed by the Guadalupe County Groundwater Conservation District Board.

The District builds flexibility into its management regime, acknowledging that demographic and climate conditions can be volatile and require rapid adjustment. For instance, the District rules mandate that the District shall regularly update its calculations of the approximate volume of saturated Carrizo sands under its jurisdiction. Along with updating its calculations to reflect potentially shifting conditions, the District must also "continually adjust" the total amount of water that may be annually withdrawn from the Carrizo Aquifer within the District ("the annual production cap").[23]

[23] District Rules, 5.4(d)

District's Legal Authority to Reform its Groundwater Management Rules

Guadalupe County Groundwater Conservation District stands on firm legal footing as it develops and enforces its market-based groundwater management system. Groundwater conservation districts are the Texas Legislature's preferred groundwater management tool and are vested with strong legal powers to achieve this policy goal.

Article XVI, Section 59 of the Texas Constitution says "the preservation and conservation of all such natural resources of the State are each and all hereby declared public rights and duties; and the Legislature shall pass all such laws as may be appropriate thereto." Such language suggests that the Texas Legislature has chosen to delegate a meaningful degree of its state police powers on groundwater issues to local groundwater conservation districts, subject to the provisions set forth in Section 36 of the Texas Groundwater Code. This conferral of authority is important because the U.S. Supreme Court has repeatedly upheld states' ability to exert their regulatory police powers "to prevent waste and to protect the 'coequal rights' of the several owners of a common source of supply."[24]

The history of Texas groundwater conservation districts reflects a delicate dance between the need for regulatory power and the reality that rural interests viewed groundwater as real property even before the Legislature and Supreme Court classi-

[24] See, for instance: *Ohio Oil Co. v. Indiana*, 177 U.S. 190; *Lindsley v. Natural Carbonic Gas Co.*, 220 U.S. 61; *Walls v. Midland Carbon Co.*, 254 U.S. 300; *Bandini Petroleum Co. v. Superior Court*, 284 U.S. 8; *Champlin Refining Co. v. Corporation Commission*, 286 U.S. 210; *Hunter Co. v. McHugh*, 320 U.S. 222; *Republic Gas Co. v. Oklahoma*, 334 U.S. 62 (1948).

fied it as such, and were less than enthused by any central interference. The Legislature passed the Groundwater District Act of 1949 to authorize the creation of underground water conservation districts for the purpose of "conservation, preservation, protection, and recharging and the prevention of waste of the underground water of an underground water reservoir or subdivision thereof."[25] The Act permitted creation of districts with the power to:

- make and enforce regulations for the conservation and recharging of underground water reservoirs;
- make and enforce rules against "waste" of underground water, as "waste" is defined in the act;
- issue permits for the drilling of wells within the reservoir;
- impose spacing rules and prorating withdrawals;
- require reports on the drilling, equipping, and completion of wells;
- acquire lands for the purpose of carrying on recharging operations;
- make surveys and plans and carry on research relative to groundwater;
- enforce, by injunction or other appropriate process, the duly adopted regulations of the district.[26]

The Act expressly recognized the landowners' "ownership and rights" in groundwater under their tracts.[27] Moreover, the language of the Groundwater Conservation District Act of 1949 influenced Senate Bill 1, a landmark water bill passed in 1997, which amended Chapter 36 of the Texas Water Code to say groundwater conservation districts "are the state's preferred method of groundwater management."[28] Senate Bill 1's explicit endorsement of groundwater conservation districts opened the door to a period of rapid groundwater conservation district formation. Indeed, while the first 38 Texas groundwater conservation districts were formed between 1951 and 1996, 60 districts came into existence between 1997 and 2012.

The Legislature's approach to groundwater conservation districts draws upon a strong historical preference among the Texas electorate for local control, shown in other areas such as school boards. Particularly in the Texas Panhandle, where the Ogallala Aquifer dominates supply, users elected to organize into local groundwater conservation districts because they feared that if they did not, harsher regulations would be imposed on them by the State of Texas or other political entities that, from a local perspective, were "outsiders."[29]

Clearly delineating groundwater resources and making them freely transferrable within groundwater conservation district boundaries introduces healthy transparency to the management system and de-fangs many potential lawsuits. To date, litigation between groundwater conservation districts and water owners has primarily focused on projects seeking to export groundwater beyond district boundaries, with some disputes centering on tract size relative to volumes pumped and some focused on takings claims by landowners within the districts. Guadalupe County Groundwater Conservation District's approach likely blunts both approaches.

A 3-dimensional management system built upon a defined pool of rights applying to all water owners can dramatically reduce the risk that a groundwater conservation district will be accused of favoring 1 set of water users over another. Creating a pool of water volumes that owners can then trade freely reduces the administrative burden on groundwater conservation districts by devolving decisions to the players on the field (the water owners). It also lessens the need for a rules committee to draft new regulations each time the game evolves, since traded markets tend to be adaptable to varying conditions. In a market system, the owners' economic self-interest, not administrative decree, allocates water. As such, a district using this system is in many ways protected from having to continually exercise administrative discretion and the risk of incurring lawsuits from exercising that discretion.

Even before the *Day* decision affirmed landowners' absolute right to water under their tracts, the Texas Supreme Court already had decided a case that highlighted the litigation risks a decree-based philosophy of groundwater conservation district operations can create. *Guitar Holding*, decided in 2008 by the Texas Supreme Court, involved a ranch located approximately 100 miles east of El Paso in Hudspeth County that sought to drill 52 new water wells and obtain a permit to transfer water out of the groundwater conservation district.[30] The groundwater conservation district linked its transfer permits to validation permits that favored historical or existing uses of groundwater within the district, most of which consisted of irrigation. Guitar argued that by doing this, the groundwater conservation district effectively granted farmers with existing or historical irrigation a preferential right to convert their irrigation

[25] Edward P. Woodruff, Jr. and James Peter Williams, Jr., *The Texas Groundwater District Act of 1949: Analysis and Criticism*, 30 Tex. L. Rev. 862 (1952).

[26] *Id.*

[27] *Id.* at 867.

[28] Amendments to Texas Water Code § 421, available at http://www.legis.state.tx.us/tlodocs/75R/billtext/html/SB00001F.htm

[29] Mark Somma, *Local Autonomy and Groundwater District Formation,* 24 Publius: The Journal of Federalism 53 (Spring 1994). Such fears of influence by outsiders or a higher political power are a recurrent theme in Texas water governance. Indeed, the Edwards Aquifer Authority Act was created in response to the federal government's threat to bring the management of the aquifer under its control if the state of Texas failed to act. To forestall federalization of the Edwards Aquifer, the state legislature promptly passed the Act in 1993.

[30] Id. at 915-916.

wells to export wells without facing more restrictive conditions applied to non-irrigator water owners such as Guitar. The Texas Supreme Court agreed with Guitar, noting that because the limitations were not uniformly applied to various water owners' applications to export water and were not necessary to protect existing uses, the District's transfer rules exceeded its statutory authority and were thus invalid.[31]

A Guadalupe County Groundwater Conservation District-style groundwater management system also protects the interests of local water owners if a large exporter wishes to develop water resources in a groundwater conservation district. One legally important way that it does so is by affirming water owners' property rights in an aquifer system in the district. To have standing, owners likely no longer need to be directly within the "area of influence" that an export-oriented well field would exert. Rather, the simple act of owning a quantifiable, marketable portion of a target aquifer layer in the district would very likely be sufficient.

Ownership of defined water rights based on a saturated sand volume model also has important implications for district boards. As the law stands, groundwater conservation districts cannot explicitly prohibit the export of groundwater.[32] Yet groundwater conservation districts can impose export fees that, in many cases, rise high enough to inhibit project development and can restrict exports based on aquifer depletion and other factors outlined in Chapter 36 of the Texas Water Code.[33] Notwithstanding the Water Code, district members can ultimately vote in directors who are willing to implement export-friendly rulesets. This could become a trend if more groundwater conservation districts adopt the Guadalupe County approach and its comprehensive distribution of economic rights in the groundwater layers in question. Unless the Texas Legislature revises the Water Code to rescind groundwater conservation districts' authority to control extra-district transfers, which would seem a reasonable next step, given that the extracted asset is private property, the decision to allow freer exports will be a district-by-district determination marked by politics and, potentially, significant litigation.

