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Cover photo: Sunrise over Coastal Bend Bays & Esturaries Program land. See winning photos at WildlifeinFocus.org

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San Antonio's Edwards Aquifer Protection Program: Review and Analysis

Francine Sanders Romero[1,*]

Abstract: The City of San Antonio's Edwards Aquifer Protection Program utilizes land and conservation easement acquisitions to protect the quality and quantity of Edwards Aquifer recharge. This review considers four key components of its viability: (1) establishing the need for action, (2) choosing an appropriate strategy and funding source, (3) defining purchase guidelines, and (4) demonstrating the program's impact.

Overall, the analysis concludes that the program has been well adapted to the city's need to protect the recharge and contributing zones beyond its regulatory jurisdiction. As such, it may serve as a significant model for other cities, particularly in Texas, where regulations may face legal and cultural resistance. The City has effectively educated the public on the value of this sales tax funded measure, even though some justification of its premises, such as inevitable development in western counties, remains subjective. A strong foundation is also evident, with a consistent focus on acquiring land that fits the original, narrow intent of the effort. An impediment to its continuation, however, may be the difficulty of presenting clear evidence of its success, a challenge for all policies designed to avert future harms to natural resources.

Keywords: Edwards Aquifer; Edwards Aquifer Protection Program; land acquisition; San Antonio

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Terms used in paper

Short name or acronym	Descriptive name
APO	Aquifer Protection Ordinance
CAB	Conservation Advisory Board
City	City of San Antonio
EAA	Edwards Aquifer Authority
EAPP	Edwards Aquifer Protection Program
EPA	Environmental Protection Agency
ETJ	extraterritorial jurisdiction
LAP	Land Acquisition Program
SAWS	San Antonio Water System
TCEQ	Texas Commission on Environmental Quality
TLGC	Texas Local Government Code
WQLAP	Water Quality Land Acquisition Program

INTRODUCTION

Efforts to ensure sustainable management of the Edwards Aquifer attract interest from scholars and practitioners, who typically emphasize the regulation of water withdrawals.[1] Researchers have paid less attention to complementary strategies that protect supply rather than rationing demand, particularly by preserving the land where recharge occurs. This omission is likely because such efforts, at least on a large scale, have been relatively scarce. However, a land-based approach to water protection can play a key role in groundwater management, and a recent report from the Texas Farm and Ranch Lands Program called it, "a low-cost, effective strategy for protecting Texas' water resources."[2] This review provides a summary and analysis of one significant effort in this regard, the City of San Antonio's Edwards Aquifer Protection Program (EAPP). In place since 2000, $225 million has been spent through this program to preserve 146,075 acres in the Edwards Aquifer recharge and contributing zones.[3]

EAPP employs a simple and indirect mechanism for water management—acquire land and/or conservation easements to protect the recharge potential of the Edwards Aquifer, thereby securing this critical regional water supply. Identifying key elements of its success and considering those elements within the context of existing literature on natural resource protection can advance understanding of this approach to protecting groundwater. Below, following a brief background section, this paper examines four components of the history and evolution of EAPP: (1) establishing the need for action, (2) choosing an appropriate strategy and funding source, (3) defining purchase guidelines, and (4) demonstrating impact.

SAN ANTONIO AND THE EDWARDS AQUIFER

The origins and growth of the City of San Antonio (City) are closely linked to its ready access to the San Antonio segment of

[1] *See* Robert L. Gulley and Jenna B. Cantwell, T*he Edwards Aquifer Water Wars: The Final Chapter?*, 4 Texas Water Journal (2013), *available at* https://journals.tdl.org/twj/index.php/twj/article/view/6423. Todd H. Votteler, *Raiders of the Lost Aquifer? Or, the Beginning of the End to Fifty Years of Conflict over the Texas Edwards Aquifer,* 15 Tulane Environmental Law Review, 258-335 (2002; 2004, revised). Todd H. Votteler, T*he Little Fish That Roared: The Endangered Species Act, State Groundwater Law, And Private Property Rights Collide Over the Texas Edwards Aquifer*, 28 *Environmental Law* 845-879, (1998).

[2] Texas A&M IRNR, *Texas Farm and Ranch Lands Conservation Program Evaluation Report* (2016), *available at* http://www.txaglandtrust.org/pdfs/TFRLCP%20Eval%20Report%2020161219_FINAL.pdf.

[3] These figures represent a summary of expenditures and purchases after full spendout of the 2010 funds, and with the 2015 funds still to be accessed. *See* Francine S. Romero, *Aquifer Protection Visionary* (2017), San Antonio Express-News (March 28, 2017), *available at* http://www.mysanantonio.com/opinion/commentary/article/A-milestone-in-Edwards-recharge-protection-11034278.php.

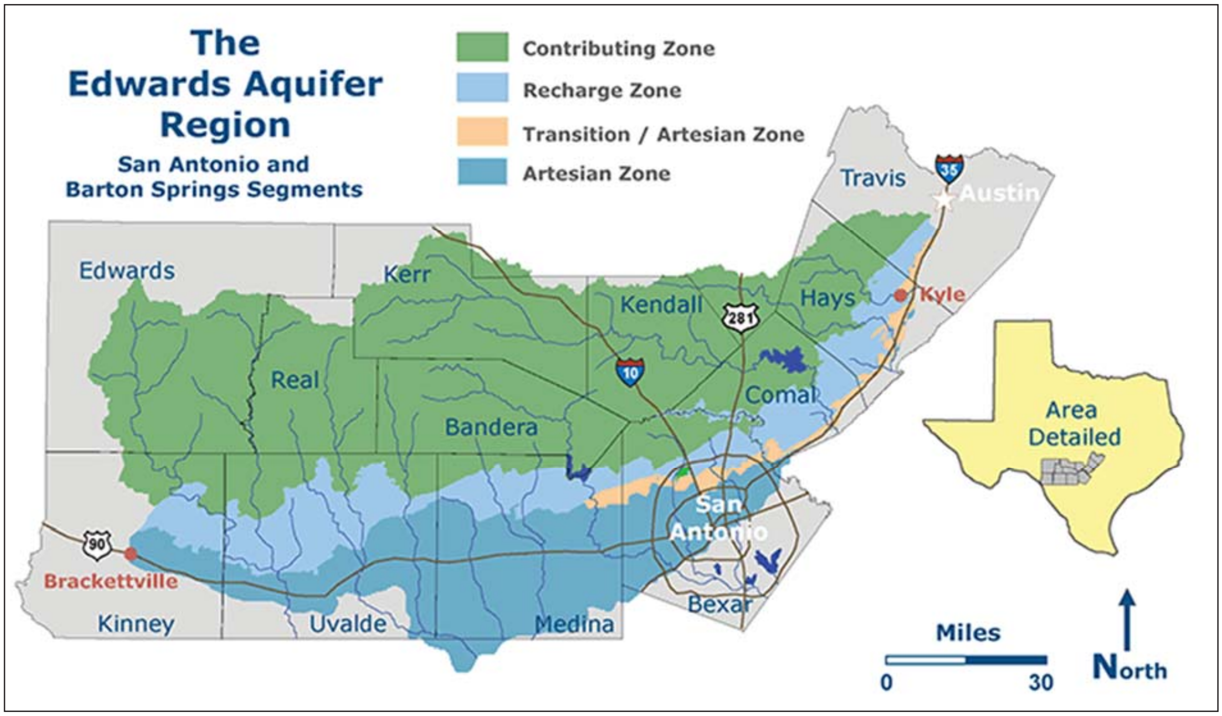

Figure 1. Hydrogeology of the Edwards Aquifer. Source: Eckhardt, supra Note 21.

the Balcones Fault Zone Edwards Aquifer, but rapid growth in the region threatens the quality and quantity of that groundwater.[4] As Figure 1 illustrates, the process by which supply reaches the City begins when "surface water from springs and streams originating on the Drainage Area [also called the contributing or catchment zone] reaches the Recharge Zone where much of the flow sinks into the Edwards Limestone," and then "flows down gradient to the Artesian Zone."[5] From there, it either naturally flows or is pumped to the surface. While variable, movement of groundwater through the aquifer is generally west to east. The recharge zone for San Antonio's artesian zone occurs in Bexar, Comal, Hays, Kinney, Medina, and Uvalde counties, with Medina and Uvalde counties effectively composing 70% of that zone.[6] The drainage, or contributing zone, includes several counties, as illustrated in Figure 1.

Several governmental entities have regulatory authority over the Edwards Aquifer. Some of their associated rules focus directly on water withdrawals, while others target pollutants and impervious cover that could threaten recharge quality and quantity. Created by the Texas Legislature in 1993 in response to a U.S. District Court ruling, the Edwards Aquifer Authority (EAA) is a political subdivision of the state, whose mission is to "manage, enhance and protect the Edwards Aquifer."[7] As an EAA-authorized permit holder, the San Antonio Water System (SAWS) passes along its own EAA-mandated restrictions to its customers through limits on landscape watering and water waste runoff.[8]

At the federal level, the Environmental Protection Agency (EPA) classified the Edwards as a sole source aquifer in 1975, a label that indicates it provides at least 50% of supply for its service area.[9] Per the Safe Drinking Water Act of 1974, this classification triggers review of federally funded development

[4]Sarah Goodyear, *Hot, Crowded and Smart*, Next City (July 22, 2013), *available at* https://nextcity.org/features/view/hot-crowded-and-smart-san-antonio-water-system-drought; Joe Nick Patoski, *Edwards Aquifer Authority has come a long way*, San Antonio Express-News (September 25, 2016), *available at* http://www.mysanantonio.com/opinion/commentary/article/Edwards-Aquifer-Authority-has-come-a-long-way-9242337.php.

[5]Edwards Aquifer Authority, *About the Edwards Aquifer*, *available at* http://www.edwardsaquifer.org/scientific-research-and-data/edwards-aquifer-overview.

[6]Leslie Lee, *Protect our land, Protect our Water*, txH2O, Texas Water Resources Institute (2014) 2, *available at* http://twri.tamu.edu/publications/txh2o/summer-2014/protect-our-land-protect-our-water/. U.S. Dep't of the Interior, U.S. Geological Survey, Recharge to and Discharge from the Edwards Aquifer in the San Antonio Area, Texas, 1997 2 (1998).

[7]*See* *http://www.edwardsaquifer.org/*. For a map of the EAA's jurisdictional boundaries, mostly in the recharge and artesian zones, *see* http://www.arcgis.com/home/webmap/viewer.html?webmap=aed0e4eddc794ec49d740a267d42560a&extent=-101.1491,28.3085,-96.6364,30.6845.

[8]*See* http://www.saws.org/conservation/droughtrestrictions/YearRound.cfm.

[9]*See* https://www.epa.gov/dwssa/overview-drinking-water-sole-source-aquifer-program#What_Is_SSA.

projects overlaying the recharge zone in order to limit contamination potential.[10] The Texas Commission on Environmental Quality (TCEQ) implements similar, but separate, state rules on all projects over the Edwards Aquifer recharge zone.[11]

Locally, the City enforces its own Aquifer Protection Ordinance (APO) that governs levels of impervious cover for new construction in the recharge zone. As the APO is similar to the EAPP, in that it focuses on limiting development per se, albeit by regulation, it is explained in further detail below. With one exception, prior to the EAPP there had been no policy in place in this region to protect land from development through acquisition. That exception was the SAWS Sensitive Land Acquisition Program (LAP), launched in 1997.[12] The LAP used a water supply fee to purchase land or easements in the recharge zone, in partnership with several land trusts. More than 9,000 acres were protected, with the last documented purchase in 2007.[13]

The EAPP began in 2000 when City voters approved a 1/8 cent (.125 %) sales tax increase to raise $45 million for purchase and preservation of land in the Edwards Aquifer recharge and contributing zones. While the EAPP would later expand its geographic range, the immediate impetus was the rapid development of recharge zone acreage in Bexar County. Since then, the EAPP has been reauthorized and expanded in both scope and funding, with a new round of $90 million approved in 2005, $90 million in 2010, and $100 million in 2015, with expenditures ongoing from the 2015 fund.[14]

ESTABLISHING THE NEED FOR ACTION

A key initial step in adopting any natural resource protection policy, especially one that requires voter endorsement, is for proponents to establish and promote a reliable narrative of its necessity. In an early piece on the topic of open space protection through voter-approved funding, Danziger pointed out the importance of communicating this "urgency of need" to citizens.[15] Furthermore, the information presented must be clear and accurate. As Steelman and Asher caution, when advocates approach voters with "a calculated degree of manipulation," the policy becomes suspect and any initial support will soon dissipate.[16]

In the case of the EAPP, the first component of the narrative is simply the mechanics of the Edwards Aquifer flow to the San Antonio pool. Second is the threat to quality and quantity of aquifer recharge posed by increased development/impervious cover in those zones. Third is the likelihood of substantial population growth in these key western counties. For the EAPP to gain initial acceptance and continued support, the City's leaders and other advocates had to communicate each of these effectively to citizens.

The first component, premised on well-established hydrogeology of the aquifer, requires only elementary presentation through explanation or maps for any residents not already aware of this dynamic. Proponents appear to have easily gained widespread public acceptance of these facts. As The Nature Conservancy Texas State Director Laura Huffman noted, central Texas is "one of the few places in the country where you can say the word *aquifer* and people know what you're talking about."[17] Beginning in 2000 and continuing through subsequent ballot measures, the City has promoted this message to voters. For example, its "Guide To 2015 Sales Tax Propositions" brochure includes maps, explanations, and "fun facts" on Edwards hydrogeology.[18] Elected officials, from Mayor Howard Peak in 2000 to Councilman Ron Nirenberg in 2015,

[10]Congressman Henry B. Gonzalez, representing Texas's 20th congressional district, added the sole source aquifer amendment to the federal Safe Drinking Water Act. While the legislation never had a notable impact on limiting development over the Edwards Aquifer recharge zone, it helped spark a local conversation on the topic. *See* Laura A. Wimberley, *Establishing "Sole Source" Protection*, in Char Miller, editor, On the Border: An Environmental History of San Antonio, Pittsburgh University Press (2001) 169-181. In 1976, Gonzalez also introduced a failed bill "to appropriate $76 million to purchase the Bexar County portion of the recharge zone." *See* Lanny Sinkin, *Private Profit over Public Good Led to Failure to Protect Aquifer Recharge Zone*, The Rivard Report (June 8, 2012), *available at* https://therivardreport.com/private-profit-over-public-good-led-to-failure-to-protect-aquifer-recharge-zone/.

[11]In a confusing duplication of terms, the TCEQ program regulating potential pollutants reaching the aquifer has the same name, Edwards Aquifer Protection Program, as the City's acquisition endeavor. *See* Texas Commission on Environmental Quality, *Edwards Aquifer Protection Program, available at* https://www.tceq.texas.gov/permitting/eapp/program.html.

[12]San Antonio Water System, *Water Resource Protection and Compliance, available a:* http://www.saws.org/environment/ResourceProtComp/aquifer_protection/acquisition.cfm.

[13]San Antonio Water System, *SAWS Board Approves Conservation Easement Purchase in Uvalde County*, July 12, 2007, *available at* http://www.saws.org/latest_news/NewsDrill.cfm?news_id=451.

[14]San Antonio City Council first voted to place these measures on the ballot, after which they were approved by voters in a general election, in May (2000, 2005, 2015) or November (2010). The 2000 ballot measure was designated as Proposition 3 and all subsequent measures as Proposition 1. In 2015, $10 million was set aside for grants for innovative, demonstration projects for recharge enhancement in Bexar County, *available at* http://saprop1edwardsprojects.org/. The EAPP and the Linear Creekways program share the 1/8 cent allotment, to reach their full funding amount, *see* http://www.sanantonio.gov/Finance/bfi/Tax-Rate-Summary.

[15]Burton Danziger, *Control of Urban Sprawl or Securing Open Space: Regulation by Condemnation or Ordinance?* 50 California Law Review 493 (1962).