In *Meyer v. Lost Pines Groundwater Conservation District*, No. 29,696 (in the 21st District Court, Bastrop County, Texas, filed Nov. 7, 2014), a group of landowners who owned groundwater in the Simsboro Aquifer claimed they would be adversely affected by the proposed actions of an investment partnership that sought to drill 14 wells and pump 56,000 acre-feet of water annually.[34] The State Office of Administrative Hearings judge denied the plaintiffs claim for standing in a September 2015 decision, saying they had failed to demonstrate a "particularized interest" that was "distinct from that sustained by the public at large."[35]

In a district managed like the Guadalupe County Groundwater Conservation District, the legal issues would shift significantly, and most likely, in the landowners' favor. Rather than needing to demonstrate in court that the proposed withdrawal project would severely impair their own access to water, the water owners could instead seek compensation for their respective defined shares of the water resource as it is drawn down over time. In this respect, the information transparency provided by the saturated volume model helps increase regulatory and legal predictability while defusing potentially protracted and expensive courtroom fights.

Market-based groundwater conservation district management can help reduce litigation costs

Litigation poses a significant financial burden for most groundwater conservation districts. Under Section 36.066 of the Texas Water Code, a groundwater conservation district can seek fees and costs only if it prevails in court.[36] Thus, if a groundwater conservation district loses, it must pay its own costs, which would be financially disastrous for many districts. For instance, the Hudspeth County Underground Water Conservation District mentioned above incurred nearly $75,000 in attorney fees and expert costs in litigating the district court and court of appeals stages of the Guitar Holding case.

Many groundwater conservation districts only allot a fraction of this amount annually for legal bills, meaning that the high cost of litigation may either: (1) force them to consider whether it is worth suing at all or (2), if they do become embroiled in litigation, they may be forced to burden local water users with significant increases in taxes and/or fees to offset the litigation costs. Such actions would likely spark significant backlash, especially since local users may often be adverse parties in groundwater conservation district-related litigation. As the above post-*Day* cases show, a groundwater conservation district may be subject to a lawsuit by neighboring landowners if it grants an application or may be subject to a lawsuit by the

[31] Id. at 918.

[32] "(o) A district shall adopt rules as necessary to implement this section but may not adopt rules expressly prohibiting the export of groundwater." Tex. Water Code Ann. § 36.122 (West)

[33] "(f) In reviewing a proposed transfer of groundwater out of the district, the district shall consider:(1) the availability of water in the district and in the proposed receiving area during the period for which the water supply is requested;(2) the projected effect of the proposed transfer on aquifer conditions, depletion, subsidence, or effects on existing permit holders or other groundwater users within the district; and(3) the approved regional water plan and approved district management plan." Tex. Water Code Ann. § 36.122 (West)

[34] Plaintiffs' Petition for Judicial Review, 3-4.

[35] Docket No. 952-13-5210. ALJ Michael O'Malley; *S. Tex Water Auth. V. Lomas*, 223 S.W.3d 304, 307 (Tex. 2007).

[36] Texas Water Code, http://www.statutes.legis.state.tx.us/Docs/WA/pdf/WA.36.pdf

applicant if it denies the application in whole or in part.

Adopting a Guadalupe County Groundwater Conservation District approach by defining the district's resources, allocating them based on saturated volume, and managing them with a liberally traded market helps immunize groundwater conservation districts against many of the potential legal claims demonstrated above. Marketization is thus not only a preferable management tool for the water resources but also a way to manage more effectively a groundwater conservation district's legal risk. A $20,000 to $25,000 upfront investment in mapping and marketization can potentially pre-empt hundreds of thousands of dollars in future legal bills.

Now that the Guadalupe County Groundwater Conservation District has operated with its new ruleset for more than a decade, it appears that the 3-dimensional groundwater management concept functions well in practice. The rules are inherently forward-looking but must also protect preexisting uses and commitments of water resources under the District's jurisdiction. The Guadalupe County Groundwater Conservation District recognizes "historic use" permits that are not immediately subject to the District's new ruleset. [37]

However, such rights are only protected until January 1, 2025.[38] After that date, all water producers must possess a production permit obtained from the District for any water produced. In order to obtain such a permit, the producer must submit a sufficient amount of attached water rights. The District's "historic use" water volumes have been known for more than 10 years because historic-use claims had to have been made by September 30, 2011. These claims can only be based on beneficial use of groundwater made during any consecutive 12-month period between November 6, 1978, and August 11, 2004.[39]

Three-dimensional groundwater management increases water's economic value

The 3-dimensional groundwater management approach also opens the door to enhancing water's economic value to property owners by allowing it to be used potentially as collateral for loans and other financial transactions. A saturated volume-based management model does 2 important things in this regard. First, it defines an actual volume of water that is available for extraction in association with a particular property tract. Second, it places a much stronger "fence" than previously existed around groundwater that has not yet been pumped, which is likely to increase potential lenders' confidence that groundwater can serve as collateral in-situ. The rule of capture undermines most potential groundwater reserve collateralization deals because a neighbor with a larger and deeper well can draw the collateral away without the lender or borrower having any practical legal recourse to halt the drawdown.

Reserve-backed loans are loans for which the borrower puts up collateral (in this case estimated water reserves underneath his land) and then gets a loan amount based on the present value of expected future sales. The loan process takes account of factors such as the level of reserves, expected water prices, a discount rate, assumptions for operational expenditure, capital expenditure, and any tax optimization and/or price hedging employed.[40]

IMPLICATIONS FOR OTHER DISTRICTS

The Guadalupe County Groundwater Conservation District's saturated volume-based rights allocation model is the first step toward creating a Texas groundwater management system where water in the ground is properly valued and where owners are not incentivized to enter a "biggest pump wins" competition with their neighbors. A saturated volume model-based 3-dimensional rights allocation system offers real potential for replication across Texas' other 99 groundwater conservation districts. A core strength of the Guadalupe County Groundwater Conservation District's saturated volume model is that it is highly adaptable and can be molded to fit a wide range of local conditions. Such flexibility is important because each groundwater conservation district in Texas faces a unique set of hydrological, economic, and demographic conditions. While to our knowledge no other groundwater conservation district has yet modernized its rules the way that the Guadalupe County Groundwater Conservation District has, it is very likely that as awareness of the 3-dimensional management model and its benefits spreads, additional districts will adopt similar approaches. The Guadalupe County Groundwater Conservation District has high confidence in its management system and may extend a similar management system to its Wilcox Aquifer layer as well.

In brief, the saturated volume model operationalizes the absolute ownership rights granted by the *Day* decision and creates a structure to which many aspects of existing Texas oil and gas law can be easily applied. The practical outcome that followed ratification is that the new ruleset lays the foundations of a more robust water market, reduces takings claims and other litigation risks to the groundwater conservation district, and sets the stage for courts to apply more easily well-established oil and gas law to settle disputes.

Moving to a saturated volume model-based allocation of

[37] "Section 5.9(h) of the District Rules addresses Historic Use.

[38] District Rules, 5.4(h)

[39] District Rules, 5.9(b)

[40] Reserves-Based Lending, SUMITOMO MITSUI BANKING CORPORATION, https://www.smbcgroup.com/emea/eu/lending/index. (last visited April 8, 2014).

water rights (also known as 3-dimensional management) using recharge rate-based withdrawal limits would help improve the balance between traditional consumption uses as well as environmental and conservation endeavors. For parts of Texas on the Interstate-35 corridor and further east—where higher precipitation levels generally promote more rapid recharge rates—using recharge rates to set withdrawal limits would mark a significant departure from the traditional use of desired future conditions that are predicated on mining groundwater. Harmonizing rulesets between adjacent districts tapping common aquifer layers would further multiply the benefits of more broadly adopted 3-dimensional management rules.

Setting withdrawal rates based on recharge encourages users to find the highest and best uses they can for their water and trade based on their respective comparative advantages. Such activity generally puts a price on water that better reflects its underlying value and fosters conservation by inducing high-volume, low-value users to reduce use and free up water for sale into sectors that add greater economic value per unit of water consumed. Water owners could also potentially "rent" their water to conservation interests seeking to incentivize lower water use.

Furthermore, a hydrological equivalent of "cap and trade" would pave the way for the emergence of greater groundwater asset collateralization and freer trading of water rights. Rural groundwater owners could finally begin cementing their property rights and maximizing their property value in preparation for interactions with thirsty cities seeking groundwater supplies. The new 3-dimensional management system helps balance private property rights and the public interest in secure water supplies and conservation in a much more equitable and transparent manner and deserves serious consideration by all Texas groundwater conservation districts. To protect Texas water resources for future generations and avoid a California-style water crisis, a new approach is badly needed, and the 3-dimensional model marks a significant step toward a more adaptable and effective water resource governance system.

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Book review: Water is for fighting over and other myths about water in the West

Fleck, J. 2016. Water is for fighting over and other myths about water in the West. Washington, D. C: Island Press. ISBN: 9781610916790. 246 p.

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The only time reporting about water policy is exciting is when people believe the water is about to run out.

Many of the great works about water governance in the West, from *Cadillac Desert* to the fictional film *China Town*, chronicle epic bureaucratic battles of greed and selfishness against a backdrop of a looming drought.

The standard characters include rich white men running cities against well-organized white farmers. Each party rushes for the moral high ground and tries to frame the other as wasteful and ungrateful. They have their fateful day in court a decade or so later, a judge chooses a winner and loser, and we start all over again.

Treaties and compacts, state and federal laws, all support and encourage this well-used plot. There is little room in this legal system or storyline for the water rights of tribes or ideas such as rivers should carry enough water to reach the sea. The winners in the short-term battle for water rights conveniently ignore the long-term reality that surface water and groundwater are related and the depletion of one will eventually have a direct impact on the other. The mantra is: take every drop you can before someone else does.

Storytellers and lawyers have applied this well-used trope to describe almost every water body, above or below ground, west of the 100th meridian. It is the go-to narrative from small town newspapers to big budget documentaries. Editors love to add that Mark Twain said: "Whiskey's for drinkin,' water's for fightin' over."

Journalist John Fleck argues this narrative is a bit dated. After more than 30 years of writing about water, he introduces a new approach to stories about water with his latest book, *Water is for Fighting Over and Other Myths about Water in the West*.

He begins with stating there is no substantive evidence Mark Twain ever said or wrote anything about the purpose of whiskey and water.

Wanting to reach a broader audience than the water wonks he spent his career chronicling, Fleck purposefully wrote what he calls a short book. With 201 pages of text and 43 dedicated to notes and the index, he introduces a new storyline that is not nearly as exciting but is much more accurate and worthy of attention.

"When people have less water, I realized they use less water," he writes about the drought that gripped the West in the first part of this century. "In spite of the doomsday scenarios, Westerners were coping, getting along with their business in the face of less water."

Fleck makes the pitch we need to move away from focusing on stories about lawsuits and shortages. The administrative nightmare of getting 19th century water law and 20th century infrastructure to meet the needs of the 21st century is scary. Climate change will further reduce and introduce more chaos to an already over allocated supply. However, there is hope in examining the adaptations that are taking place. These changes are usually small and do not meet everyone's ecological, economic, and recreational desires. But, they are working and meeting more of those desires than they are getting credit for.

Even with the crutch of a pending disaster, explaining water policy is not easy. Fleck makes this even harder on himself by introducing readers to the psychology and game theory that goes into compromises with a backdrop of water law, traditional water management, and the massive engineering projects that has allowed cities and farms to sprout up in deserts.

The skill Fleck has for this task is from having written about water policy for a general audience for three decades as a newspaper reporter and that he dedicated his book to the water issues of the Colorado River.

The Colorado is the most litigated and over-allocated river in the West. The economies of entire cities and states and vast ecosystems depend on it. Failure is not an option and yet it seems assured. As such, it is one of the best places to see how experiments in compromise are playing out. Fleck then tackles these solutions and breaks them down to a simple narrative.

Fleck explains how successful farmers are increasing their profits while using less water via new crops, research, and monitoring. He shows how others are collaborating with cities to share water during droughts to make even more money. He highlights Las Vegas' record of conserving water and reducing demand while it continues to grow. He chronicles the excitement generated by the breakthrough multi-national agreement to allow the Colorado River to trickle into the Gulf of California for a couple of weeks. He explains how cities, pumping from the same aquifer, worked together to protect their mutual interests instead of harming each other.

The details of how these realities came to be are not nearly as exciting or as easy to understand as the narrative of specific interests groups fighting for their own limited interests. The new winners are those who are able to understand the positions others have taken and look for common ground and ways to share that benefit everyone. Fleck is really just re-introducing us to a storyline most of us were supposed to learn in kindergarten.

Fleck also points out that even the water buffaloes—the members of the once exclusive club that controlled the rivers and aquifers—are realizing they too have to make room for the groups they used to ignore. The commercial and recreational fishermen, birders, tribes, and river runners are becoming organized, hiring lawyers, and learning the lawsuit game. They too can sue if a project or plan does not incorporate their needs. They do not always win, but they can bring entire process to a standstill.

Fleck knows the stories about sharing, conservation, and compromise are not as sensational as a governor using the National Guard to delay the construction of a federal dam or as understandable as farmers versus cities versus the environment. Instead, his stories are about lots of long meetings, formal and informal, where actual people propose and analyze ideas and then build up the courage to try them.

"They have to be implemented painstakingly, one farm district and municipal water agency at a time," Fleck explains. "That is the project ahead of us."

Every compromise Fleck examines shares a common thread of groups that used to battle each other coming together. The actual combination of facts on the ground, personalities, and history of the issue are as unique as the drainages and aquifers they are about. Fleck's book does not spell out the solution. Rather it documents where and how solutions are found.

Fleck points out there is also less tolerance by the public for the old guard who point to 100-year-old treaties and compacts as proof that they cannot do anything. Under such agreements, Phoenix would lose all of its Colorado water, while California would lose none. The Colorado River would also never reach the sea again. We would lose our best tools for adapting to climate change. The public will eventually demand that the system changes, because letting a city of 2 million lose its main water supply will not work.

"We need new rules," Fleck writes. "Absent that, we simply end up with a tragedy of the commons."

West Texas is full of examples of the later. Springs and rivers have gone dry and cities and farms have disappeared.

In short, Fleck's book points out that we have alternatives if we are willing to try.

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Regulating unregulated groundwater in Texas: how the state could conquer this final frontier

Vanessa Puig-Williams[1]

Abstract: Texas has 9 major aquifers and 21 minor aquifers underlying the state. These aquifers are a vital water supply source in Texas, providing approximately 60% of the 16.1 million acre-feet of water used in the state annually. These underground waters also sustain surface water flow in rivers across Texas; thus, they are integral to the health of watersheds throughout the state and the economies that depend on this water. However, approximately one-third of Texas is not regulated by a groundwater conservation district. During a time of unparalleled pressure on groundwater resources across the state, the lack of groundwater protection in some areas of Texas is undermining important areas of law and policy—from property rights and natural resource protection, to groundwater management and regional water planning. The presence of a groundwater conservation district, however, does not guarantee effective management of groundwater resources or protection of private property rights, springflow, and surface water flow. Groundwater policy in Texas permits aquifers to be mined and fails to protect the property rights of landowners who wish to conserve their groundwater. In addition, a fragmented regulatory structure and insufficient funding for groundwater conservation districts impede effective management of groundwater resources. To bring effective groundwater management to areas of the state where groundwater conservation districts do not exist, therefore, Texas must resolve fundamental challenges in the way groundwater is managed in areas where it is regulated.

Keywords: rule of capture, groundwater, private property, regulation, springflow

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Terms used in paper

Acronym	**Descriptive term**
BSEACD	Barton Springs Edwards Aquifer Conservation District
DFC	desired future condition
EP	Electro Purification
GCD	groundwater conservation district
GMA	groundwater management area
MAG	modeled available groundwater
PGMA	priority groundwater management area
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board

INTRODUCTION

Beneath the great state of Texas, there is water. Texas has 9 major aquifers and 21 minor aquifers underlying the state. These aquifers are a vital water supply source in Texas, providing approximately 60% of the 16.1 million acre-feet of water used in the state annually.[1] These underground waters also sustain surface water flow in rivers across Texas; thus, they are integral to the health of watersheds throughout the state and the economies that depend on this water. When W.H. Auden wrote, "Water is the soul of the Earth," he must have been referring to groundwater.

In 1917, as a result of several droughts, voters passed the Conservation Amendment to the Texas Constitution. The Conservation Amendment places the duty to protect the state's natural resources in the hands of the Legislature. Article 16, section 59 of the Texas Constitution provides:

> The conservation and development of all of the natural resources of this State, ... and the preservation and conservation of all such natural resources of the State are each and all hereby declared public rights and duties; and the Legislature shall pass all such laws as may be appropriate thereto.[2]

The Conservation Amendment provided the authority for the Texas Legislature to establish groundwater conservation districts (GCDs) to conserve the state's groundwater resources. Not all areas of the state, however, are controlled by a GCD. Approximately one-third of the surface area of Texas is not regulated by a GCD. These areas where a GCD does not exist are depicted on the map as areas without color (Figure 1). Out of the 254 counties in the state, 174 counties are either fully or partially within a confirmed or unconfirmed GCD.[3] In unregulated areas, there is no regulatory authority to monitor the rate and amount of groundwater withdrawal. Landowners can pump unlimited amounts of groundwater.