[16]Toddi A. Steelman and William Ascher, *Public Involvement Methods in Natural Resource Policy Making*, 30 Policy Sciences 71-90 (1997).

[17]Amy Crawford, *Liquid Assets*, Nature Conservancy Magazine (2017) at 54.

[18]*See* https://www.sanantonio.gov/Portals/0/Files/AquiferPark/EdwardsInitiative_Booklet-English.pdf.

have also stressed the EAPP's significance through speeches and newspaper editorials.[19]

While basic aquifer dynamics found ready public acceptance, the next two components of the narrative were more ambiguous, beginning with the link between physical development and the recharge process. As Crawford emphasized, it makes fiscal sense for cities to invest in upstream watershed protections in the form of some limit to construction and impervious cover. This may prevent expensive treatment fixes or potential supply shortages.[20] Nevertheless, in the absence of a looming crisis, the public may not embrace this strategy. Furthermore, while the scientific community generally accepts the negative impact of development on recharge quality and quantity, there is no agreed upon trigger level at which impervious cover causes significant harm.[21] This can make it difficult to justify spending public money to preclude any, or virtually any, development.

San Antonio did not face an urgent catalyst for action in this regard as, for example, New York City did in the 1990s. Although New York City does not rely on an aquifer, its water supply originates in massive watersheds outside city limits, similar to the San Antonio context. The federal Safe Drinking Water Act updates of 1986 required all municipal water originating from surface sources to be filtered, which for New York City would have required construction of expensive filtration systems (estimated at between $10 and $20 billion) for its Catskill/Delaware and Croton watersheds. In order to avoid this burden, New York City instead received permission to initiate its LAP in 1997. Like the EAPP, New York's LAP is based on acquiring land and conservation easements to prevent development-linked pollutants reaching the municipal water supply.[22]

While San Antonio's main water supplier, SAWS, also functions without filtration for Edwards water, there have been no major alarms triggered by contamination and/or possible federal filtration requirements, although some observers have warned of this risk.[23] Drought periods, with the most recent in 2011, underscore the impact of significant impervious cover on recharge *quantity*, but public attention may wane when the drought ends. For City dwellers, the immediate impact of drought is more likely to be the landscape watering limits imposed by SAWS than fears of actually running out of water. As Lindgren, et al. reported, "(a)lthough recurring droughts and floods have caused appreciable short-term fluctuations in water levels, long-term hydrographs (about 80 years) indicate no net decline (or rise) of water levels in the San Antonio area."[24]

Finally, the third component of this narrative is that EAPP acquisitions would serve as an essential, proactive bar to the impact of imminent growth in Medina and Uvalde counties in particular. Since this premise is grounded partly on demographic projections, it has faced some resistance. In 2005, a San Antonio Express-News columnist suggested as much, opining that the EAPP, "is dedicated to sucking $90 million from the wallets of consumers and using it to enrich back country land speculators," implying these lands were becoming valuable *solely* because of the EAPP's interest, and that pending growth in the area was a myth.[25] And, in 2017, Councilman Joe Krier stated that his "constituents question the logic behind San Antonio protecting land outside of the city and county limits," because they are "skeptical that the land would ever be developed anyway."[26]

There is, however, considerable media coverage of new residents moving to Texas, with San Antonio projected to gain 28% more residents by 2030.[27] The Texas Demographic Center estimates population increases of 53% in Medina County and 35% in Uvalde County by 2050.[28] More immediate than these projections, residents can readily observe intensive

[19]*See* Linda Prendez, *Mayor sways officials,* San Antonio Express-News (April 26, 2000), at 1H; Ron Nirenberg, *Aquifer protection needs to be renewed*, San Antonio Express-News (May 17, 2014), at A15.

[20]Crawford supra Note 17, at 48.

[21]Chester L. Arnold and C. James Gibbons, *Impervious Surface Coverage: The Emergence of a Key Environmental Indicator*, 62 American Planning Association Journal (1996) 246, report that degradation of streams first appears with 10% impervious cover, and at 30% is "so severe as to become almost unavoidable." However, for the range in between those two endpoints, the point at which regulation is necessitated remains subjective. Furthermore, the development community may resist any limits. *Also see* David Todd and Jonathan Ogren, *The Texas Landscape Project*, Texas A & M University Press (2016) 219; Gregg Eckhardt, *The Edwards Aquifer Website*, http://www.edwardsaquifer.net/faqs.html.

[22]*See* David Soll, *Empire of Water*, Cornell University Press (2013). Adam Wisnieski, *City's Watershed Protection Plan Seeks Difficult Balance Upstate*, City Limits (June 15, 2015) 3 (online*), available at* http://citylimits.org/2015/06/15/citys-watershed-protection-plan-seeks-difficult-balance-upstate/.

[23]Robert Rivard, *The Edwards Aquifer Comes Under Increasing Threats,* The Rivard Report (June 8, 2012).

[24]R.J. Lindgren, A.R. Dutton, S.D. Hovorka, S.R.H. Worthington, and Scott Painter, *Conceptualization and Simulation of the Edwards Aquifer, San Antonio Region, Texas,* Scientific Investigations Report 2004–5277, U.S. Department of the Interior, U.S. Geological Survey, *available at* https://pubs.usgs.gov/sir/2004/5277/pdf/sir2004-5277.pdf, 41-42.

[25]Roddy L. Stinson, *Don't look now, but you are standing next to a bottomle$$ pit*, San Antonio Express-News, (April 19, 2005) 3A.

[26]Iris Dimmick, *Council Votes to Protect 2,830 More Acres Over Edwards Aquifer*, Rivard Report (March 30, 2017), *available at* https://therivardreport.com/council-votes-to-protect-2830-more-acres-over-edwards-aquifer/.

[27]Robert Rivard, *Check Out San Antonio (and All U.S. Cities) in 2030*, Rivard Report (January 22, 2015), *available at* https://therivardreport.com/check-san-antonio-u-s-cities-2030/.

[28]Texas Demographic Center, 2014 Population Projections Data, *available at* http://osd.texas.gov/Data/TPEPP/Projections/.

growth already occurring in eastern Medina County in particular as San Antonio sprawls in a westward direction. While much of this growth may be at a less intense level than occurs within the City, even the spread of single-family homes on smaller ranchettes can exert significant impact on recharge by fragmenting and contaminating natural flow.

Overall, the foundational narrative establishing a need for the EAPP was strong, with some aspects of the argument more objective than other aspects. Most citizens and public officials either already understand, or can be easily educated on, Edwards Aquifer hydrology. On the other hand, the impact of development on recharge functions cannot be precisely demonstrated, and future growth in the western counties is not guaranteed, despite current trends. Still, voters may pay less attention to the details of future growth and simply decide it makes sense to ensure preservation sooner rather than later.

Ultimately, the final vote counts indicate strong public agreement with the need for the EAPP. Support started out high and increased over time, with approval moving from 55% in both 2000 and 2005 to 66% in 2010 and 78% in 2015.[29] A poll conducted by The Nature Conservancy early in 2015 revealed the strength of support for that round, indicating that 54% of voters were "definitely in favor," and 24% "probably in favor," even months before the vote.[30]

CHOOSING AN APPROPRIATE STRATEGY AND FUNDING SOURCE

Regulatory Challenges

Given this substantial public backing for a land-based approach, the crucial next step was to identify a strategy that best fit the goal. Preservation of any natural resource may occur via regulation, acquisition, or incentive-based tools, or some combination of those. Generic regulatory approaches, where a particular practice is required or banned, are common. Regulation is relatively inexpensive compared to both public acquisition and to policies that financially incentivize sustainable management of private land. Because regulation only requires the price of enforcement, it can more efficiently protect resources.

Yet, a regulatory strategy may fall short of effectiveness. Since some natural resources, such as aquifers, transcend political boundaries, there is likely no single entity (e.g., city or county) possessing jurisdiction for full control. Furthermore, inter-jurisdictional collaboration or coordination is difficult and uncommon. As Lubell, et al. observed, "since common interests do not necessarily lead to common action, partnerships will not emerge automatically in response to potential benefits."[31] Others (Bengston, et al. 2003; Steelman 2000) found these limitations constrain open space protection in particular.[32]

As noted above, various entities enforce numerous policies directly focused on Edwards Aquifer *water*, such as the withdrawal rules enforced by EAA and the pollutant controls overseen by TCEQ. Other researchers have focused on the impact and challenges of those. Here, however, I focus on the topic at hand—a strategy of protecting water supply indirectly, by limiting development of the *land* overlaying the recharge and contributing zones.

In San Antonio's case, only one regulation targeting land development to protect groundwater has been successfully enacted.[33] The 1995 APO controls impervious cover over the recharge zone, setting maximum levels by category/location of development.[34] However, several factors dilute this policy. First, illustrating the common mismatch of political and natural resource boundaries, it only applies within the relatively small area of the recharge zone that falls within the City limits or its extraterritorial jurisdiction (ETJ).[35] (Since the majority of recharge to the San Antonio pool occurs in unincorporated areas of counties that lack zoning and most subdivision regulatory authority, county officials have virtually no power to limit development, even if inclined to do so.)

Second, even within its jurisdiction, the APO was constrained by state protection of vested rights in the development process,

[29] *See* Bexar County Elections Department, Election Results (2000, 2005, 2010, 2015), https://www.bexar.org/2186/Election-Results.

[30] The Nature Conservancy, San Antonio Voter Support for Protecting Water Supply in the Edwards Aquifer and Linear Parks (2015), *available at* https://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/texas/multimedia/san-antonio-voter-poll.pdf.

[31] Mark Lubell, Mark Schneider, John T. Scholz and Mihriye Mete, *Watershed Partnerships and the Emergence of Collective Action Institutions*, 46 American Journal of Political Science 148-163 (2002), at 159.

[32] David N. Bengston, Jennifer Fletcher, Kristen C. Nelson, *Public Policies for Managing Urban Growth*, 69 Landscape and Urban Planning 271-286 (2003). Toddi A. Steelman, *Innovation in Land Use Governance and Protection*, 44 American Behavioral Scientist 579-597 (2000). *See* Craig R. Smith, *Institutional Determinants of Collaboration: An Empirical Study of County Open-space Protections*, 7 Journal of Public Administration Research and Theory 1-21 (2009), on the challenge of providing goods across generations.

[33] Courts struck down several prior efforts. In 1976, for example, a City referendum invalidated the requisite zoning granted to developers of a shopping mall over the recharge zone at the Highway 281/1604 intersection, but the Fourth Court of Texas Appeals reversed that vote two years later. In 1978, San Antonio City Council approved an 18-month moratorium on all recharge zone construction, to allow for studies of its impact, but the ban was blocked by both federal and state courts. *See* Eckhardt, supra Note 21.

[34] *See* http://www.saws.org/environment/ResourceProtComp/aquifer_protection/ordinance.cfm. The APO is enforced by SAWS.

[35] Texas state law grants large cities such as San Antonio a five-mile ETJ beyond city limits where certain municipal development regulations apply. *See* http://www.statutes.legis.state.tx.us/Docs/LG/htm/LG.42.htm.

per Section 245 of the Texas Local Government Code (TLGC).[36] Donohue and Sanders reported that 30% of recharge zone properties filed plans for development in advance of the APO's passage, a strategy that released them from subsequent limits.[37] Finally, impervious cover is permitted at levels higher than scientists recommend, even given the disagreements on the precise point at which impervious cover threatens recharge quality and quantity. For example, within City limits, commercial developments (without vesting) may include up to 65% impervious cover over the recharge zone.

Another factor undermines the likelihood of vigorous enforcement of this and other potential regulatory efforts. Although the vested rights doctrine has likely meant the avoidance of potential lawsuits, future legal challenges could determine that regulation of land to protect water supply is too far removed from a legitimate use of the police power. In the case of regulation, costs are borne primarily by the landowner, whose options for sale and development are now limited. Therefore, it is at least arguable that land-based controls provide a public benefit that can be legally obtained only through the exercise of eminent domain and compensation to the owner.[38] As Eckhardt observed, "Texas is a state that is very respectful of private property rights, and many will simply not accept the notion that land use and development should be regulated."[39]

The Acquisition Option

Daniel Press, an advocate of the superiority of acquisition strategies for land protection (for whatever underlying purpose), is skeptical of regulatory approaches. Even at their strongest, he argued, they slow, rather than stop, development.[40] In San Antonio, the APO's limitations demonstrate that point. However, the challenges of pursuing an acquisition-based strategy may also be substantial and surprisingly analogous to the barriers to regulation. For example, coordinating regional collaboration on land purchases can be difficult; that would require two entities identifying an appropriate funding source and agreeing on purchase guidelines. If a city is willing and able to act unilaterally, it is at least possible to extend acquisition beyond its borders, unlike its confined regulatory jurisdiction. Even that process can be tricky, however, since state restrictions on expenditures of public funds may constrain acquisition efforts as well.

In fact, such a barrier occurred with the EAPP, resulting in the City advocating for a change to state law to improve its acquisition strategy. At the inception of the program in 2000, section 334.001 of the TLGC provided just five options for a "venue" (using the state terminology) funded by a City-imposed sales tax. The one that best fit the City's intent was for a "municipal parks and recreation system, since it at least allowed for land purchases."[41] However, another TLGC provision (331.001) limits parks purchases to "the county in which the municipality is situated," thus restricting expenditures to Bexar County and precluding acquisitions in the western counties.[42]

Therefore, under the 2000 EAPP, the City spent $45 million to buy about 6,500 acres, in fee-simple land purchases, classified as new parkland in order to comply with state law. These early acquisitions included some publicly accessible natural areas that remain in the municipal park inventory. These purchases, which were mostly completed by 2005, are illustrated in Figure 2 and noted in the key as Proposition 3 (2000) Properties. The City later transferred some acquisitions, including parcels associated with the Government Canyon State Natural Area, to the Texas Parks and Wildlife Department.

While the 2000 EAPP averted development on substantial recharge acreage, the process was slow and expensive. It had become clear to proponents that a legislative change would allow the City to more efficiently employ the sales tax tool. This came with a 2004 amendment to the TLGC, advocated by a City-led lobbying effort, adding the following option to the list of allowable venues: "A watershed protection and preservation project; a recharge, recharge area, or recharge feature protection project; a conservation easement; or an open-space preservation program intended to protect water."[43] The City used this new opportunity to allocate tax funds "for conservation easements and open space preservation over the Recharge and Contributing Zones."[44] Subsequent EAPP authorizations (2005, 2010, 2015) have been primarily expended on con-

[36]*See* http://www.statutes.legis.state.tx.us/Docs/LG/htm/LG.245.htm.

[37]John M. Donohue, Jon Q. Sanders, *Sitting Down at the Table*, in Char Miller, editor, On the Border: An Environmental History of San Antonio, Pittsburgh University Press (2001) 182-195. *Also see "Developers Bypass Aquifer Limits",* John Tedesco, San Antonio Express-News http://projects.expressnews.com/growth-and-the-aquifer.

[38]Danziger, supra Note 15 at 484.

[39]Eckhardt, supra Note 21. See http://www.legis.state.tx.us/BillLookup/Text.aspx?LegSess=85R&Bill=SB1385 for SB 1385, proposed in the Texas Senate in 2017, regarding the mandatory use of conservation easements in lieu of municipal land regulations in certain cases.

[40]Daniel Press, *Saving Open Space*, University of California Press (2002) 14.

[41]*See* Texas Local Government Code, http://www.statutes.legis.state.tx.us/Docs/LG/htm/LG.334.htm.

[42]Texas Local Government Code, http://www.statutes.legis.state.tx.us/SOTWDocs/LG/htm/LG.331.htm. Even without that provision in place, it would be difficult to justify the purchase of parks in other counties, given the management expenses and decreased likelihood of use by City residents.

[43]Texas Local Government Code, supra Note 41.