Texas landowners own the groundwater beneath their land as private property. Chapter 36 of the Texas Water Code states, "[t]he legislature recognizes that a landowner owns the groundwater below the surface of the landowner's land as real property."[4] In *Edwards Aquifer Authority v. Day*, the Texas Supreme Court held that "land ownership includes an interest in groundwater in place that cannot be taken for public use without adequate compensation guaranteed by article I, section 17(a) of the Texas Constitution."[5] Ownership of groundwater entitles a landowner to certain rights, which Chapter 36 of the Water Code articulates. A landowner is entitled to "drill for and produce the groundwater below the surface of real property, subject to section (d), without causing waste or malicious drainage of other property or negligently causing subsidence."[6] This statutory language describes the rule of capture in Texas—a court-created doctrine, which, with a few exceptions, does not impose liability on a landowner who depletes his neighbor's groundwater by pumping groundwater from beneath his own land for a beneficial purpose.[7]

While a landowner is entitled to drill for and produce groundwater below the surface of his property, as the Court in *Day* noted, he is also subject to reasonable regulation through GCDs.[8] Chapter 36 authorizes GCDs to regulate groundwater production to achieve Chapter 36's purpose of protecting property rights and balancing the conservation and development of groundwater.[9] In GCD-managed areas, therefore, a landowner's right to pump is tempered by the Water Code's goals of protecting property rights in groundwater and the groundwater resource.

In areas of the state without a GCD, however, a landowner's right to pump groundwater from beneath his property is limited only by the minimal exceptions to the rule of capture—he cannot cause waste, malicious drainage, or subsidence. Beyond these exceptions, groundwater is unprotected. It is important to note that the existence of a GCD does not eliminate the rule of capture in regulated areas of the state. Rather, regulation overlays the rule and ideally prevents one landowner from pumping to such an extent that nearby wells are impacted.

Unregulated areas in Texas are the final frontier—the last remaining, lawless parts of the state where groundwater regulation is nonexistent. Drought, coupled with booming population growth in many parts of the state, has placed increased pressure on the state's underground water resources and exacerbated tensions between people who want to pump groundwater and people who want to conserve it. During a time of unparalleled pressure on groundwater resources across the state, the lack of groundwater protection in some areas of Texas is undermining

[1] *See* https://www.twdb.texas.gov/groundwater/

[2] TEX. CONST. art. XVI, § 59(a).

[3] *See* http://www.twdb.texas.gov/groundwater/conservation_districts/facts.asp

[4] Tex. Water Code § 36.002.

[5] Edwards Aquifer Auth. v. Day, 369 S.W.3d 814, 817 (Tex. 2012).

[6] Tex. Water Code § 36.002(b)(1).

[7] The Texas Supreme Court has crafted a few exceptions to the rule of capture. A landowner cannot pump and use groundwater maliciously with the purpose of injuring a neighbor or in a manner that amounts to wanton and willful waste of groundwater. *See* City of Corpus Christi v. City of Pleasanton, 154 Tex. 289, 276 S.W.2d 798, 801 (1955). A landowner can be held liable for the negligent pumping of groundwater that causes subsidence of adjacent land. *See* Friendswood Dev. Co. v. Smith-Southwest Indus., Inc., 576 S.W.2d 21, 30 (Tex. 1978).

[8] Day, 369 S.W.3d 814, 840-841 (Tex. 2012).

[9] Tex. Water Code § 36.002 (d)(1)-(3); Tex. Water Code § 36.0015(b).

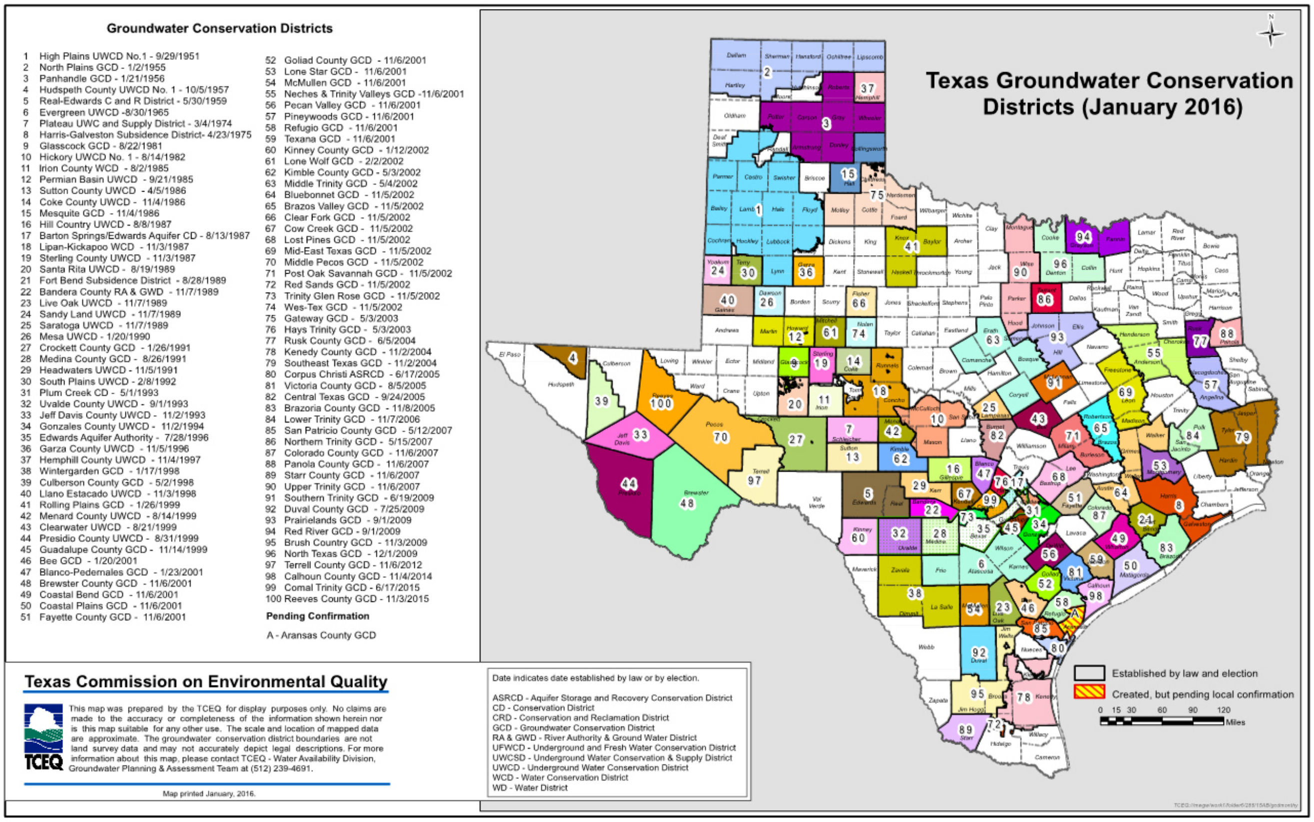

Figure 1. Groundwater conservation districts in Texas (Texas Commission on Environmental Quality).

important areas of law and policy—from property rights and natural resource protection, to groundwater management and regional water planning. These unregulated areas, therefore, are more akin to black holes, as the state's efforts to manage groundwater are lost in the regulatory void.

The solution to filling these regulatory black holes, however, is not for the Legislature to create poorly funded, single-county GCDs only to fill in regulatory gaps. As discussed below, when GCDs are ineffective at managing groundwater or when GCDs do not adequately protect springflow, they experience some of the same problems associated with a lack of groundwater regulation. Now, more than ever, groundwater use in Texas is wrought with complications and conflicts, whether it is regulated by a GCD or not. This paper examines these problems and explores possible solutions the state could use to ensure effective management of groundwater across Texas.