[44]*Edwards Aquifer Protection Program & Linear Creekway Parks Development Program*, (presentation to San Antonio City Council, January 29, 2015, *available at* https://www.sanantonio.gov/Portals/0/Files/AquiferPark/Props1and2.pdf.

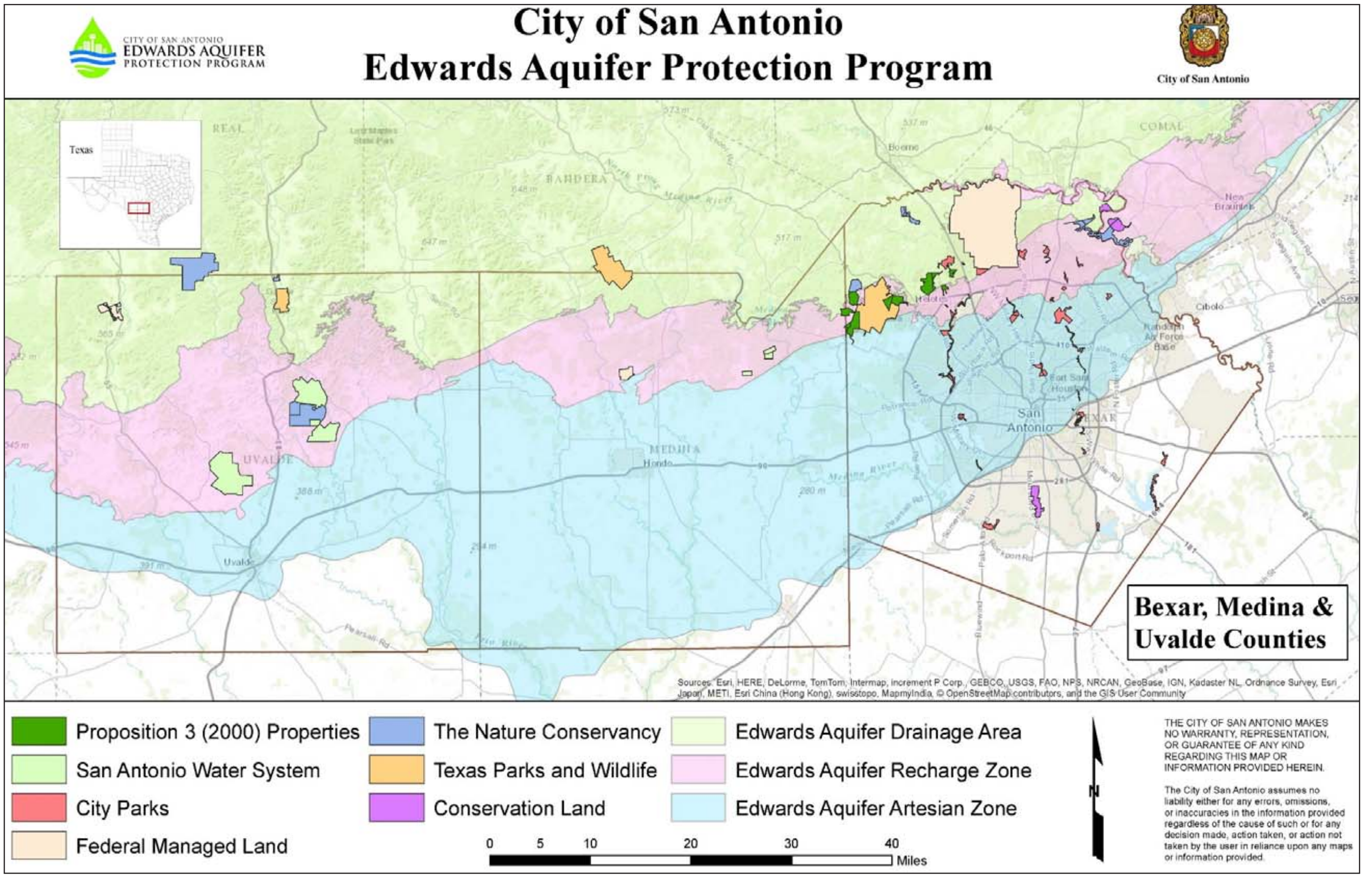

Figure 2. EAPP purchases through 2005 and other protected acreage. Source: City of San Antonio Edwards Aquifer Protection Program.

servation easements within the recharge zone in Medina and Uvalde counties, although six additional properties (representing about 800 acres) in Bexar County have been purchased in fee-simple in these subsequent rounds.[45] While the measure allows for contributing zone purchases, the recharge zone has remained the principal focus, a point I return to in the concluding section.

According to Bengston, et al.'s review of generic resource protection mechanisms, the use of conservation easements represents a transition from an acquisition to incentive-based mechanism. The City is not acquiring the property but providing the financial inducement for the owner to manage the land in a particular way.[46] Still, conservation easements do involve the sale of development rights to the City. Whether the acquisition or incentive label is used, there are several benefits to the use of conservation easements over fee-simple acquisitions. For example, easements are considerably less expensive, there are fewer associated management obligations, and the City avoids the liability concerns that ownership entails.[47]

Conservation easements also fit into the Texas private property ethos, in that they operate on a willing buyer/willing seller model. The EAPP does not utilize eminent domain, so landowners have complete discretion on whether to participate. Interestingly, in her commentary on a very different issue (state law governing groundwater withdrawals in the absence of a groundwater conservation district such as EAA), Puig-Williams observed how that system "only affords the landowner the option to claim and use his property interest rather than preserve or conserve his property for future use."[48] Conceptually, the EAPP presents a markedly different opportunity, one

[45]Lee, supra Note 6.

[46]Bengston, et al., supra Note 32.

[47]While easements "grant no right of access to the general public . . . the City of San Antonio, the Edwards Aquifer Authority and their contractors must be allowed to enter the property, with prior landowner notification and approval, to conduct annual monitoring of the easement," *see* www.sanantonio.gov/EdwardsAquifer/ConservationEasementFAQs.

[48]Vanessa Puig-Williams, *Regulating unregulated groundwater in Texas: how the state could conquer this final frontier*, 7 Texas Water Journal (2016) 92. https://journals.tdl.org/twj/index.php/twj/article/view/7039/pdf_19

that rewards the property owner who seeks to use their land to conserve water resources.[49]

Identifying Funds

Acquisition options can offer a number of improvements over regulation in particular contexts. A primary barrier, however, is the funding mechanism. Financing preservation through taxes or bond obligation effectively transfers the burden to citizens at large, versus particular landowners, when a municipality chooses acquisition over regulation. In San Antonio, the 1/8 cent sales tax for the initial $45 million EAPP funding was viable at its initiation in 2000, since there was still room for an additional 1/4 of a cent in the state mandated cap of 2% for municipalities.[50] A voter-approved funding mechanism is a crucial foundation for future public acceptance, according to Berry. He observed that, in the absence of citizen choice, "no value can be imputed to [the acquired good] that has any explanatory or ethical content."[51]

Beyond the initial identification of a funding source, land acquisition programs must also present a transparent pricing mechanism to justify that purchase value. As Berry noted, the utility of open space, and therefore its objective value, can be difficult to estimate and defend to the public.[52] However, since the EAPP operates through purchase of land or conservation easements, pricing relies on traditional real estate appraisals but with a small twist for easements. An appraiser experienced with conducting conservation easement valuations in this region provides two property appraisals, reflecting the fair market value price with, and without, full development rights. Typically, the forfeit of the full rights, and thus the price paid for the easement, is roughly in the range of 40% of the value with development rights. For example, a ranch valued at $10 million with full development rights, might appraise at $6 million with the loss of virtually all development options. Therefore, the City through the EAPP would pay $4 million to the owner for the extinguishment of those rights, memorialized through the conservation easement.[53]

As Daniels pointed out in his general review of easement strategies, however, appraisal processes that include projections of lost development value can be controversial. The public may believe that estimate is unrealistically inflated or may argue that the owner should not profit from the "windfall" price, since they did not earn it.[54] Returning to the high levels of support at the polls, however, it would be surprising that citizens would support the EAPP so strongly only to later question the prices paid to protect the land. Indeed, there is no evidence of these sorts of reservations emerging.

Another potential source of contention comes from the other side of this purchase price equation. The "lost" development value, for which the owner is compensated through the price of the easement, is also lost to local property tax rolls. Citizens and officials in the areas of acquisition could protest that these transactions, by removing land from development (and value from property tax appraisals), are constraining the future tax base. In fact, New York City's LAP program has encountered notable resistance from upstate communities for this reason. In response, New York City pays $157 million a year in property taxes on land acquired in the Catskill/Delaware Watershed to cover the lost development value, although even that has not alleviated complaints.[55] While EAPP easements similarly preclude significant development in perpetuity, San Antonio has avoided any such backlash from the western counties.

Bringing this full circle, the acquisition mechanism matches up well with San Antonio's geographic/legal context. As Daniels noted, the choice of any policy demanding significant financial resources (such as acquisition or incentives) always begs the question of why the goal was not achieved by the cheaper (at least for the government) means of regulation. Specifically concerning land preservation, he suggested that citizens will always ask why the municipality did not use zoning or some other relatively economical regulation to keep the land in its natural state, encumbering the landowner's development options rather than paying for them.[56] However, the fact that most of the recharge zone is beyond the City's regulatory jurisdiction

[49]For a useful discussion of the link between conservative stewardship and EAPP, see rancher Todd Figg's comments in the San Antonio portion of the documentary, Water Blues/Green Solutions, produced by Penn State Public Media, http://www.waterblues.org/themes/san-antonio/san-antonio-segment.

[50] Texas levies a state sales tax of 6.25%, allowing cities to add an additional 2% for some combination of general funds and authorized projects. The 2% ceiling for the City of San Antonio was reached in 2012, with approval of a 1/8 cent increase through 2020, for the Pre-K4SA program. Thus, the 2015 EAPP renewal occurred within a different context, in which any newly proposed uses for sales tax funds could have succeeded only by being chosen *instead* of EAPP, although no serious contenders emerged. In addition to the EAPP, Creekways, and Pre-K for SA allocations, the City sales tax includes 1% for the general fund and .75% for transportation projects.

[51]David Berry, *Preservation of Open Space and the Concept of Value*, 35 American Journal of Economics and Sociology (1976) 113-124, at 115.

[52]Berry, *ibid*.

[53]More precisely, these perpetual easements normally restrict development to ½ of 1% impervious cover. Most allow "limited development rights, such as building a small number of additional homes on the land," while "no-development zones are included in agreements for properties that contain extra-sensitive features, such as sinkholes, streams or springs." *See* Lee, supra Note 6.

[54]Thomas L. Daniels, *The Purchase of Development Rights: Preserving Agricultural Land and Open Space*, 57 Journal of the American Planning Association (1991) 421-431.

[55]Wisnieski, supra Note 22, 2 (online).

[56]Daniels, ibid Note 54.

renders this question largely moot, and the choice between regulation and acquisition mechanisms is averted.

DEFINING PURCHASE GUIDELINES

Once a governmental entity has identified a mechanism and funding source, the next challenge for any acquisition program is developing clear guidelines that align spending with goals. As Danziger argued, "absent economic and utilitarian considerations, the planner is left with little or no objective standard or discipline," leading to a "highly questionable" use of public funds.[57] Land preservation programs in general can be susceptible to imprecision in prioritization, as a number of valid but subjective targets, such as protecting scenic views or preserving farmland can guide purchases. When programs concentrate on acquiring land or development rights to sustain recharge to a particular aquifer, however, developing parcel identification and prioritization methodology tightly bound to the narrow goal should be relatively straightforward.

For the EAPP, the change in state law allowing use of the sales tax for conservation easements in the western counties was an important step toward ensuring the policy's goal of significant recharge protection. Nevertheless, it does not alone guarantee that the City will only pursue appropriate lands in those counties. To support that outcome, the EAPP first employs a Geographic Information Systems (GIS) model that ranks all land in the target area through four data layers, applied down to the 1-meter level. The model was developed by a Scientific Evaluation Team "consisting of aquifer experts convened to prioritize undeveloped properties based on their environmental characteristics in order to achieve maximum value for voter-approved dollars."[58]

Fifty percent of the model score is determined by best available information regarding the presence of caves, faults, sinkholes, and other recharge features. Biological cover contributes another potential 20%, awarding higher scores for vegetation associated with greater recharge potential. The final 30% is evenly split between property size and adjacency to similarly protected lands (whether through EAPP, conservation easements held by other entities or public ownership).

The first two factors, permeability and vegetative cover, ensure prioritization of properties with the strongest links to recharge quality and quantity. The Edwards Aquifer recharge zone presents some variation in its recharge potential that is considered by these factors. The second two factors, size and adjacency, contribute to building an integrated system of protection, especially in regard to safeguarding entire watersheds from development in an efficient manner. This is accomplished through the acquisition of contiguous easements on large swaths of land.

Beyond reviewing a parcel's rank in the model, the next step for assessment is a site visit to gather additional evidence. Through an inter-local agreement, the City cooperates with EAA staff to provide detailed geologic reports from these in-person inspections, particularly highlighting observable karst geology such as caves and sinkholes, some of which the model may not have captured. The reports grade each parcel, indicating relative value for quality and quantity of aquifer recharge.

All of these factors work toward ensuring that appropriate properties are considered by the Conservation Advisory Board (CAB), which serves as the initial recommending group, and then by the San Antonio City Council for final decision on acquisition. Furthermore, these procedures enable both bodies to prioritize available land. Either CAB or the city council, however, is free to decline purchase for other reasons. Typically, this might involve a property owner insisting on a price above fair market value or asking for too much flexibility for future development. Another scenario would involve the perception that development is unlikely to occur even in the absence of a conservation easement, for example if the land lacks road frontage or is particularly remote or rugged.

Overall, guidelines that fully reflect the goals of the EAPP provide a foundation for recommended purchases. Even when acquisitions may fulfill some other purpose, such as preservation of a historic ranch or endangered species habitat, the City expends funds only upon evidence of recharge integrity.[59] While opponents could assail any such ranking model as based on questionable science, no criticisms of that sort of have emerged for the EAPP. Probably the most likely threat to the program using the model to maximum efficiency is the human factor limitation, i.e., when the property owner of a significant parcel simply is not interested in participation.

DEMONSTRATING IMPACT

General Efficiency

While EAPP's decision rules and strategies appear well defined and feasible to implement, the next step toward determining success is whether the property protections are in fact

[57]Danziger, supra Note15, at 484 and 486.

[58]City of San Antonio, Edwards Aquifer Protection Program, *available at* www.sanantonio.gov/EdwardsAquifer/About.

[59]These sorts of multi-purpose purchases may still raise questions about dilution of the Program's goals. The most controversial in this regard was use of funds for the Bracken Bat Cave in 2014. *See* Mark Reagan, *Bracken Bat Cave Would Save More Than Bats*, SA Current, (October 14, 2014), *available at* https://www.sacurrent.com/sanantonio/bracken-bat-cave-would-save-more-than-bats/Content?oid=2326588. Iris Dimmick, *City Acts to Protect Bracken Cave's Bat Colony*, Rivard Report (October 16, 2014), *available at* https://therivardreport.com/bracken-bat-cave-protected-by-conservation-easement/.

Table 1. Comparison of Urban Land Acquisition Programs.

City	Program	Year started	Spent so far (millions of dollars)	Acres Protected	Price Per Acre (Average)
Austin[a]	Water Quality Protection Land	1998	$143	28,308	$5,051
New York[b]	Land Acquisition Program	1997	$438	135,149	$3,240
San Antonio	EAPP	2000	$225	146,075	$1,540

[a]City of Austin, Austin Water, Water Quality Protection Land website http://www.austintexas.gov/department/water-quality-protection-land; 2014 Annual Report, *available at* http://www.austintexas.gov/edims/document.cfm?id=240099. *Also see* Asher Price, *Austin's water quality protection land purchases*, Austin American-Statesman (October 15, 2012). It is difficult to find comprehensive and up to date information on Austin's program in one place, and the numbers from different sources vary a bit from each other.
[b] Wisnieski, supra Note 22.

achieving expectations. There are a number of ways to approach assessment, making this an intricate task. I present a rudimentary first step in Table 1, through a comparison of the EAPP to New York City's LAP and Austin's Water Quality Land Acquisition Program (WQLAP). There are several implications, and limitations, to this simple comparison.

Most obviously, the EAPP has protected more acres, and at a lower average price, than the other two programs, indicating an efficient model of land acquisition. The comparison programs are analogous in that both use a strategy of purchasing land to protect water quality and quantity. As noted above, New York City is protecting surface water and not groundwater but is similarly targeting private lands outside of city limits. Austin's WQLAP, like EAPP, focuses on recharge and contributing lands, with its emphasis on the Barton Springs segment of the Edwards Aquifer recharge and contributing zones.

However, the comparison is somewhat unbalanced, as the three programs have important differences. For example, the City of San Antonio has spent most of the EAPP funds on less costly conservation easements, with only about 5% of total expenditures for fee-simple land purchases. In comparison, about 35% of Austin's WQLAP properties are fee-simple. New York City's LAP includes roughly 65% fee-simple lands and has encountered another unique problem, in which "the city's buying presence has created more competition for land, causing prices to rise."[60] Since municipalities are unlikely to pay more than fair market value for fee-simple land or conservation easements, the price per acre indicated on Table 1 simply reflects lower market values in EAPP's area of interest, as well as greater ease in acquiring conservation easements over fee-simple purchase. Still, this simple comparison indicates the EAPP as a comparably efficient use of public funds.

[60]Wisnieski, supra Note 22; New York City Department of Environmental Protection, Long-Term Acquisition Plan, 2012-2022 *available at* http://www.nyc.gov/html/dep/pdf/resources/lt_plan_final.pdf.

Another important indicator of conformity with EAPP's programmatic goal success is the geographic distribution of fee-simple and conservation easement purchases. This tracks roughly proportional to recharge location. About 67% of protected parcels are in Uvalde County, which provides the highest percentage of recharge to the San Antonio pool, 24% in Medina (second highest contributor to San Antonio pool), and 7% in Bexar (lowest contributor of the three counties to San Antonio pool).[61] As Figure 3 shows, indicating all EAPP purchases through 2015, identified as Proposition 3 and Proposition 1 Properties in the key, there is also a pattern of securing blocks within particular watersheds, such as the Blanco Creek and Frio River watersheds, rather than assembling a disjointed patchwork of protected land.

A final indicant of fiscal efficiency is purchases where the City leveraged EAPP funds with other resources. Although limited, there are some examples of this occurring. In 2016, the City expended over $5 million from the EAPP for fee-simple purchase of a 165-acre portion of the Classen-Steubing Ranch, a parcel with unusually high recharge capacity and imminent

[61]The exact breakdown of recharge to the San Antonio pool is difficult to ascertain, partly because of yearly variation and partly depending on the source. The EAA reports recharge from five counties: Uvalde, Medina, Bexar, Kinney, Comal, and Hays, but it is not clear that all flows to the San Antonio pool. *See* Edwards Aquifer Authority Hydrologic Data Report for 2006, *available at* http://www.edwardsaquifer.org/documents/2007_Hamilton-etal_2006HydrologicData.pdf. About 37% of that reported recharge occurs in Comal, Hays and Kinney counties. Per an email to the author from Geary Schindel, (Chief Technical Officer, Aquifer Management Services, EAA) on July 21, 2017, "Comal and Hays counties are down gradient of the City's water supply; Kinney County distribution is very small and probably not worth considering. Most of that water discharges at the San Felipe Springs." By eliminating Comal, Hays, and Kinney counties from EAA figures, a very rough estimate is that Uvalde County provides about 56.7%, Medina County 27.5%, and Bexar County 15.7% of recharge to the San Antonio pool.

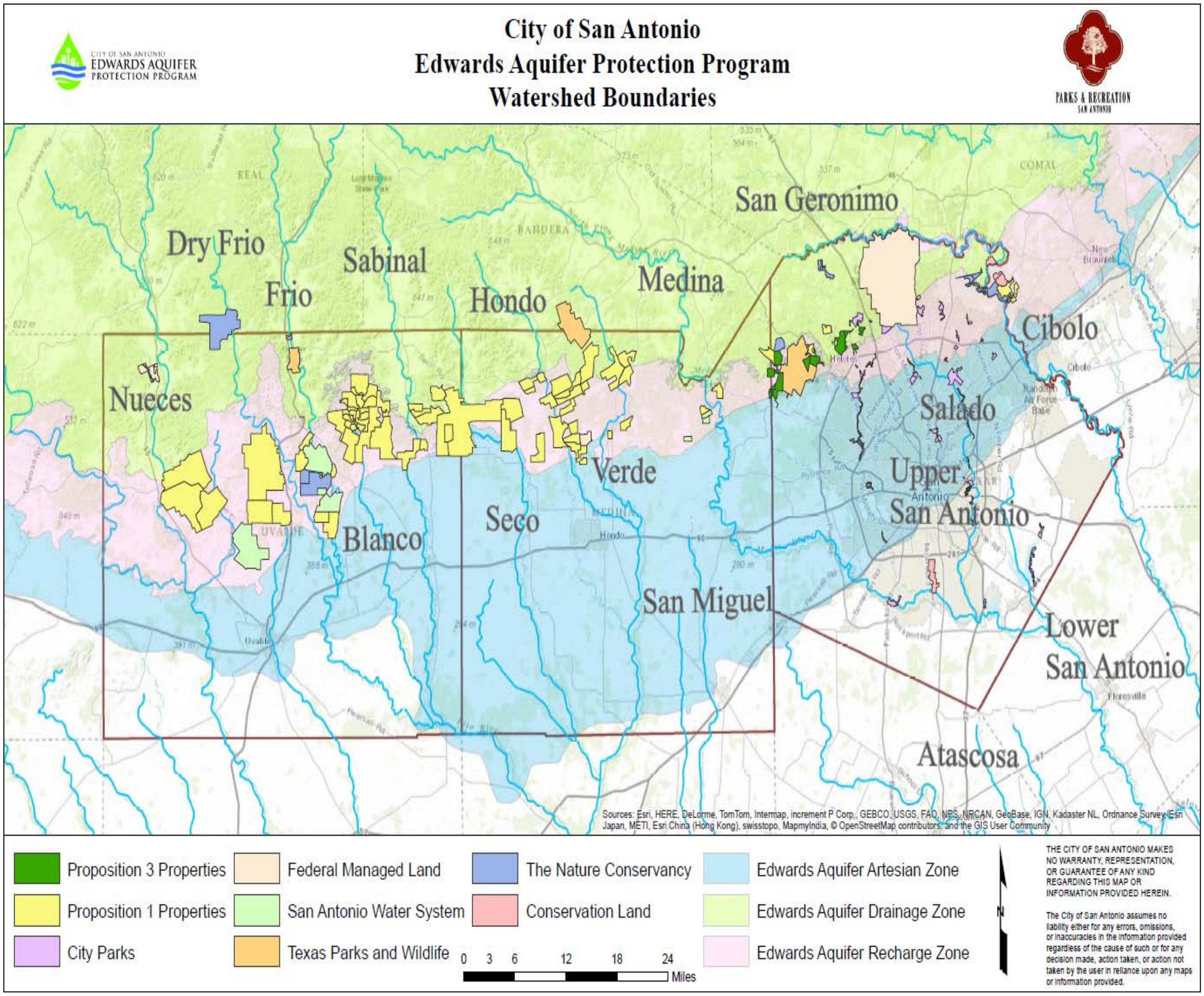

Figure 3. EAPP purchases through 2015 and other protected acreage, with watersheds.
Source: City of San Antonio Edwards Aquifer Protection Program.

development threat.[62] However, the seller would agree to that transaction only if the City purchased the entire property, which included an additional 39 acres. The city council therefore combined program funds with an option to buy the remaining piece for parkland from a pending bond election.[63]

In 2015, the City secured a matching grant from the U.S. Department of Agriculture Natural Resources Conservation Service's Agricultural Conservation Easement Program to purchase an easement appraised at almost $7 million on Rancho Blanco, a 1,100-acre property along the San Geronimo Creek Watershed, and one of the few contributing zone properties targeted by EAPP.[64] With the federal grant covering almost $3 million of that price, the EAPP's portion was reduced to $4 million.[65] In this case, the two programs have complementary

[62]Josh Baugh, *Part of land deal's funding OK'd,* San Antonio Express-News (June 17, 2016) A3.

[63]*See* City Council Agenda Item/Map, *available at* https://sanantonio.legistar.com/LegislationDetail.aspx?ID=2746971&GUID=81F9CDF3-AD42-4284-A9B4-30FF85151F7F&FullText=1; https://sanantonio.legistar.com/View.ashx?M=F&ID=4490679&GUID=B2C9CD6A-1BC7-4591-86C3-A82F0A6833DB.

[64]See map at: https://sanantonio.legistar.com/View.ashx?M=F&ID=3908998&GUID=4FF586F8-9506-4ED1-B309-A2C327E6F13B.

[65]*See* https://sanantonio.legistar.com/LegislationDetail.aspx?ID=2404049&GUID=7A1BB6DB-A093-4642-9348-2D9EFCEA29C6&Options=&Search=&FullText=1.

goals—recharge protection for the City and native grassland preservation for the U.S. Department of Agriculture.[66]

Impact on Recharge Quality and Quantity

The full implication of all these indicants, however, is more difficult to estimate. An efficient record of land/conservation easement purchases, in the appropriate locations, is an instrumental measure that does not necessarily demonstrate impact on recharge quality and quantity. One of the inherent limitations of a preventive policy strategy, particularly one that safeguards land to ensure future water integrity, is adequately documenting success. As acknowledged by New York City's Department of Environmental Protection, in justifying its LAP, "land acquisition is an anti-degradation tool that does not have any immediate impact on water quality. Further, it is impossible to predict with certainty whether or how a property protected by LAP might have been developed and how such development would have impacted water quality."[67]

With that proviso in mind, additional evidence appears in an Assessment Report of the EAPP produced by LMI in 2014, commissioned by the City.[68] Its conclusions on recharge quality and quantity impact are favorable but not conclusive, reflecting the difficulties in demonstrating effectiveness of preventive measures. The water quality section does little more than lay out the generic need for local efforts, beyond existing state and federal regulations, to prevent the intensified pollutants linked to residential expansion and commercial or industrial land uses. On this point, all the Assessment Report can do is to highlight the EAPP as a means of potentially minimizing future contamination by protecting critical land from development. Again, the preventive strategy eliminates possible evidence of what might have happened in the absence of EAPP.

The Assessment Report is more specific and detailed, however, on the importance of protecting lands directly along streambeds in the recharge zone, stating "management of activities that might degrade water quality in this area (such as urban development, contaminant storage, and industrial activities) is essential for protecting water quality."[69] It points out that the EAPP had protected just 18.4% of recharge zone streams through 2013. The report's authors highlight the role of streams in the contributing zone as well, focusing on the rapid contamination that could affect the Edwards Aquifer if pollutants entered these waters, and observing that the EAPP has protected only 3.6% of contributing zone streambeds. While purchases since 2013 have likely resulted in additional protected land in these areas, this section of the Assessment Report points to both the potential benefits of the EAPP and the limits on what it has achieved so far.

In the water quantity section, the Assessment Report concludes that the EAPP had already protected 51% of current annual SAWS withdrawals from the Edwards Aquifer for delivery to local customers. Figure 4 represents an assessment of various EAPP continuation options against SAWS-estimated future need. The red dot added to this chart emphasizes an important benchmark: the year (2030) in which enough supply would be secured through the EAPP (assuming it is renewed at least at the $90 million level in 2020 and 2025) to meet the City's projected 2060 demand for Edwards Aquifer water.[70]

This discussion of the dynamic between the EAPP and recharge quantity links to the question of the extent to which impervious cover disrupts recharge volume. The Assessment Report operates on the premise that, in the absence of EAPP protection, *zero* recharge would occur on these properties. This is an oversimplification; allowing development to proceed unabated, while lowering recharge volume, would likely not reduce it to zero. Still, purchases/conservation easements are the only way to ensure an absence of disruption to the natural recharge process.

CONCLUSIONS AND GOING FORWARD

This review of the EAPP has explicated key components of its creation and implementation. Overall, the need for the EAPP appeared well documented and accepted by voters, although some aspects of that narrative are more subjective. The acquisition mechanism adapts well to the hydrogeology of the Edwards Aquifer, given that the City has limited options for regulation. Purchase guidelines focus squarely on the goal of recharge protection. Finally, while there are challenges to documenting impact, the EAPP presents a record of efficient-

[66] *See* https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/easements/acep/.

[67] Soll, supra Note 22, 193. Also, see Danziger, supra Note 15, on the impossibility of presenting information on what would have occurred in the absence of any acquisition program.

[68] Justin A. Cleveland, et al., *City of San Antonio Edwards Aquifer Protection Program, Office of Eastpoint and Real Estate, Assessment of the Current Status and Long-Term Viability of the City's Edwards Aquifer Protection Program*, Report ATN30TI, LMI (2014), *available at* https://www.researchgate.net/publication/272023372_ASSESSMENT_OF_THE_CURRENT_STATUS_AND_LONGTERM_VIABILITY_OF_THE_CITY'S_EDWARDS_AQUIFER_PROTECTION_PROGRAM. LMI, originally known as Logistics Management Institute, is a non-profit government contracting and consulting firm founded in 1961. Its Southwest Region office is located in San Antonio, *see* http://www.lmi.org/en/About-LMI/Locations-Directions-(1)/Southwest-Region/Southwest-Region.

[69] Cleveland, ibid, at 3-1.

[70] This projection is based on SAWS 2012 Water Management Plan, which already included the development of several non-Edwards Aquifer sources, but preceded adoption of the Vista Ridge Regional Water Supply Project. Cleveland, ibid, at 4-2.

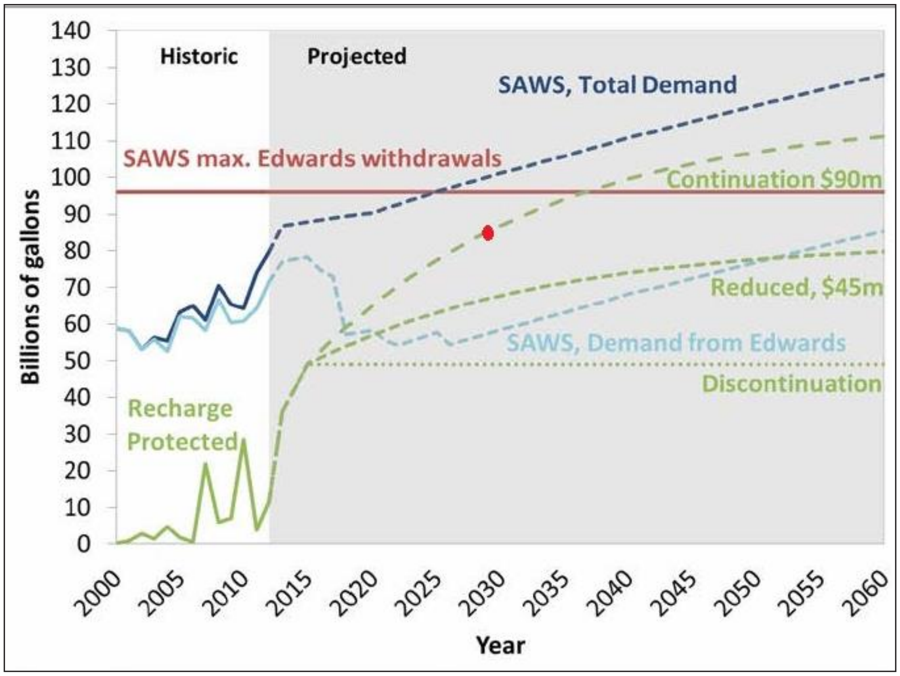

Figure 4. Estimated link between continuation of program and future demand. Source: Cleveland, supra Note 70, 4-7.

ly spending funds to meet the overall goal. This section now describes how particular programmatic components may evolve.