PROBLEMS CAUSED BY A LACK OF REGULATION

Groundwater Management

Large-scale groundwater pumping from unregulated areas in an aquifer can affect the ability of an adjacent GCD to effectively manage the portion of the aquifer within its jurisdiction. Under Chapter 36 of the Water Code, the Legislature has created a process where GCDs with jurisdiction over shared aquifers work together in a groundwater management area (GMA) to establish desired future conditions (DFCs) for these aquifers. DFCs are "the desired, quantified conditions of groundwater resources (such as water levels, water quality, springflow, or saturated thickness) at a specified time or times in the future…."[10] Under Chapter 36, a GMA submits the DFC for an aquifer to the Texas Water Development Board (TWDB), which uses it to determine the modeled available groundwater (MAG) for the aquifer. A MAG value is the

[10] Tex. Water Code §36.108.

amount of groundwater production, on an average annual basis, that will achieve a DFC according to the results of TWDB's model run. [11] Ideally, GCDs use the MAG as a factor in their permitting decisions, as Chapter 36 requires groundwater districts to manage groundwater in a way that achieves the adopted DFC.[12]

Unregulated pumping from a common aquifer, however, can affect the ability of a GCD to achieve the DFC. As "pumping in these areas is unregulated and, similarly, groundwater conditions are generally not monitored…the ability of a GMA to achieve a DFC with any level of confidence" is impacted.[13] GCDs had this exact concern with the Electro Purification (EP) Project in a formerly unregulated portion of the Trinity Aquifer in Hays County. The EP Project is a paradigm for the conflicts that are borne out of a lack of groundwater regulation. The project, which sought to pump almost 6,000 acre-feet of water a year from the Trinity Aquifer and pipe it to growing communities along the I-35 corridor, was highly controversial. The EP well fields are located in GMA 10, very close to the border of GMA 9. (Figure 2.) Groundwater production in this area was outside of the jurisdiction of the Hays-Trinity GCD, a member of GMA 9 and the Barton Springs Edwards Aquifer Conservation District (BSEACD), a member of GMA 10. Both GCDs were concerned that the project would interfere with their ability to achieve the DFCs for the Trinity Aquifer within their jurisdiction. For the portion of the Trinity Aquifer within GMA 9 and managed by the Hays-Trinity GCD, the annual amount of water EP intended to pump (5,600 acre-feet) was more than half of the MAG (9,100 acre-feet per year) that the TWDB determined is available for production based on the DFC. For the portion of the Trinity Aquifer within GMA 10 and managed by BSEACD, the TWDB determined that the MAG is 1,288 acre-feet a year. The amount of groundwater EP intended to pump was 4,300 acre-feet more than the MAG. BSEACD was worried that this excessive withdrawal of groundwater would interfere with the district's ability to achieve the DFC for the Trinity Aquifer.

Similarly, in other areas of the state, pumping from aquifers in unregulated counties threatens the ability of GCDs and GMAs in nearby areas to manage groundwater from the same aquifer. A GCD does not exist in the northern part of Travis County and all of Williamson County. Unregulated pumping of groundwater from the Edwards Aquifer in Williamson County is causing localized drawdown in Bell County, where the Clearwater Underground Water Conservation District has jurisdiction. In a 2005 report prepared for Williamson, Burnet and northern Travis counties, the Texas Commission on Environmental Quality (TCEQ) pointed out that there is no entity in northern Travis County or Williamson County that has "authority to control large-scale groundwater pumpage for private purposes that could potentially impact a shared groundwater supply."[14] According to the TCEQ, "[t]he Clearwater Underground Water Conservation District in Bell County noted the effectiveness of their groundwater management measures may be lessened if surrounding areas are not likewise managing the shared groundwater resource."[15]

As Chief Justice Hecht noted in his concurring opinion in *Sipriano v. Great Spring Water of Am., Inc*, "[w]hat really hampers groundwater management is the established alternative, the common law rule of capture."[16] The lack of groundwater regulation in parts of the state conflicts with the Legislature's duty to conserve natural resources under the Conservation Amendment to the Texas Constitution and undermines the implementation of this responsibility by GCDs under Chapter 36 of the Water Code.[17]

Water Planning

In addition to interfering with groundwater management, a lack of groundwater regulation makes water planning more uncertain in Texas because key areas of Texas groundwater are off radar. In general, the boundaries of a GMA are based on the hydrological boundaries of aquifers.[18] GCDs within these boundaries make up the voting members of a GMA.[19] Chapter 36 of the Water Code requires GCDs within a GMA to engage in joint planning, meeting annually to review management plans and proposals to adopt or amend DFCs.[20] Through this joint planning, every 5 years a GMA either adopts a new DFC or amends an existing one and submits the new or amended DFC to the TWDB. The TWDB uses the DFC to determine

[11] Tex. Water Code § 36.001(25).

[12] Tex. Water Code §36.1071(a).

[13] John Thomas Dupnik, P.G. *A Policy Proposal for Regional Aquifer-Scale Management of Groundwater in* Texas 27 at 85 (2012) (unpublished Masters Thesis, The University of Texas) *available at* https://repositories.lib.utexas.edu/bitstream/handle/2152/19658/dupnik_thesis_20129.pdf?sequence=1Dupnik, (referencing SENATE COMMITTEE ON NATURAL RESOURCES, Implementation of House Bill 1763 and Groundwater Management in Texas, INTERIM REPORT TO THE 81ST LEGISLATURE, at 5 (2009)).

[14] Updated Evaluation For the Williamson, Burnet and Northern Travis Counties Priority Groundwater Management Study Area, Texas Commission on Environmental Quality at 3 (2005) *available at* https://www.tceq.texas.gov/groundwater/gw.html/at_download/file

[15] *Id.*

[16] Sipriano v. Great Spring Water of Am., Inc., 1.S.W.3d 75 at 81, 83. (Tex. 1999) (Hecht, J., concurring).

[17] *See* TEX. CONST. art. XVI, § 59(a). and Tex. Water Code § 36.0015(b).

[18] Tex. Water Code § 35.004.

[19] Tex. Water Code § 36.108(c).

[20] Tex. Water Code § 36.108.

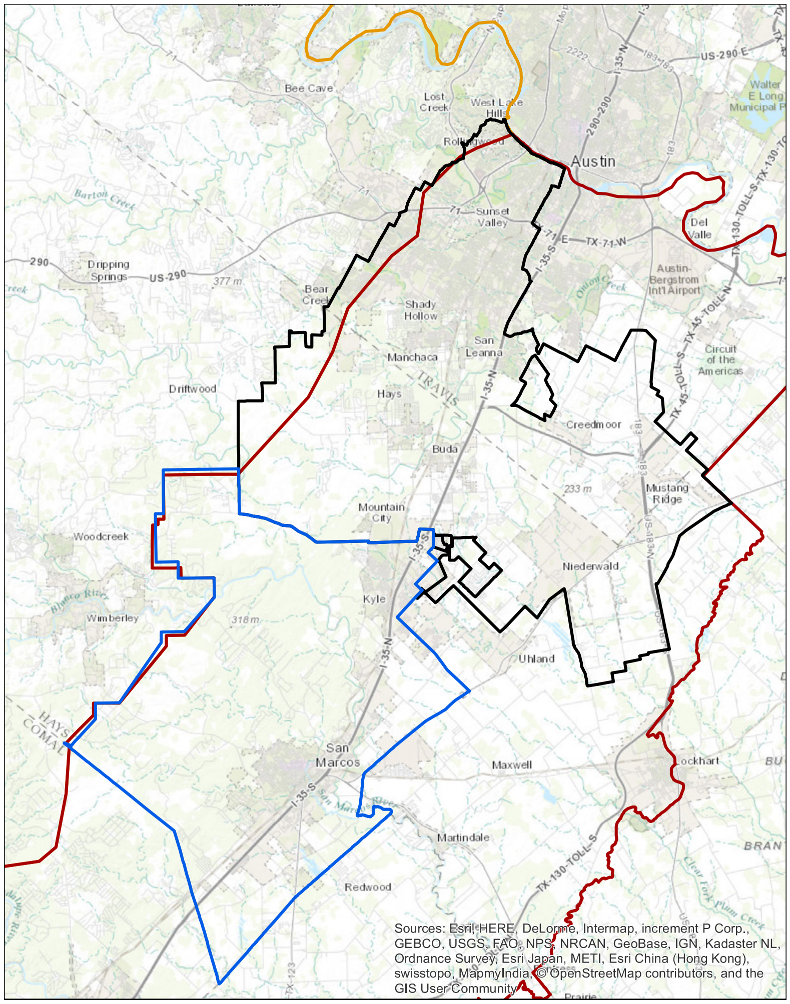

Figure 2. January 2016. Map of GMA boundaries near EP well field. (Prepared by BSEACD for author.)

the MAG for a particular aquifer. As stated earlier, GCDs use the MAG as a factor in their permitting decisions, but the MAG plays an important role in regional water planning decisions as well.