Ironically, the region's rapid population growth, a key pillar of the EAPP's justification, could represent a threat to its continuation going forward. This is largely a matter of perception, linked to the declining share of San Antonio's total water supply that comes from the Edwards Aquifer. In its 2017 Water Management Plan, SAWS shows that the aquifer's share of water provided to customers has dropped from 70% of total supply in 2000 to 42% (drought year)/60% (average year) in 2017. Furthermore, Edwards Aquifer water will represent only 31% (drought year)/52% (average year) by 2070, the result of a diversification initiative, including such endeavors as the Carrizo Aquifer Water Project, H2Oaks Desalination Plant, and the Vista Ridge Regional Water Supply Project.

However, it is important to keep these projections in perspective. The declining percentage is not a function of the City using less Edwards Aquifer water, but rather the result of increasing population requiring a larger supply, in turn diminishing the aquifer's proportional share. The management plan declares that "the Edwards Aquifer has been, and will continue to remain, the cornerstone of San Antonio's water supply," suggesting that the full SAWS-permitted annual Edwards withdrawals will still be necessary.[71]

In sum, these new water sources might weaken but never eliminate justification for Edwards recharge protection. Rather, the major challenge to the EAPP moving forward will more likely be competition for that limited sales tax with exhaustion of the current $100 million funding pool, probably in 2020. At that point, other funding priorities could present a challenge to securing additional funds for EAPP.

This is where another possible limitation of EAPP emerges, again concerning its justification. While each funding phase met its goal through the efficient expenditure of allocated funds to protect sensitive land, challengers could highlight the absence of a clearly defined, *ultimate* endpoint. In the extreme, that endpoint could be when the City has acquired easements on all undeveloped recharge zone land and perhaps even extending to the contributing zone. That goal is clearly unrealistic, but may present an opportunity to prioritize certain property types even further, such as focusing on land adjacent to river and streambeds.

The question of whether the EAPP should move toward similar protections of contributing zone acreage remains unsettled. Given the basic flowpath from contributing to recharge zone, the former may warrant significant protection, and the authorizing language for EAPP allows purchases in both zones. Nevertheless, that would involve a great deal more funding and years of effort. While "recent research clearly highlights

[71] *Available at* http://www.saws.org/Your_Water/WaterResources/2017_wmp/docs/20171107_SAWS-2017-Water-Management-Plan.pdf (17)

the importance of the contributing zone to recharge," it is too extensive for the EAPP feasibly to protect its entirety.[72]

In short, shifting priorities and emerging competition for the sales tax will challenge EAPP advocates to specify how much is enough, if asking voters to endorse another renewal.[73] Relatedly, defining indicators of success for the EAPP may inherently be its most vulnerable component, given the challenge of demonstrating the prevention of future harms to recharge quality and quantity. To a point, conclusions on whether it has been successful relies a great deal on belief in whether it was necessary in the first place. That public perception seems strong and makes a case for the definition of EAPP's success as simply the evidence that it protects as much sensitive land as possible. However, as competition for the sales tax emerges, the challenge of demonstrating results could shape the community dialogue on future renewals. At the same time, the evidence of accomplishment, at least on the simpler scale of dollars expended and acres protected, may convince citizens that the EAPP has successfully run its course, completing all it set out to do.

Overall, this review makes the case for the rationality and utility of a strategy that focuses on land in order to protect water. Some aspects of the EAPP are specifically linked to the San Antonio context. For example, the hydrogeology of the region, in combination with jurisdictional limits, makes acquisition the only feasible option for protecting sensitive lands that influence the San Antonio supply. Furthermore, the City has benefitted from a market with relatively low land appraisal values, and a steady supply of willing participants. However, this review may provide generalizable principles for any governmental entity considering this approach, emphasizing the importance of clear public communication, guidelines that appropriately match the overarching goal, and the ability to demonstrate the efficient expenditure of funds.

[72] Ronald T. Green, Geary Schindel, and Rebecca Nunu, *Refined Weighting of Parcels in the Edwards Aquifer Contributing Zone.* Presentation to EAPP CAB, February 24, 2017.

[73] In the wake of the Hurricane Harvey induced gas shortage in the Fall of 2017, and subsequent failure of public transit to fill commuters' needs, the *San Antonio Express-News* already broached the topic. An editorial stated, "(i)f Mayor Ron Nirenberg and a majority of the San Antonio City Council want to better fund transit—bus service, rail and more bike paths—they will have to wrestle with some hard choices. This could mean supporting a dedicated transit fee, or shifting sales tax dollars away from Edwards Aquifer protection or (and this is incredibly unlikely) Pre-K 4SA. Perhaps it's time to look at other ways to protect the aquifer from overdevelopment," *available at*: http://www.mysanantonio.com/opinion/editorials/article/Gas-shortage-reveals-VIA-s-flaws-12215996.php.

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Book review: The international law of transboundary groundwater resources

Eckstein, G. 2017. The international law of transboundary groundwater resources. New York City (New York): Routledge.
ISBN 9781138842984. 174 p.

Reviewed by Dr. Rosario Sanchez[1*]

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I once heard that water should not be considered a human right but a survival right. This simple statement can change the paradigm in which international law evolves toward the construction of an international groundwater legal framework, which today is nonexistent.

As Professor Gabriel Eckstein describes in his most recent contribution to the law of transboundary water — *The International Law of Transboundary Groundwater Resources*, "Groundwater resources have historically been both neglected under and often omitted from international agreements and legal norms and therefore cursorily misunderstood among the lay, political, and legal communities." As population increases at a rate higher than society's ability to fulfill water needs, drought conditions become more ordinary, and land use patterns favor development and economic gain over ecosystems preservation, the risks associated with lack of groundwater regulation becomes more clear and pressing. Regardless of the political boundary, groundwater tends to be presumed as a never-ending resource, mostly because of limited understanding of the hydrogeological complexity of an aquifer system. An additional barrier to public understanding is the lack of policies designed to protect and efficiently manage the "hidden treasure," as the author has referred to transboundary aquifers in the past. If we add the transboundary element to the discussion of managing groundwater, the result is a less-than-adequate attention to the topic, probably avoiding the fear of what lies beneath or acknowledging too much for a limited political appointee.

The law of transboundary groundwater resources – if there is any, as the author suggests — has not received proportional attention considering the level of dependency on groundwater resources for all uses and current or potential vulnerability of the overlying population, economic activities, and ecosystems. The compilation and analysis that this book achieved makes the book a required read for anyone interested in groundwater resources, as well as the role of groundwater in the international arena. It constitutes a textbook of the basics and interrelated topics and challenges that aquifers face as part of the hydrological cycle, in the context of the geopolitical boundaries that reign over the natural systems.

The author begins his writing offering a practical hydrological description of the physics of groundwater to set the stage of how groundwater moves and behaves underneath shared land, some implications of the present level of groundwater use, and current challenges from a global perspective. It then addresses the different models of transboundary aquifers that could potentially be subjects of international water law (currently limited to the 1997 UN Watercourse Convention), and those aquifers that fell outside the realm of the international legal context. Eckstein and Eckstein 2005 previously published these models in detail. The following sections focus on the development of the legal instruments that exist to address transboundary groundwater resources, early efforts since the middle of 1800s until the current stage of development of bilateral agreements (again limited to a couple), and evaluating the priority that the international arena has given to shared groundwater resources vis-à-vis surface water. The book analyzes in-depth the common principles and criteria that govern the UN Watercourse Convention that came into force in 2014 and its applicability to groundwater resources. It is worth mentioning that the United States, Mexico and Canada are not signatories to the convention; though it might be a source of international customary law, its enforceability is limited in this part of the continent.

The book's last two chapters constitute the most important contribution from the author. In these chapters, Eckstein discuss in-depth the current stage of groundwater and aquifers from an international law perspective, particularly the recent Draft Articles of the Law of Transboundary Aquifers. He covers this section from an interdisciplinary approach addressing the different aspects included in the discussion of shared groundwater resources: legal considerations, criteria and principles, governance and institutional challenges, and binational agreements. Eckstein brings a truly international perspective with a variety of examples that cover the global spectrum. He offers an in-depth analysis of the scope and potential long-term effectiveness of the law of transboundary aquifers, as well as limitations including the gaps and grey areas that have not been clearly defined. For example, the principle of "not to cause significant harm" has been commonly referred as one of the most contentious principle of the current stage of the law given its ambiguity and relativeness to the subject. The "threshold of significant harm" as the author refers to it, "has yet to be considered."

This book can easily be considered as the most important reference on the law of transboundary groundwater resources. The beauty of *The International Law of Transboundary Groundwater Resources* derives from its ability to present the complexity of the topic in plain and simple language for anyone interested in the topic without any specific expertise, bridging the science and policy perspectives into one book.

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Peak flow trends highlight emerging urban flooding hotspots in Texas

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Abstract: In the aftermath of flooding disasters, a temptation is to pursue recovery while also dismissing the event as unlikely to recur. Is it possible that underlying streamflow trends, which often avoid detection, help explain individual flooding episodes and should influence future expectations? How do impoundments (dams) affect these trends? Our study provides a comparative analysis to answer these key questions that help determine whether flood planning will be successful. Examining the 25 largest Texas metropolitan areas, we assessed peak flow trends for stream gages having at least 25 years of data. Of 181 total gages, 34 (18.8%) exhibited significant upward trends. Over 85% of those with upward trends are located in the Dallas-Fort Worth-Arlington (17.6%) and Houston-The Woodlands-Sugar Land (67.6%) areas. Approximately 62% of gages with upward trends are in Harris County. Among 84 sites impacted by impoundment, 11 (13.1%) still exhibited upward trends. These findings show that increasing peak flows underlie recent flooding in some areas, spotlighting streams in greatest need of examination. Increasing peak flows in some locations even after impoundment suggest dams might not be a complete solution. Finally, maintaining a robust monitoring network is critical to flood planning, and analysis is hampered when data are lacking.

Keywords: Flooding, peak flow, streamflow, impoundment, planning

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Terms used in this paper

Acronym	Descriptive name
USGS	U.S. Geological Survey

INTRODUCTION

When not bearing the load of extreme weather events, the rivers, creeks, bayous, and lakes in many portions of Texas are often viewed as valuable community amenities—and rightly so (Kulshreshtha and Gillies 1993; Wilson and Carpenter 1999; McKean et al. 2005). But these peaceful periods conditions belie a lengthy historical dark side. Texas has gained its reputation for flooding the hard way. The particular geographic and climatic setting of the state makes it vulnerable to some of the most intense precipitation events in the world, resulting in exceptional stream discharges and extensive landscape inundation (Slade, Jr. and Patton 2003; O'Connor and Costa 2004; Winters 2012; Breaker et al. 2016; Schumann et al. 2016). As a result, Texas leads the nation in flood damages and averages more flood-related deaths than any other state (Brody et al. 2008; Costa and Jarrett 2008; Sharif et al. 2015).

When the state's waters invade homes, schools, businesses, roads, and other critical infrastructure, a frequent quick response is a loud call to action to prevent similar impacts in the future. Even before the landfall of Hurricane Harvey in 2017, the Texas Legislature announced its interest in flood planning by releasing funds to the Texas Water Development Board in support of initial steps toward statewide coordination. Such flood planning, while requiring thoughtful interregional cooperation for any real chance at success, is inherently and operationally a local endeavor (Brody et al. 2008). Measures to moderate floods may have widespread benefits, but the most pronounced impacts, both positive and negative, typically are site-specific.

Similarly, the causes of flooding are location-specific, dependent upon a suite of local characteristics (Changnon et al. 2001; Douben 2006). By analyzing historical streamflow data, it may be possible to highlight emerging hotspots in greatest need of preventative action—but only after a thorough investigation of specific local causes. Streamflow trend analyses are common in Texas and neighboring states for a variety of water resources needs, often including questions of water supply and water quality (Esralew and Lewis 2010; Esralew et al. 2011). Such studies frequently focus on mean values or minimums to meet critical resource needs, but there is also tremendous value in examining maximums for the purpose of flood planning. Utilizing this approach allows us to compare different locations and supports resource prioritization for where the need is greatest.

In some Texas basins, particularly on major rivers, the construction of dams for various purposes has dramatically affected streamflows, from the creation and prolonging of flood-like hydrographs in areas upstream from such impoundments to large reductions in peak flows in others (Asquith 2001; Heitmuller and Greene 2009; Barbie et al. 2012; Lucena and Lee 2017). And while these impoundments can dramatically decrease peak flood magnitude downstream from their sites, dikes and levees often actually increase flood stage by reducing overall channel capacity (Pinter et al. 2001; Alexander et al. 2012). To develop a fuller understanding of statewide peak flow trends, it is important to account for the impact of impoundments on trends in peak flow.

As efforts proceed to analyze flooding impacts and make specific recommendations, two critical questions emerge: 1) to what degree should we consider flood events as chance occurrences as opposed to part of deeper, developing trends; and 2) given the perceived popularity of dams as a flood mitigation solution, what has been the impact on peak flows of such structures already in place?

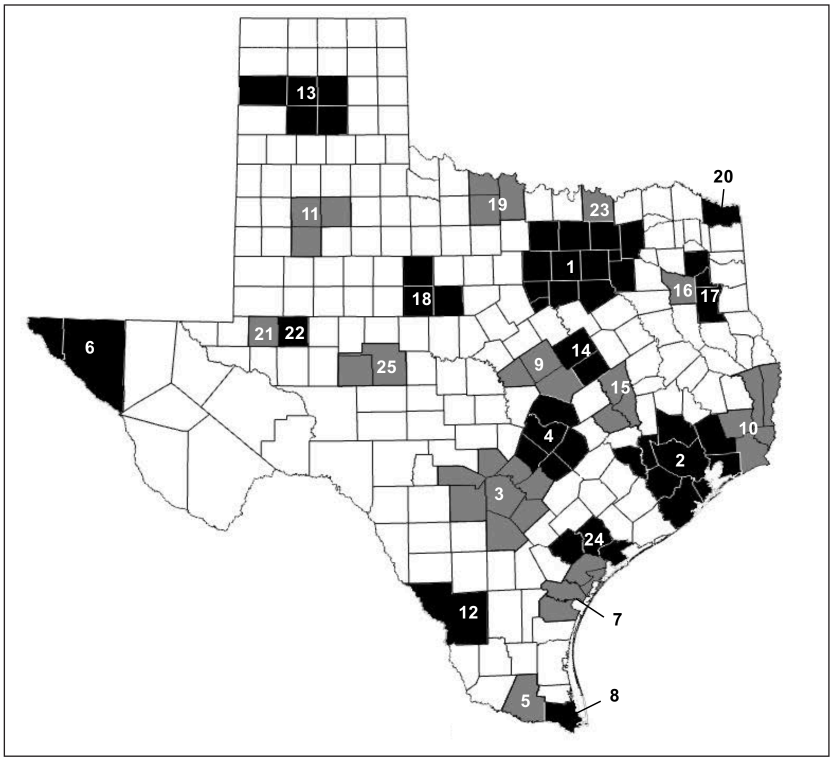

Figure 1. The 25 most-populated Texas metropolitan areas. Differences in color are simply used to distinguish the boundaries of adjacent metropolitan areas.

METHODS

To improve our understanding of the growing challenges posed by urban flooding in Texas, we conducted a detailed analysis of streamflow trends in major cities across the state (Figure 1 and Table 1). For each of the 25 most populous metropolitan areas in Texas (as designated by the 2010 United States Census), we identified the U.S. Geological Survey (USGS) stream gages located in the counties comprising these areas (https://nwis.waterdata.usgs.gov/nwis/peak?state_cd=tx). Within the designated metropolitan counties, we obtained streamflow data for each stream gage meeting the following

Table 1. The 25 largest Texas metropolitan areas (as designated by 2010 United States Census) used in this study. Metropolitan areas marked with an asterisk (*) did not include any qualifying stream gages.

1) Dallas-Fort Worth-Arlington	14) Waco
2) Houston-The Woodlands-Sugar Land	15) College Station-Bryan
3) San Antonio-New Braunfels	16) Tyler*
4) Austin-Round Rock-San Marcos	17) Longview
5) McAllen-Edinburg-Mission*	18) Abilene
6) El Paso*	19) Wichita Falls
7) Corpus Christi	20) Texarkana*
8) Brownsville-Harlingen*	21) Odessa*
9) Killeen-Temple-Fort Hood	22) Midland*
10) Beaumont-Port Arthur	23) Sherman-Denison
11) Lubbock*	24) Victoria
12) Laredo	25) San Angelo
13) Amarillo	

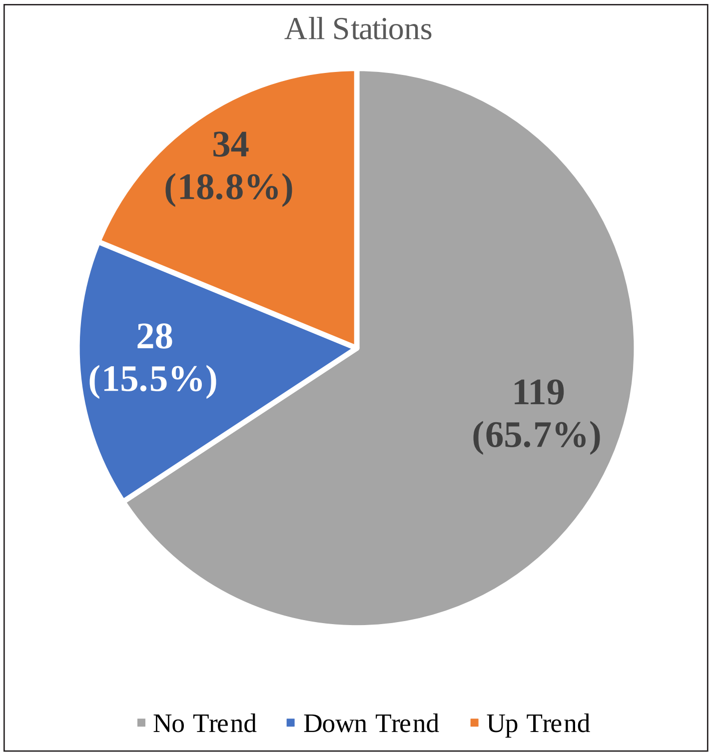

Figure 2. Proportion of examined stream gages from all metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow.

criteria: 1) period of record at least 25 years; 2) period of record extends until at least 2010; and 3) most recent 10 years of data represent 10 consecutive years. We then performed non-parametric Mann-Kendall trend analyses using the annual peak streamflow measurements for each qualifying stream gage. Two-tailed statistical tests were assessed for significance at $\alpha = 0.1$ (Lettenmaier et al. 1994; Berg et al. 2016). Streamflow data were used in favor of gage heights because these volume measures are considered to be absolute, more robust to changes in channel morphology and gage placement, and comparable between locations. We excluded historical data points outside the instrumental record due to the imprecise nature of their measurement and the problematic nature of including historical outliers in trend analysis.

For those stream gages that yielded a significant trend in Mann-Kendall analysis, we computed the best-fit regression equation for the period of record. Resulting regression equations were used to calculate relative changes in peak flows at each stream gage over the period of record.

A number of stream gages across the state, particularly those on large rivers, are impacted by impoundment. To account for these effects on historical streamflow trends, we conducted a parallel analysis of these gages, truncating datasets to the period during which each site has been considered to be affected by regulation or diversion (USGS Qualification Code 6 in stream gage metadata). We then proceeded with the same Mann-Kendall and regression analyses. At certain sites, the entire period of record is impacted by impoundment. In these cases, the entire period of record is included in both the overall analysis and the impoundment analysis.

In all analyses, we limited the data examined to the water year ending in 2016. This allowed us to both consider the most recent available full year of data and also exclude data associated with Hurricane Harvey. This decision was made to prevent the objection that upward trends are unduly influenced by catastrophic outlier events.

RESULTS

Of the 181 stream gages we identified, a majority (65.7%) displayed no trend in peak flows over the period of record. A total of 28 (15.5%) actually exhibited significant downward trends, while 34 (18.8%) exhibited significant upward trends (Figure 2). While all stations showed variability between years, many displayed clearly discernible patterns over time even before quantitative analysis (Figure 3). When considering the geographic distribution of stream gages, a few observations are immediately apparent (Figure 4). First, nearly all metropolitan areas are predominately characterized by stream gages exhibiting no trend in peak flows. In addition, nearly all areas host one

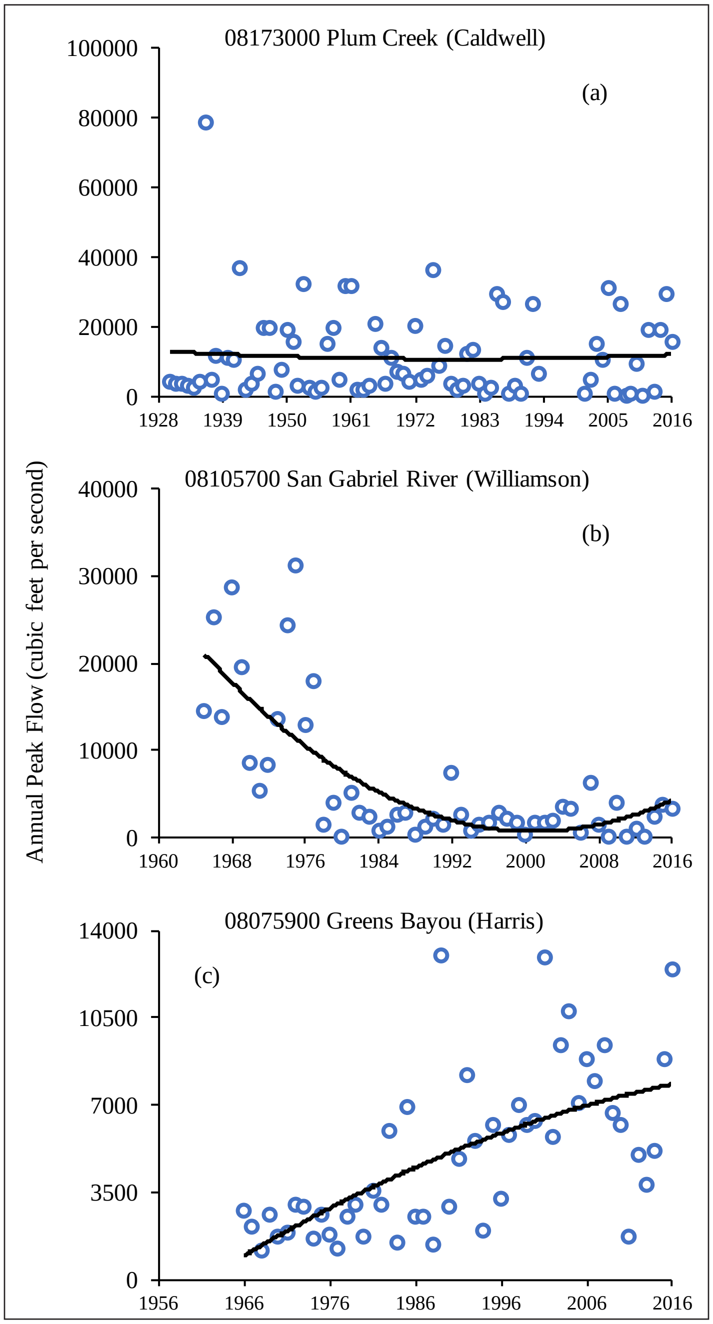

Figure 3. Examples of different peak flow patterns over time. No trend (a), downward trend (b), and upward trend (c).

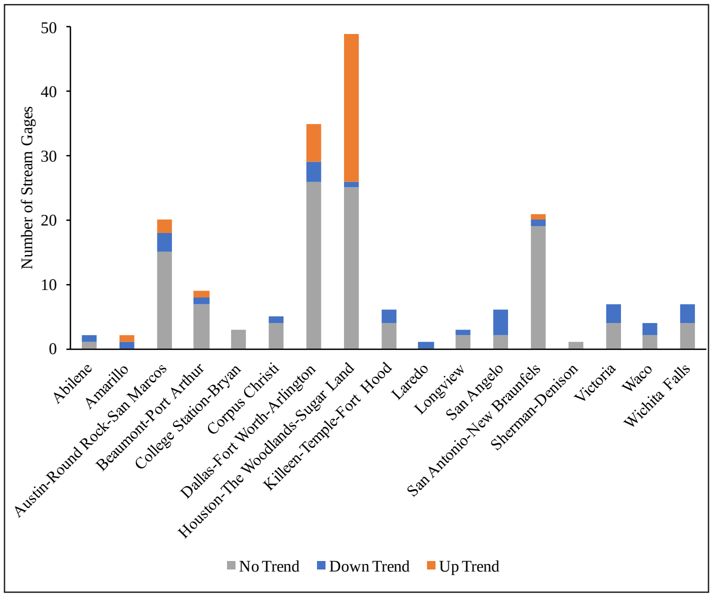

Figure 4. Number of examined stream gages exhibiting no statistically significant trends, downward trends, and upward trends in peak flow, separated by metropolitan area.

or two stream gages with streamflows that exhibit a downward trend. Finally, the geographic distribution of upward trends is illuminating, with such stream gages in a small number of metropolitan areas and nearly entirely concentrated in Dallas-Fort Worth-Arlington (6 gages) and Houston-The Woodlands-Sugar Land (23 gages). Approximately 85% of all stream gages with increasing peak flows are located in these two areas.

Examining the data at an additional level of geographic detail, the distribution of stream gages and those exhibiting trends is roughly equivalent across the counties of the Dallas-Fort Worth-Arlington area (Figure 5a). However, the number of stream gages in the Houston-The Woodlands-Sugar Land metropolitan area is dominated by Harris County, home to the City of Houston. In Harris County, an incredible 70% of stream gages exhibited upward trends (Figure 5b). Considering the data another way, Harris County represents 16.6% of urban stream gages across the entirety of Texas but a full 61.2% of gages with significantly increasing peak flows.

When including the length of the instrumental record and examining the relative change in peak flows over time, it is clear that tremendous variation exists between stream gage sites (Figure 6). Among gage locations with significantly increasing peak flows, current peak flows ranged from 102.3% of those at the beginning of the historical record to nearly 6400%—a whopping 64-fold increase. Taking into account the timing and magnitude of peak flow trends, the longest-running stream gages tend to be those with decreasing trends. These are sites on major rivers (e.g., Colorado, Brazos, Concho, and Neches rivers), and some of these today are characterized by peak flows that are essentially 0% of early historical peak flows. At the other end of the spectrum, those with the most rapidly rising peak flows tend to be found where stream gages have been installed more recently, in many cases within the last 50 years. Of note, it is interesting that 12 of 13 of the fastest rising peak flow trends are found in Harris County.

For those stream gages impacted by impoundment, the proportion of upward and downward trends is somewhat similar to that in the overall analysis. Of 84 affected locations, 22 (26.2%) exhibited significant trends, distributed equally between increasing and decreasing peak flow trends (Figure 7a).

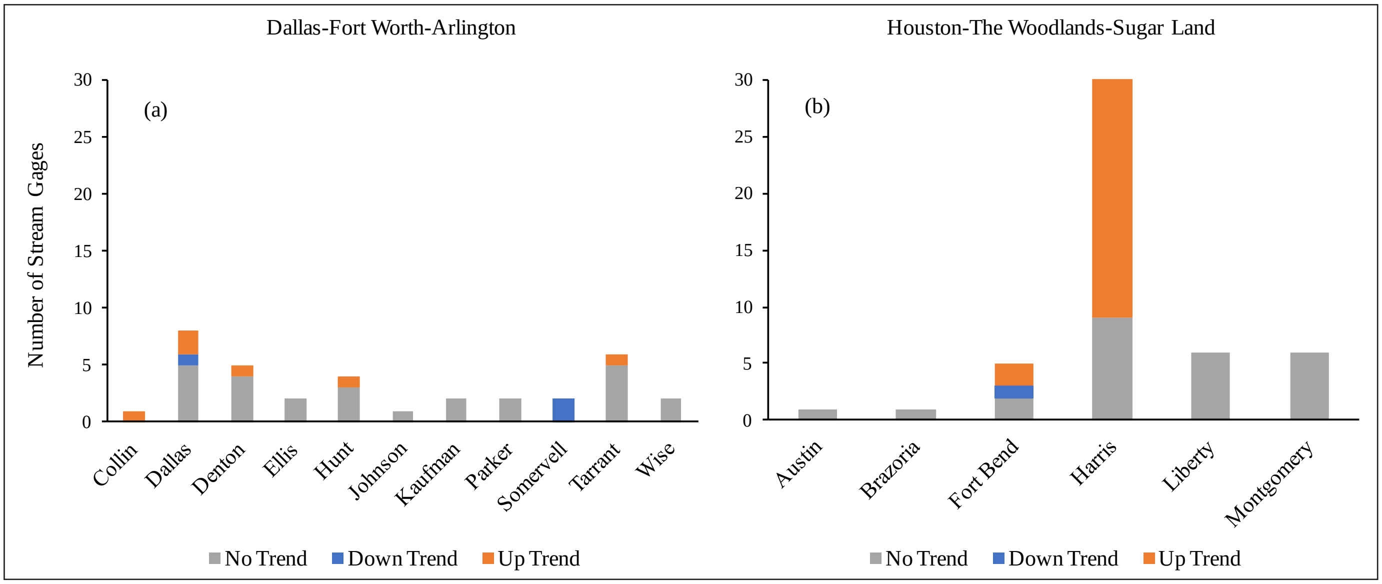

Figure 5. Number of examined stream gages in (a) Dallas-Fort Worth-Arlington and (b) Houston-The Woodlands-Sugar Land metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow, separated by county.