To help the state develop future water supplies, the Water Code tasks regional water planning groups with, among other things, quantifying current and projected population and water demands over a 50-year planning horizon and evaluating and quantifying current water supplies within each region.[21] Chapter 16 of the Water Code requires regional water plans to be consistent with the DFC for the relevant aquifer in the regional planning area and requires regional planning groups to use the MAG volume for groundwater availability.[22] Regional water planning groups may not recommend water management strategies that exceed MAG volumes.[23]

As the boundaries of GMAs follow the boundaries of aquifers, within a GMA there can be portions of an aquifer not regulated by a GCD. One example is GMA 8, which includes unregulated portions of the Edwards Aquifer in northern Travis and Williamson counties in addition to the regulated portion in Bell County. Because the MAG is based on the DFC adopted by GCDs within the GMA, unregulated areas within a GMA are not represented in this process. While GCD representatives may appoint an advisory committee to represent the interests of unregulated areas during the joint planning process or seek input from stakeholders within the unregulated area,

[21] *See* Tex. Water Code §16.053.

[22] 31 Tex. Admin. Code § 357.32(d) and Tex. Water Code §16.053(e)(2-a).

[23] 31 Tex. Admin. Code § 357.32(d). In August 2016, TWDB issued proposed rules that would allow regional water planning groups to recommend water management strategies that exceed the MAG under certain situations if approved by the GCDs within the relevant GMA. *See* 41 Tex. Reg. 5685 (August 5, 2016) (to be codified at 31 Tex. Admin. Code, Chapter 357).

these members are unable to vote, thus their contribution is limited.[24] The consequence is that stakeholders within unregulated areas of Texas do not have a meaningful, determinative role in establishing DFCs and the water management strategies that result. This is, "perhaps the most egregious example of insufficient representation,"[25] and it is entirely a consequence of a lack of groundwater regulation.

Furthermore, a regulatory void within a GMA threatens not only equitable water planning but also reliable water planning. The absence of a GCD means that, with the exception of some wells monitored by TWDB, no entity is collecting pumping data from groundwater wells across the unregulated area. Since the amount of pumping in unregulated areas is unknown and unreliable in GMAs with unregulated areas, there is a risk that the MAG underestimates total pumping and, as a result, regional water planning groups may recommend water supply strategies that contribute to over production from the aquifer.

Protection of Springflow and Surface Water

As discussed earlier, the Conservation Clause of the Texas Constitution declares that "the preservation and conservation of all such natural resources of the State are each and all hereby declared public rights and duties."[26] In unregulated areas of the state, however, the law—or lack of it—conflicts with this duty by failing to preserve and conserve not only groundwater but surface water as well.

When unregulated groundwater pumping threatens springflow or surface water flow, Texas law provides no mechanism for protection. Texas law regulates groundwater and surface water as though they are distinct bodies of water. This is contrary to the water cycle, where, as Professor Charles Porter explains, "surface water, diffused surface water, and groundwater are, have been, or will be ultimately in union with one another; water exists in a conjunctive relationship in all three geological containers all the time."[27] As groundwater from an aquifer is pumped for irrigation, municipal, or industrial use, the water level in the aquifer is lowered and can result in decreased flow from springs at the surface. The lack of recharge to the aquifer caused by drought can exacerbate the decline in groundwater levels and resulting diminished springflow. Reductions in springflow are problematic because springs sustain numerous creeks and rivers, especially during drought when surface runoff from rainfall is low. As springflow decreases, so does the flow of surface water, degrading aquatic habitats, threatening consumptive uses of water, interfering with recreational activities, and harming water quality. For example, Comanche Springs in Fort Stockton was once a treasured watering hole for travelers in West Texas and was the habitat of the endangered Comanche Springs pupfish before unregulated pumping of the Edwards-Trinity Aquifer caused springflow to cease.[28]

For many endangered or threatened groundwater-dependent species, the quality of their habitat depends on consistent springflow of clean water. Increased groundwater pumping causes reductions in aquifer levels and decreased flow from springs, which in turn can degrade a stressed species' habitat and lead to death or injury, which is a "take" under the Endangered Species Act (ESA).[29] In 1991, the Sierra Club made that argument in a lawsuit brought against the United States Fish and Wildlife Service (Service), which has become the poster child case for how "[t]he Endangered Species Act became the instrument that eventually brought state regulation to the [Edwards] Aquifer and the end to unrestricted withdrawals of groundwater."[30]

In areas of the state without a GCD, where the law does not restrict groundwater pumping, there is no mechanism to protect springflow or surface water flow. For example, the GCDs in GMA 8 adopted DFCs that maintain minimum flows for aggregated springs and streams in unregulated areas of the Edwards (Balcones Fault Zone) Aquifer. But these DFCs are impossible to achieve without a GCD managing groundwater withdrawals in these specific areas. Additionally, Val Verde County does not currently have a GCD to restrict pumping to protect the Devils River minnow habitat in San Felipe Creek. The Devils River minnow is listed as a threatened species under the ESA. Proposals by a water supply corporation to pump groundwater from the Edwards-Trinity Aquifer in Val Verde County to counties in the Permian Basin, where the natural gas industry is prompting the need for an additional water supply, has many locals and environmental advocates concerned about the impact large-scale groundwater withdrawals from the Edwards-Trinity Aquifer will have on the habitat of the Devils River minnow. In the Recovery Plan for the Devils River minnow, the Service states that "delisting the Devils River minnow should be considered when "[a]dequate flows in streams supporting Devils River minnow have been assured…through State or local groundwater management

[24] Tex. Water Code § 36.1081(b).

[25] *See* Dupnik supra note 15, at 86.

[26] TEX. CONST. art. XVI, § 59(a).

[27] Charles R. Porter, *Sharing the Common Pool, Water Rights in the Everyday Lives of Texans* 8 (2014).

[28] U.S. Fish and Wildlife Service Recovery Plan for the Comanche Springs Pupfish, 2-4 (1981), *available at* www.fws.gov/ecos/ajax/docs/recovery_plan/051221a.pdf (viewed on November 11, 2014).

[29] 16 U.S.C. § 1538.

[30] Todd H. Votteler, *The Little Fish that Roared: The Endangered Species Act, State Groundwater Law, and Private Property Rights Collide Over the Texas Edwards Aquifer*, 28 Envtl. L. 845, Winter (1998).

plans…"[31] In addition, this year the Service is expected to issue a listing decision for the Texas Hornshell, a species of mussel found in the Devils River. Large groundwater withdrawals from the Edwards-Trinity Aquifer may also impact flows to the Devils River and the habitat of the Texas Hornshell. Without a GCD in Val Verde County, however, there are no mechanisms in state law to ensure adequate springflow in San Felipe Creek or the Devils River.

Protection of Private Property

Texans are passionate about protecting private property rights. The Texas Supreme Court's decision in *Edwards Aquifer Authority v. Day* clarified that land ownership includes a vested interest in groundwater in place that cannot be taken for public use without compensation, holding that "[g]roundwater rights are property rights" and that landowners own the groundwater beneath the surface of their land in place.[32] The Court's decision, however, has resulted in an inequitable outcome, where the law now adds heightened protection of the property interest of landowners who seek to pump their groundwater over those who wish to conserve it. As a result of *Day*, to protect his property interest, a landowner in a regulated area of the state can bring a takings action against a GCD that limits the landowner's ownership interest in groundwater by denying or reducing his production permit.[33] In an unregulated area, however, a landowner whose groundwater is drained and pumped away by another landowner has no remedy or no ability to protect his property interest. The landowner's only recourse, following the law of oil and gas, is to drill his own well and begin producing the groundwater he desired to preserve. This recourse only affords the landowner the option to claim and use his property interest rather than preserve or conserve his property for future use.

In *Day*, the Court expressly stated that the rule of capture is not "antithetical" to ownership of groundwater in place.[34] As water law professor Gerald Torres notes, however, "[a]lthough Rule of Capture may not preclude the idea of ownership of groundwater in place, it certainly strips the idea of ownership of what we normally regard as important attributes of property, including the fundamental right to exclude others from the use of one's property.[35] In other words, for those landowners who desire to conserve their groundwater—or who do not want their groundwater pumped out from beneath them by large-scale production projects—the rule of capture prevents them from protecting their property interest by excluding others from taking their groundwater. In *Day*, the Court pronounced that groundwater is a private property right deserving of protection, but this is not the case in unregulated areas of Texas.