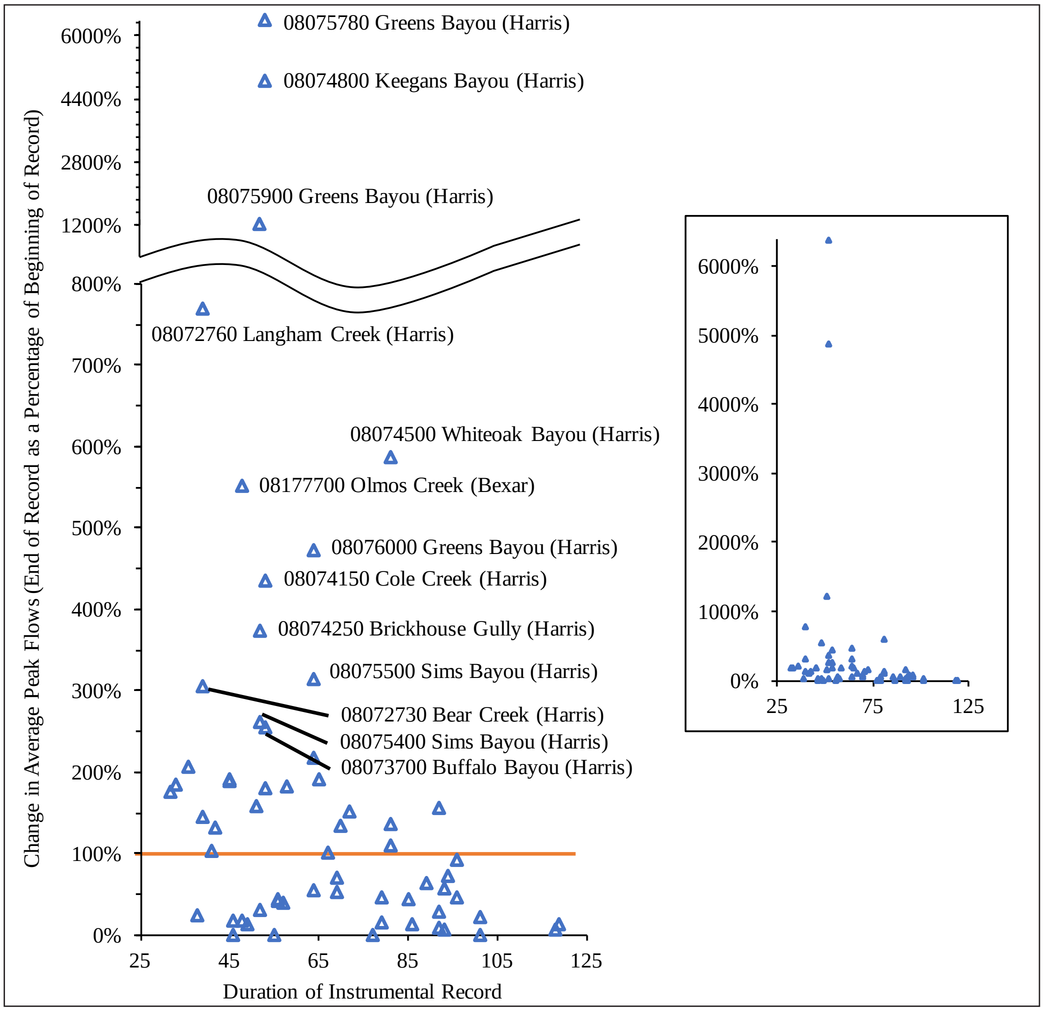

Figure 6. Relative change in peak flows (as a percentage of initial values) for those stream gages exhibiting significant trends over the period of record. The horizontal line at 100% separates increasing trends above and decreasing trends below. Inset at right displays the same data with an unbroken vertical axis and unmodified scale to visualize very high values.

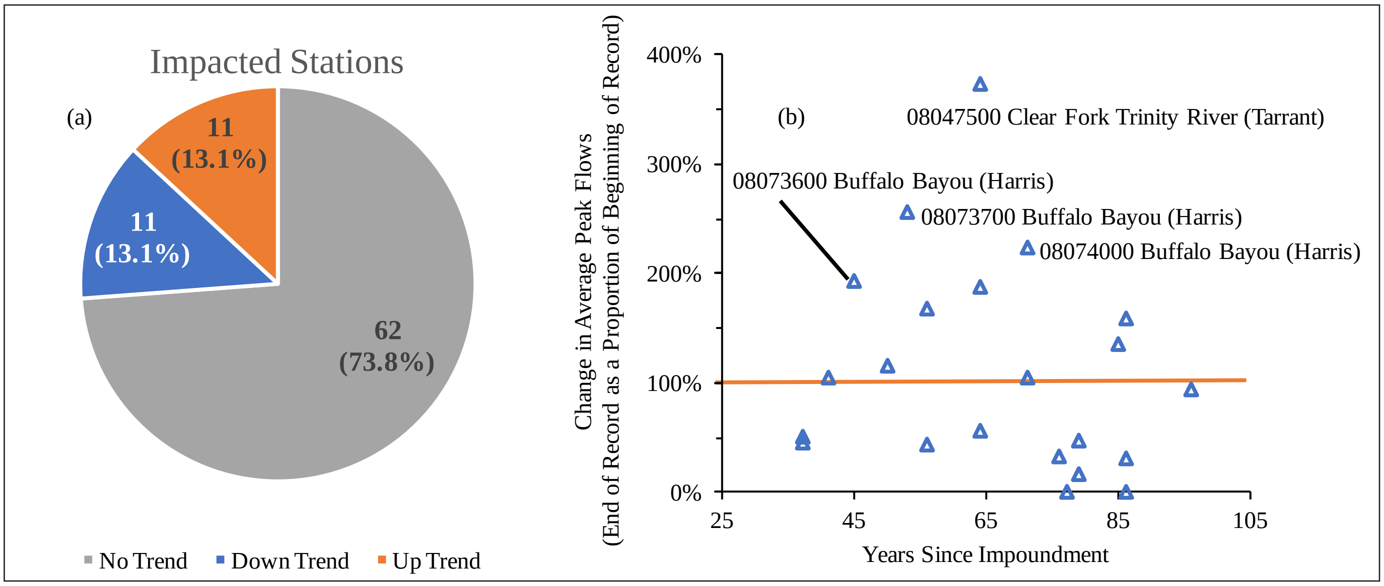

Figure 7. Summary data for stream gages impacted by impoundment in all metropolitan areas. Proportion of stream gages exhibiting no statistically significant trends, downward trends, and upward trends in peak flow (a). Relative change in peak flows (as a percentage of initial values) for those stream gages exhibiting significant trends over the period since impoundment (b). The horizontal line at 100% separates increasing trends above and decreasing trends below.

In contrast with trend magnitudes over time among all gages (Figure 6), the range of increases among this subset is much smaller, reaching a maximum of 372% (current peak flows compared with peak flows immediately following impoundment). Again, Harris County features prominently, with three different Buffalo Bayou stream gages experiencing some of the greatest increases in peak flows since upstream impoundment (Figure 7b).

DISCUSSION

Increasing peak flows

We found that, in most of the largest metropolitan areas across Texas, increasing trends in annual peak flows are rare and are actually outnumbered by decreasing trends. However, some trouble spots become clear. Nearly all of those urban streams with increasing peak flows are located in only two metropolitan areas, with the vast majority located within a single county (Harris) of one single region (Houston-The Woodlands-Sugar Land). All of these stations are within the Buffalo Bayou Basin. Identifying and comparing such emerging flooding hotspots must be a part of any statewide efforts to mitigate flooding impacts.

Of greatest importance, what do these results mean? Principally, we must understand that an upward trend in peak flows does not necessarily equate to flood frequency or severity. If a stream regularly fills only a small portion of its channel, then even a sizable increase may be manageable, with flood damage remaining minimal. However, if such increases are sustained over years (or decades) the margin between peak flows and flood impacts narrows—or worse. In many places, stream channel capacity changes over time, whether through natural processes or planned efforts to increase stormwater conveyance. However, unless such capacity increases occur along the entire length of a stream, increasing flows will eventually cause problems downstream where channel enlargement has not occurred.

Likewise, a lack of increasing trends does not indicate that floods do not occur nor even that they are not increasing. Increasing flood frequency or severity may still be possible even when mean peak flows themselves are not significantly increasing. Take, for example, the case of USGS gage 08158700 (Onion Creek at Driftwood in Hays County, Figure 8). At this location, the highest of peak flows do appear to exhibit an upward trend, while an increasing number of very low peak flows balances the highest peak flows, resulting in no overall increasing trend. Such apparent increasing variability poses significant challenges to development, management, and the environment (Ahn and Merwade 2014; Kelly et al. 2016).

With that established, identifying trends helps us see past individual flood events for a more comprehensive, deeper story. Only then can we begin to understand and ask bigger questions of the mechanisms behind stream dynamics in and near urban areas. This is an important component of successful planning and focuses on addressing root causes, not being lured into addressing symptoms. Just as steadily rising temperatures send us to a doctor to accurately diagnose the cause before prescribing a solution to the symptoms, steadily rising

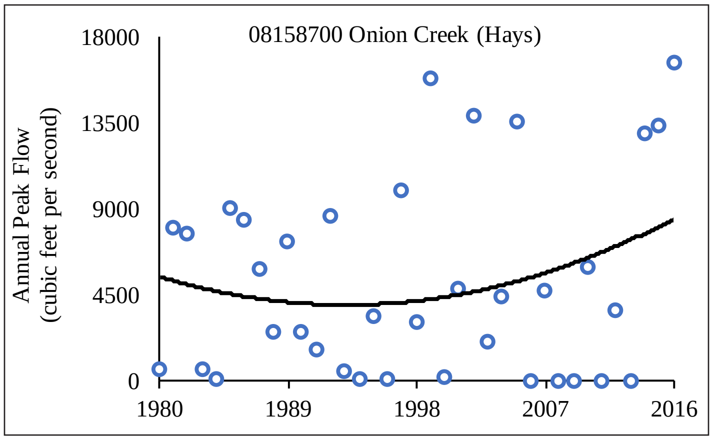

Figure 8. Peak flow history for stream gage 08158700 Onion Creek in Hays County (Austin-Round Rock-San Marcos metropolitan area). Though not exhibiting a statistically significant trend in peak flows overall, this site does reveal some interesting dynamics among very high and very low values.

peak flows should lead us to dedicate time, care, and detail in assessing flooding causes to ensure we pursue the right remedy. Anything short of this would miss an opportunity to provide adequate change, potentially with damaging consequences.

If a stream exhibits consistent increases in peak flows year after year, that raises eyebrows. If such trends are seen at a number of different locations in the same part of a single region of the state—all within the same small river basin—this should raise a series of key questions.

If that particular part of Texas (Harris County) is home to most of the increasing peak flows in the state, what might be driving these changes not seen elsewhere? Among Texas counties, Harris County by far is home to the greatest number of long-running USGS stream gages, yielding a comparatively large dataset for this study. In addition, the Harris County Flood Control District itself has an extremely robust rainfall and streamflow monitoring program (https://www.harriscountyfws.org/). That there is such a dense data collection network speaks to the long-perceived need to understand flooding in the region. Indeed, the area boasts a very large urban population and associated infrastructure, exhibits very low slopes, is typified by a climate prone to intense tropical downpours, and features a concentration of low-permeability soils. As a result, this region has experienced some of the most devastating historical floods in the state. All of these local traits point to an inherent vulnerability to high streamflows. However, the proportion of local stream gages with upward peak flow trends, not just the total number, is much larger than in any other urban area, so we must consider other factors.

Some of the large number of increasing trends in and immediately surrounding Houston are due to multiple gaging stations on certain streams (e.g., Greens Bayou and Buffalo Bayou, Figure 6), where individual gages reflect systematic and correlated changes along entire water bodies. Not coincidentally, these streams also have reputations as recurring trouble spots. However, that many streams in this area prone to flooding—each of which is a tributary of Buffalo Bayou—also display increasing trends in peak flows should draw major attention. Systematic increases suggest an underlying regional mechanism driving these changes. What could that be? Soils themselves do not evolve on annual timescales. There is some evidence that the frequency and intensity of downpours is increasing locally (Berg, in preparation). While slope changes do not occur at the watershed scale in human timescales, they might occur within streams themselves, particularly along segments where channel straightening has taken place. This process can serve to accelerate the removal of water from some locations but to deliver larger, faster flows downstream to points where the capacity to receive higher streamflows does not exist. Of note, already by the early 1980s, studies indicated an increase in storm runoff in highly developed parts of the Houston area compared with prior decades (Liscum and Massey 1980; Liscum et al. 1987). The exact response of local hydrology to urbanization varies among metropolitan areas, but this is consistent with findings in watersheds near Austin (Veenhuis and Gannett 1986) and with principles of urban hydrology (Niemczynowicz 1999; Brown et al. 2009; Fletcher et al. 2013).

To guide regional drainage design, more recent studies of the Houston area indicated a need to account for significant increases in peak streamflow as the degree of watershed development increases (Asquith et al. 2011). However, our findings indicate that these increasing peak flow trends have continued and even accelerated. Identifying the drivers in play in multiple specific locations is beyond the scope of this study. To further untangle the specific place-based drivers of increasing peak flow trends where they exist, we recommend a thorough clarification of local rainfall-runoff relationships, maintaining a very high level of spatial resolution and documenting changes with as much temporal resolution as possible.

Impoundment impacts

In the aftermath of severe flooding, a common response is to call for new dams and associated reservoirs to store floodwaters and reduce downstream impacts. This was a favorite approach among most of the state's large rivers, many of which were dammed relatively early in the state's history to address flooding and meet other needs. Our findings indicate that in some cases, this has paid major dividends in reducing peak flows. Those stream gages with the longest period of record (major rivers) typically have decreasing peak flow trends compared with historical levels (Figure 6). In a small number of cases, impoundment occurred even before stream gages were installed, obscuring the true impact of such streamflow regulation. As a result, the proportion of impounded streams with either downward or upward trends may actually be slightly higher.

With these observations, it would seem that reservoirs have a key place as part of a comprehensive flood control strategy. However, great caution is urged here. Impoundment has major economic, political, agricultural, and ecological drawbacks, sometimes extreme. If the goal is merely to reduce peak flows, then this can be effective, but with the tradeoffs of displaced landowners and communities, reduced recreation, curtailed fisheries productivity, decreased soil fertility for agriculture, and increased evaporative losses (García et al. 2011; Maestre-Valero et al. 2013; Veilleux 2013; Auerbach et al. 2014; Null et al. 2014; Stafford et al. 2017;). The decision to rely upon flood control reservoirs as a primary strategy must be made only after considering a large suite of priorities; priorities that are often in competition with one another. In considering these costs, many jurisdictions increasingly have decided to forego such projects (Poff and Hart 2002; O'Connor et al. 2015).

Even when implemented, impoundment does not guarantee permanently suppressed peak flows (Figure 7). Additionally, gaging stations impacted by impoundment actually exhibited a slightly lower frequency of downward trends in peak flows (13.1%) than did stations not impacted by impoundment (17.5%, Figure 9). While modern peak flows may no longer match historical pre-impoundment extremes, many sites impacted by impoundment yet exhibit significant increases in peak flows, in one case increasing to almost 400% of post-impoundment peak flows. In fact, as many sites exhibit increasing peak flow trends as do those exhibiting decreasing trends. And, logically, if streams are already impacted by upstream impoundments, the potential for further benefits from additional impoundment is limited. Of the 181 stream gaging stations examined in this study, 84 (46.4%) currently are affected by impoundment. Constructing flood storage reservoirs in remaining locations may prove extremely difficult, given that many of these locations are in highly developed, urbanized watersheds with limited open space.

A further caution on the reliance on dams for flood mitigation is the so-called levee effect. In many cases where engineered structures are installed, earthen or otherwise, damages behind these structures can actually increase (Tobin 1995; Burton and Cutter 2008; Di Baldassarre et al. 2015). Shifting expectations, loss of institutional memory of past events, and a perceived elimination of risk can result in catastrophic losses when upstream dams fail or are forced into emergency operations. One can see similarities with the events along Buffalo Bayou, which experienced severe and sustained flooding during and after Hurricane Harvey. Clear and aggressive communication of not just current risk but also past events can help prevent widespread underestimation of vulnerability. An increasing number of economic analyses is recognizing the value (if not complex difficulty) of accepting and adapting to the reality of periodic flooding in improving long-term viability of community development (Eakin and Appendini 2008; Merz et al. 2009; Brody and Highfield 2013). In short, reservoirs by themselves are not a silver bullet when it comes to flood mitigation.