CHALLENGES WITH GROUNDWATER REGULATION

While a lack of groundwater regulation causes a number of inequities and management dilemmas, groundwater regulation in Texas has its own share of controversies. The difficulty in proposing solutions to problems caused by an absence of groundwater regulation is that some of these same problems occur when groundwater is regulated. Thus, to bring effective management of groundwater in areas where regulation does not exist, it is essential to offer solutions aimed at improving the management of groundwater regulation where it does.

For the reasons discussed in this paper, unregulated areas need to be regulated, but this does not necessarily mean that the Legislature should create ineffective GCDs only to fill in regulatory black holes. This might fill a regulatory void, but it will exacerbate larger problems related to effective management of the resource. An in-depth discussion of the challenges and benefits associated with groundwater regulation in the state is beyond the scope of this paper. However, since the alternative to no regulation is regulation, it is important to understand some of the challenges with groundwater regulation in Texas in order to offer worthwhile solutions for areas of the state that lack regulation. As a caveat, the discussion below is meant to be a general critique of the existing regulatory framework and is not necessarily applicable to all GCDs statewide.

Priority Groundwater Management Areas

Texas statutory law appears to have an answer for addressing the state's challenges in unregulated areas—by authorizing the TCEQ to designate Priority Groundwater Management Areas (PGMAs). PGMAs are areas of the state that the TCEQ has determined are experiencing or expected to experience critical water problems in the next 50 years and where groundwater

[31] U.S. Fish and Wildlife Service Recovery Plan for the Devils River Minnow, Executive Summary at iv (September 2005) *available at* http://ecos.fws.gov/docs/recovery_plan/050913.pdf (viewed on November 11, 2014).

[32] Edwards Aquifer Auth. v. Day, 369 S.W.3d 814, 833, 817 (Tex. 2012).

[33] Day at 838-40 (citing Sheffield Development Co. v. City of Glenn Heights, 140 S.W.3d 660 (Tex. 2004); Lingle v. Chevron U.S.A., Inc., 544 U.S. 528 (2005))(other citations omitted). A landowner would have to allege that a regulatory taking has occurred under the facts articulated in Sheffield Development Co. v. City of Glenn Heights, 140 S.W.3d 660 (Tex. 2004). As stated in the U.S. and Texas Supreme Court cases cited in *Day* and *Sheffield*, there are three inquiries in a takings claim under the federal decisions in Loretto v. Teleprompter Manhattan CATV Corp., 458 U.S. 419(1982), Lucas v. South Carolina Coastal Council, 505 U.S. 1003 (1992), and Penn Central Transp. Co. v. New York City, 438 U.S. 104 (1978).

[34] Day, 369 S.W.3d at 823.

[35] Gerald Torres, *Liquid Assets: Groundwater in Texas*, 122 Yale L.J. Online 143 (2012), *available at* http://yalelawjournal.org/forum/liquid-assets-groundwater-in-texas.

management is needed.[36] In a PGMA evaluation, the TCEQ will consider whether creation of a GCD is necessary, and within a PGMA, the Water Code gives TCEQ authority to either create a GCD where one does not exist or require that an unregulated area be annexed by an existing GCD.[37]

But this process has not been extremely effective. TCEQ has designated 8 PGMAs.[38] Yet unregulated areas remain in 4 of the designated PGMAs. [39] In 1990, TCEQ designated the majority of the Hill Country as a PGMA because, among other things, groundwater demand from the Trinity Aquifer was expected to exceed availability.[40] According to TCEQ, "[b] etween 1997 and 2003 seven GCDs were created through local initiatives in the designated Hill Country PGMA counties.[41]

In 2010, TCEQ recommended the formation of a new GCD to jointly manage the Trinity Aquifer in Hays, Comal and Travis counties.[42] At the time of TCEQ's recommendation in 2010, the Trinity Aquifer in Comal County and southwestern Travis County was not regulated by a GCD. In the 2010 recommendation, TCEQ discouraged the creation of two new GCDs to manage Comal and Travis counties, instead recommending a regional approach. The report explains that "creating two new GCDs does not provide for the most effective or cost efficient management of the groundwater resources because it would require duplicative management programs be established. In addition, the boundaries would not provide for the most effective management program because each GCD would manage only a limited, politically delineated portion of the Trinity aquifer."[43]

Political opposition, however, thwarted TCEQ's efforts to create a regional GCD over Travis, Hays, and Comal county.[44] Rather than forming a regional groundwater district as the TCEQ recommended, legislative proposals have created smaller, local GCDs. For example, the Legislature recently passed a bill creating a GCD to manage the Trinity Aquifer in Comal County. The Trinity Aquifer in southwestern Travis County, however, remains unregulated, although the county is currently discussing the option of creating a GCD this upcoming Legislative session.

Fragmented Regulatory Structure

The solution to an absence of groundwater regulation is not necessarily for the Legislature to create a new district in unregulated areas, which could compound the challenges of a fragmented regulatory structure. When numerous GCDs with different rules and management plans regulate a shared aquifer, effective management can be difficult to achieve long term. Under this circumstance, each GCD must work hard to develop a local regulatory approach that is consistent with and does not impair the regulatory approaches of other area GCDs. The aquifer is not confined by GCD boundaries, and GCDs managing the same aquifer can have different management goals, unique rules, permitting and spacing requirements, and often entirely distinct concerns. As a result, "[m]anaging for sustainability or even some level of allowable depletion breaks down with small-scale county-based GCDs that do not have the power to regulate wells that are outside their district, even though such wells may draw from and deplete groundwater resources common to multiple districts."[45]

To avoid further fragmenting groundwater management, Chapter 36 of the Water Code provides processes where existing GCDs can annex additional territory, such as what BSEACD did in the unregulated area of Hays County. The TCEQ can use its authority under the Water Code to order existing GCDs in PGMA's to annex unregulated areas.[46] Furthermore, one possible solution to preserve local accountability and control but move toward a more regional, aquifer-based management structure, is for the Legislature to require GCDs within a GMA to develop consistent rules and management plans that apply regionally to aquifers.

Lack of Funding

Many smaller GCDs have difficulty managing the groundwater resources within their jurisdiction because their budgets are limited. Unfortunately, "GCDs in Texas face significant funding challenges, as they have statutorily restricted water use fee rates and low ad valorem taxation rates" and "[b]oth of these revenue-generating mechanisms are affected by the areal extent of the jurisdiction of a GCD."[47] Chapter 36 provides GCDs with the authority to levy taxes and require permitees

[36] Tex. Water Code §35.007(a).

[37] Tex. Water Code §36.0151

[38] For a map of PGMA areas, *see* https://www.tceq.texas.gov/assets/public/permitting/watersupply/groundwater/maps/pgma_areas.pdf

[39] Texas Commission on Environmental Quality, What is a Priority Groundwater Management Area, *available at* http://www.tceq.com/groundwater/pgma.html/#whatis

[40] Groundwater Conservation District Recommendation for Hill Country Priority Groundwater Management Area, Texas commission on environmental quality, 3-4 (June 2010).

[41] *Id*. at 5.

[42] *Id*. at 4.

[43] *Id*. at 19.

[44] *Id.*

[45] Dupnik, supra note 15 at 41.

[46] Tex. Water Code §36.0151.

[47] Charles Porter, Groundwater Conservation District Finance in Texas: Results of a Preliminary Study, Texas Water Resources Institute, Texas Water Journal, Vol. 4 No. 1 at 65 (2013); Dupnik supra note 15 at 43.

to pay user fees and production fees, but enabling legislation for many GCDs across the state limits this revenue authority. Many GCDs do not have the authority to levy taxes and others, such as the Hays Trinity GCD, are not permitted to set production fees or production fees are set at a very low rate. This can "hinder operational efficiency and limit the availability of resources and human capital needed to effectively manage the resource."[48] Without sufficient funding, some GCDs are limited in their ability to study aquifer dynamics, develop modeling, monitor drawdown, and study the connection between groundwater and surface water.

To avoid problems associated with insufficient funding, the Legislature can use its authority to ensure that GCDs have the funds to carry out their responsibilities under the Water Code: to balance the conservation and development of groundwater resources while also protecting property rights. At a minimum GCDs need the authority to set reasonable production fees and the ability to assess taxes if approved by voters. Moreover, if the *state* provided funding to GCDs, GCDs would have the financial ability to conduct scientific studies and monitoring and to defend their permitting decisions in the face of takings lawsuits.

Failure to Protect Springs and Surface Water

The presence of a GCD does not necessarily mean that springs and surface water are protected. Throughout Texas, in regulated areas and in unregulated areas, aquifers are declining.[49] The pressure to develop water supplies has resulted in more groundwater being pumped from aquifers than what these aquifers receive through recharge. As aquifer levels decline, flows from springs are reduced or completely cease, diminishing surface water flows in creeks and rivers, and ultimately inflows into bays and estuaries.

Currently, most of the DFCs adopted by GCDs across the state allow for some level of drawdown in aquifers. Under DFCs that allow for declining aquifer levels, GCDs are essentially managing the depletion of aquifers across the state rather than their sustainability. For example, the GCDs in GMA 9 approved a DFC that allows for 30 feet of drawdown in the Trinity Aquifer over the next 50 years, despite the fact that Jacob's Well—a Trinity Aquifer spring and the sole source of water for Cypress Creek—will cease to flow if the aquifer declines by just 2 to 3 feet.[50]

While Chapter 36 of the Water Code requires GCDs to consider impacts to springflow when adopting DFCs for aquifers, it does not require GCDs to protect springflow. Currently, only 3 GCDs (not including the Edwards Aquifer Authority) have established DFCs that incorporate minimum flow levels for springs within their jurisdiction: Barton Springs Edwards Aquifer Conservation District, Clearwater Underground Water Conservation District, and Kinney County GCD. All of these GCDs have done so, in part, because maintaining springflow is essential to maintaining endangered or threatened species habitat. As increased groundwater pumping occurs in areas where GCDs have not established minimum flow levels for springs, such as in the Hays Trinity GCD where Jacob's Well is located, springflow is likely to be impacted.

Furthermore, Chapter 36 of Water Code requires GCDs, before granting or denying a permit, to consider whether "the proposed use of water unreasonably affects existing groundwater and *surface water* resources,"[51] but many GCDs fail to meaningfully consider this permitting criteria because they lack the tools to do so. For GCDs to know whether localized pumping or a regional DFC will impact surface water, scientific studies are necessary. Many GCDs lack the funding necessary to conduct these studies. While the Water Code contemplates the connection between groundwater and surface water by requiring GCDs to consider the impact to surface water in both adopting DFCs and making permitting decisions, the state has not assisted GCDs in making these considerations because it has not provided the necessary funding.

Recently, in advance of the 85th Legislative Session, groundwater developers are maintaining that there is far more groundwater available in storage from aquifers across the state than what MAGs and corresponding DFCs allow GCDs to permit. Students at the Bush School of Government and Public Service at Texas A&M University recently authored a report claiming that the supply of groundwater in most of the state's aquifers is "unlimited" at current consumption rates.[52] The arguments in favor of pumping water stored in aquifers ignore the reality that in many parts of the state, before water from an aquifer is pumped, base flows to rivers and springflow will be captured. In other words, in some areas of the state, you cannot pump stored water without impacting surface water and springflow.[53]

The Legislature can craft and implement policy that requires GCDs to sustainably manage aquifers so that aquifers are not mined and surface water resources are not diminished. To

[48] Dupnik supra note 15 at 43.

[49] *See* Ronald Kaiser and Frank F. Skiller, *The Threat of Aquifer Depletion In Texas*, 32 Tex. Tech. L. Rev. (2001).

[50] Wierman, D.A., *Water Level Fluctuations in the Middle Trinity Aquifer during the drought of 2007-2009, with emphasis on correlating water level fluctuations and flow from Jacob's Well* (2010).

[51] Tex. Water Code §36.113(d)(2), *emphasis added.*

[52] Wayne Beckermann, et. al., The Bush School of Government and Public Service Report, *An Assessment of Groundwater Regulation in Texas* at 17 (January 2016).

[53] Bill Hutchison, Ph.D., P.E., P.G., *Groundwater–Surface Water Interaction: Implications for Groundwater Planning and Management,* Presentation at the Texas Water Law Institute (October 2015).

protect springflow and surface water flows, the Legislature can amend Chapter 36 of the Water Code to require GCDs to adopt DFCs tied to maintaining base flows and springflows for rivers and springs within their jurisdiction. Another possible avenue is for surface water interest groups, such as downstream water right holders and environmental and recreational interests within the relevant watersheds in a GMA to become voting members in the GMA so surface water interests are represented in the DFC adoption process. Policies that allow groundwater pumping to diminish a public resource and impede surface water rights or environmental flows should be reconsidered.

Failure to Protect Property Rights

The presence of a GCD does not guarantee that property rights in groundwater are protected. As discussed above, in *Day* the Texas Supreme Court held that "land ownership includes an interest in groundwater in place," and Chapter 36 states that landowners have a real property interest in groundwater.[54] The Water Code burdens GCDs with the responsibility of protecting these private property rights, declaring that GCDs are "the state's preferred method of groundwater management in order to *protect property rights*, balance the conservation and development of groundwater to meet the needs of this state, and use the best available science in the conservation and development of groundwater…"[55] In developing rules to regulate groundwater production, therefore, GCDs must consider groundwater ownership and rights, and in adopting DFCs, GCDs are required to consider the impact the proposed DFC will have "on the interests and rights in private property."[56] GCDs must walk a fine line of managing a common pool resource that is privately owned.

Section 36.113(d)(2) of the Water Code states that "before granting or denying a permit a GCD must consider whether the proposed use of water unreasonably affects existing permit holders."[57] There are many landowners across Texas who do not have wells, either because they rely exclusively on rainwater or because they intend to drill a well at some point in the future. The Texas Supreme Court has declared that these landowners own the water beneath their property in place; the Court did not differentiate between use and nonuse of groundwater, but instead emphasized ownership. Yet the regulatory structure under Chapter 36 of the Water Code favors use of the resource. Landowners who wish to conserve the groundwater they own in place are not always protected by groundwater regulations in Texas, arguably in contravention to the holding in *Day*. For example, in 2013 Lost Pines GCD denied landowners in Bastrop County party status to contest a large groundwater production permit application on the basis that the landowners did not have wells on their property. This decision was made even though aquifer tests showed pumping would cause substantial drawdown beneath the landowner's properties. The landowner plaintiffs have appealed Lost Pines' decision to the Bastrop County District Court.[58]

Furthermore, if a GCD's regulations are not adequately protecting wells or groundwater near a large-scale groundwater development project, the rule of capture prevents affected landowners from being able to take legal action against the groundwater developer to protect their property interest. The Texas Supreme Court has declared that groundwater is a private property right worthy of protection, but unless a landowner is using this groundwater, the legal system and regulatory structure fail to provide adequate protections.

To protect private property, the Legislature can amend Chapter 36 of the Water Code to ensure that all affected landowners, including those who wish to conserve their groundwater in place, have the legal right to defend their property interest in groundwater regardless of whether they own a well. Additionally, while this might be far reaching and logistically complex, the Legislature could amend the definition of "beneficial use" in the Water Code to include conservation. Landowners who desire to conserve their groundwater in place could apply for a "conservation permit" that essentially removes their ownership interest from the amount of groundwater available for production. If there is indeed a legislative push in the 85th Session toward statewide adoption of correlative rights for groundwater, it is important for legislative proposals to protect landowners' ability and right to *conserve* their fair share of the groundwater they own, as this is a logical and equitable extension of a correlative rights approach.

CONCLUSION

Texas' growing population is placing pressure on aquifers across the state, as groundwater developers seek additional water supply sources to meet increased consumption. While groundwater provides important water supply needs, it does much more; it is connected to and sustains the ecology and economy of entire watersheds. For this reason, even though there is a tremendous amount of groundwater beneath the state of Texas, there is far less available for people to use. Groundwater has value in place. Current policy does not adequately

[54] Day, 369 S.W.3d 814 at 817;Tex. Water Code §36.002.

[55] Tex. Water Code §36.0015(b).

[56] Tex. Water Code §36.101(3) and §36.108(d)(7).

[57] Tex. Water Code §36.113(d)(2).

[58] *See* Plaintiff's Initial Brief, Andrew Meyer, Bette Brown, Darwyn Hana, Individuals and Environmental Stewardship, Plaintiffs v. Lost Pines GCD, Cause No 29,696, 21st Judicial District Court of Bastrop County, Texas, *available at* http://www.environstewardship.org/wp-content/uploads/2016/06/Plaintiffs-Initial-Brief.pdf

recognize or protect this intrinsic value. Texas groundwater policy is allowing aquifers to decline at the expense of springs, at the expense of surface water, and at the expense of landowners' private property interests. To bring effective groundwater management to areas of the state where it does not exist, Texas must resolve these fundamental challenges; otherwise efforts to conquer this final frontier will be in vain.