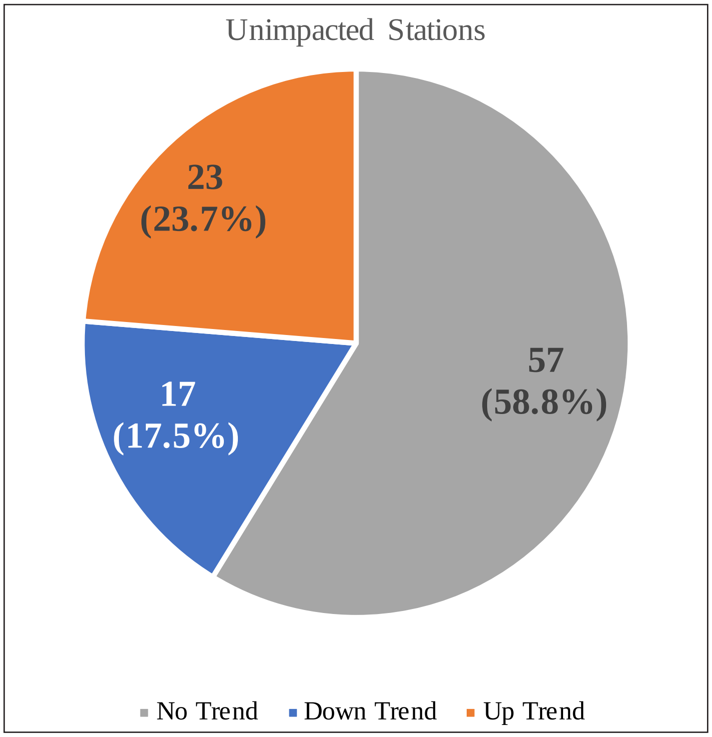

Figure 9. Proportion of examined stream gages not impacted by impoundment from all metropolitan areas exhibiting no statistically significant trends, downward trends, and upward trends in peak flow.

As an interesting last note on the impact of impoundment on peak flows, consider the difficulty of maintaining lower peak flows below a reservoir when the inflows to the reservoir exhibit extraordinary increases year over year. Of the largest upward trends in this study, two gages (on Langham Creek and on Bear Creek) are the major tributaries to Addicks Reservoir in Harris County. This flood control reservoir figured into severe flooding impacts both upstream and downstream of the critical U.S. Army Corps of Engineers dam adjacent to Buffalo Bayou. It is much easier for impoundments to store flood flows when these flows are not rapidly increasing on an annual basis. Thus, relying on large impoundment projects alone likely will not achieve success and again points back to our central emphasis of identifying causes, not just symptoms.

Challenges and needs

Peak flow frequency estimates can be computed with relative ease for natural, unregulated catchments in various areas of Texas, even those without stream gages (Heimann and Tortorelli 1988; Asquith and Slade, Jr. 1997; Asquith 1998; Asquith and Slade, Jr. 1999). At the same time, identifying baseline conditions for assessing streamflow trends can be a difficult task, especially when historical data are lacking (Tortorelli and McCabe 2001; Esralew 2010; Harwell and Asquith 2011). Furthermore, some such exercises yield single numbers that essentially assume a stationarity that, given our results, does not seem to be accurate (Sivapalan and Samuel 2009). In light of our findings, these challenges of uncertainty and watershed change generate complicated philosophical questions, such as: What does the concept of a 100-year floodplain even mean for a stream in which peak flows are 6400% of those just a couple decades ago? If peak flows in reservoir tributaries display strongly increasing trends, does it make sense to build a reservoir—within a reservoir?

Finally, we point to the eight of 25 largest metropolitan areas in Texas that have no long-term stream gaging stations, significantly hampering our ability to draw conclusions from these areas. We acknowledge that many complex variables go into decisions on stream gage placement (e.g., local population, exposure to economic impacts from floods, contributing drainage area, annual precipitation, precedent of historical events, funding availability), while also highlighting the irreplaceable value of long-term records. By focusing on urban areas in this study, we by no means intend to diminish the importance of flood damage of any degree to homes, schools, businesses, and the lives of individuals and families that do not happen to be located within metropolitan counties. Indeed, many of the costliest floods and many of the counties exposed to repeated floods are those outside designated metropolitan areas (Brody et al. 2008). In many instances, locations both within and outside of metropolitan areas are impacted by the same flood events and can provide advance notice of imminent threats to communities downstream. Metropolitan areas were simply chosen due to generally higher concentrations of population and property values in these areas, and, more importantly, the greater abundance of usable data. We applaud the recent steps by the USGS and Texas Water Development Board to expand the coverage of both stream and rain gages (AquaStrategies and Vieux 2016). As our analysis excluded a number of stations with long records that nevertheless ended years ago, we also emphasize the critical importance of not just adding new gages but maintaining existing gages in place for robust historical datasets. This will pay dividends for urban and rural communities alike.

That the trends described here are apparent even without the addition of data from Hurricane Harvey emphasizes our core message: that trends, not just events, matter. When data are incorporated from the water year that includes this tropical system, many of the increasing trends in this analysis become even more pronounced and some gages exhibiting no trends begin to exhibit significant upward trends as well.

CONCLUSIONS

A common response to severe flooding is to focus on individual events, isolated from temporal context and historical trends. Our findings suggest that this tendency is at best incomplete and a recipe for missed opportunities. We encourage decision makers to see past the events to the real trends and to resist the temptation to view floods—even the most catastrophic of disasters—as dismissible as one-off tragedies, unavoidable forces of nature, or acts of God, particularly when long-term trends paint a clear picture of increasing peak flows. Similarly, we further encourage flood planning efforts to look beyond the mere symptoms of flooding to consider and address the root causes of floods themselves. When significant increases in peak flows have been observed for many years, there is a deeper story that demands attention. Without this dedicated attention, flood mitigation planning efforts likely will not be successful. As solutions are developed, we also suggest against an overreliance on flood storage reservoirs. Finally, we urge the full maintaining of financial and technical support for streamgaging stations so that we can continue to build on the long-term records of historical sites, include additional sites as their periods of record increase, and position new sites where growing urban footprints may experience—or contribute to—flood impacts.

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Effects of the Rincon Bayou Pipeline on salinity in the upper Nueces Delta

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Abstract: A pipeline to pump water from the Nueces River to the upper delta at Rincon Bayou was constructed to mitigate the reduction of inflow from impoundments. Pumping has restored ecological function to the Nueces Estuary by increasing inflow and decreasing salinity, and transitioned the marsh into a positive estuary (lower salinities upstream increasing downstream towards the bay). Pumping has decreased the occurrences of salinities greater than 35 practical salinity units during drought conditions; however the current pumping regime causes a disturbed environment by creating extreme fluctuations in salinities in a very short time period. Immediately after pumping salinity fluctuations at the pumping outfall commence from hypersaline to fresh. When pumping ceases, salinity fluctuates from fresh to hypersaline until the next pumping event. Pumping often occurs during rainfall and flooding events when reservoir levels meet certain capacities that trigger pass-through requirements. This strategy provides inflow when it is not needed, and inhibits pumping during drought conditions when inflow is needed to maintain the quality of the estuarine ecosystem. While the current pumping regime has restored estuary conditions to Rincon Bayou by increasing inflow and decreasing salinity, it also causes extreme fluctuations in salinity that act as a disturbance. A lower magnitude, longer duration pumping strategy would create a more stable environment by providing freshwater continuously and would be an improved hydrological restoration strategy.

Keywords: freshwater inflow, freshwater management, pumped inflow, estuary, salinity, hydrology, restoration

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Terms used in paper

Short name or acronym	Descriptive name
BOR	U.S. Bureau of Reclamation
CBBEP	Coastal Bend Bays & Estuaries Program
CBI	Conrad Blucher Institute for Surveying and Science
cfs	cubic feet per second
m^3/s	cubic meters per second
NRA	Nueces River Authority
psu	practical salinity units
RBP	Rincon Bayou Pipeline
TCEQ	Texas Commission on Environmental Quality
TNRCC	Texas Natural Resource Conservation Commission
USGS	U.S. Geological Survey

INTRODUCTION

The amount of freshwater reaching the Nueces Estuary has been reduced by the construction of two dams in the Nueces River Basin: the Wesley E. Seale Dam (Lake Corpus Christi) on the Nueces River and the Choke Canyon Reservoir on the Frio River (tributary to the Nueces River) (HDR Engineering Inc. 2001). Irlbeck and Ward (2000) reported that the change in the annual mean flow into the Nueces Delta from the river during the period after the construction of the Wesley Seale Dam was decreased by about 39% (1958 to 1982), and that the change during the period after construction of Choke Canyon Dam was decreased by more than 99% (1982 to 1999) from that of historic flows (1940 to 1957) (BOR 2000). In response to this reduction of flows, the State of Texas issued an Agreed Order that required the City of Corpus Christi to provide not less than 185 million cubic meters (149,982 acre-feet) of water per year to the Nueces Estuary by a combination of releases (stored water that is let out) and spills (overflows) (Montagna et al. 2009). In April 1995, the Texas Natural Resource Conservation Commission—formerly Texas Water Commission, but now the Texas Commission on Environmental Quality (TCEQ)—issued an amendment to the Final Agreed Order reducing the amount required to be released per year. The amendment required inflows to be delivered in a monthly regimen to mimic natural hydrographic conditions in the Nueces Basin. Three other revisions also took effect: (1) the minimum mandatory inflows were changed to targeted monthly inflows, (2) the releases were changed to be based on the passage of reservoir inflows, known as "pass-through or (*sic*) Pass-Thru," rather than the release of previously stored water, and (3) drought relief was granted in the form of different pass-through requirements based on the reservoir level (TCEQ 1995). The concept of letting water pass-through is meant to mimic the natural inflows of nature while also taking into account area water demands. This is accomplished by placing constraints on pass-throughs that are based on a combination of reservoir elevation level, precipitation, and bay salinity (Spruill 2013). These constrains require the water to be released only when these conditions are met.

Rincon Bayou Demonstration Project

From the combined effects of reservoir construction, changes in land use patterns, increased groundwater withdrawals, and other human activities, the mean annual flow of freshwater diverted into the upper Nueces Delta has been reduced from that of historical flows (127,997 acre-feet (1940–1957) to 537 acre-feet (1983–1996)) (BOR 2000). In October 1995, the U.S. Bureau of Reclamation undertook the Rincon Bayou demonstration project to provide scientific information regarding the freshwater needs of the Nueces Delta and its response to changes in freshwater inflows. A diversion channel was excavated from the Nueces River to the headwaters of Rincon Bayou to increase the opportunity for more frequent and higher magnitude inflow events (BOR 2000). The diversion channel successfully increased the amount of freshwater diverted into the upper Nueces Delta returning a significant degree of ecological function to the Nueces Estuary ecosystems (BOR 2000; Montagna et al. 2009). The diversion channel was filled in after the completion of the demonstration project in 2000 as required in the initial contract (BOR 2000).

Rincon Bayou Pipeline

In 2001, the TCEQ, the City of Corpus Christi, the Nueces River Authority (NRA), and the City of Three Rivers adopted an Agreed Operating Order for the Lake Corpus Christi and Choke Canyon Reservoir System requiring the City of Corpus Christi to pass-through freshwater to the Nueces Estuary. The pass-through was based on seasonal requirements of estuarine organisms and inflows into the Reservoir System, up to a monthly target amount, if sufficient flows enter the reservoir (Lloyd et al. 2013; TNRCC 2001). To meet the Order's pass-through requirement, the City of Corpus Christi agreed to: (1) reconstruct the Nueces River Overflow Channel, a diversion channel dug during the demonstration project; (2) construct a pipeline (Rincon Bayou pump station and pipeline) to convey up to 3,000 acre-feet per month directly to the Nueces Delta; and (3) implement an ongoing monitoring and assessment program to facilitate adaptive management for freshwater flow into the Nueces Estuary (TNRCC 2001; Montagna et al. 2009; Lloyd et al. 2013; Hill et al. 2012).

In November 2007, the pipeline was completed from the San Patricio Municipal Water District, W. A. Edwards Pump Station location, northward along the Nueces River, and then eastward across U.S. Highway 77 to the headwaters of Rincon Bayou (Figure 1) (HDR Engineering, Inc. 1993). The pump

Figure 1. Map of station locations for measuring flow, salinity, and rainfall in Rincon Bayou. Stations C, F, G, and 467 are historical locations sampled by Montagna. Image source (USDA-NRCS 2006).

Table 1. Hydrology data obtained from the listed sources for the date range specified on 11 January 2016.

Name	Hydrological parameter	Recorded interval	Date range	Agency	Website
Rincon Bayou Pipeline (RBP)	Pumped inflow	Daily total (acre-feet/day)	Sept. 2009–Dec. 2015	Nueces River Authority (NRA)	http://www.nueces–ra.org/CP/CITY/rincon/
USGS 08211503 Rincon Bayou Channel Gage	Natural inflow and discharge	Mean daily rate (f^3/sec)	Sept. 2009–Dec. 2015	United States Geological Survey (USGS)	http://nwis.waterdata.usgs.gov
CBI 042-NUDE2 CBI 074-SALT03	Salinity	Every 15 minutes (psu)	May 2009–Dec. 2015	Conrad Blucher Institute for Surveying and Science (CBI)	http://cbi.tamucc.edu/datums/042 http://cbi.tamucc.edu/datums/074
CBI 069-NUDEWX	Computed cumulative rainfall	Daily total at midnight (cm)	Jan. 2014–Dec. 2015		http://cbi.tamucc.edu/datums/069

station consists of three pumps, which are capable of moving up to 3.8 cubic meters per second (m^3/s) (134 cubic feet per second (cfs)) when all pumps are in operation (Lloyd et al. 2013; Hill et al. 2012).

During flooding events, water would flow over the Calallen Saltwater Barrier Dam into the upper marsh supplying the estuarine ecosystem with freshwater. In 2009, the pipeline and pumping station began pumping freshwater from the Calallen Pool into the Nueces Delta at the Rincon Bayou headwaters so that inflow would no longer rely on overflowing of the Calallen Saltwater Barrier Dam (Figure 1). Pumping events typically occur when salinities in the Nueces Delta are greater than 30 practical salinity units (psu) and when reservoir levels and rainfall events allow for pass-through conditions (Lloyd et al. 2013). The purpose of this study was to determine the effects of the Rincon Bayou Pipeline on the salinity of the upper Nueces Delta.

STUDY SITE

The Nueces River Basin is one of the 15 major river basins in Texas and is an important water supply for the Nueces-Rio Grande Coastal Basin area. The Nueces Estuary is contained within the Nueces River Basin and is supplied with inflow from the Nueces River that flows into the Nueces Bay in the Gulf of Mexico near Corpus Christi. The Nueces River provides freshwater to the City of Corpus Christi and the surrounding Coastal Bend area. The Calallen Pool (Saltwater Barrier Dam) (Figure 1) is located adjacent to Interstate 37 and was constructed in 1898 to restrict saltwater intrusion to the upstream non-tidal segment of the Nueces River (Montagna et al. 2009).

The main stem channel of the Nueces Delta marsh is located at Rincon Bayou, a creek connecting the tidal segment of the Nueces River to the delta (Figure 1). Rincon Bayou was the historic location of river inundation events in the northeastern portion of the upper Nueces Delta following seasonal rainfall events farther inland along the Nueces River. This provided nutrients and enough freshwater to reduce salinity in the estuarine system (Montagna et al. 2015).

METHODS

Hydrographic measurements were taken with an YSI 6600 multi-parameter sonde at Station C and Station G. Station C is located at 27.89878 °N latitude and 97.60417 °W longitude (Figure 1). Salinity observations were collected every 15 minutes for a duration of two weeks at a time from January 2014 through December 2015. Salinity was automatically corrected to 25 °C. Long-term salinity data was collected at Station G located at 27.88992 °N latitude and 97.56910 °W longitude (Figure 1). Salinity observations were collected on a quarterly and monthly basis. Stations C and G are historic stations and previously named 466C and 463G respectively.

Hydrology data were downloaded from the corresponding websites listed in Table 1 as follows: Natural inflow and discharge data were collected at the U.S. Geological Survey (USGS) Rincon Bayou Channel Gage No. 08211503 located at 27.896667 °N latitude and 97.625278 °W longitude; salinity data were collected at Nueces Delta 2 (CBI 042-NUDE2) located at 27.8888 °N latitude and 97.5696 °W longitude and CBI 074-SALT03 located at 27.85155 °N latitude and 97.48203 °W longitude; and rainfall data were collected at the

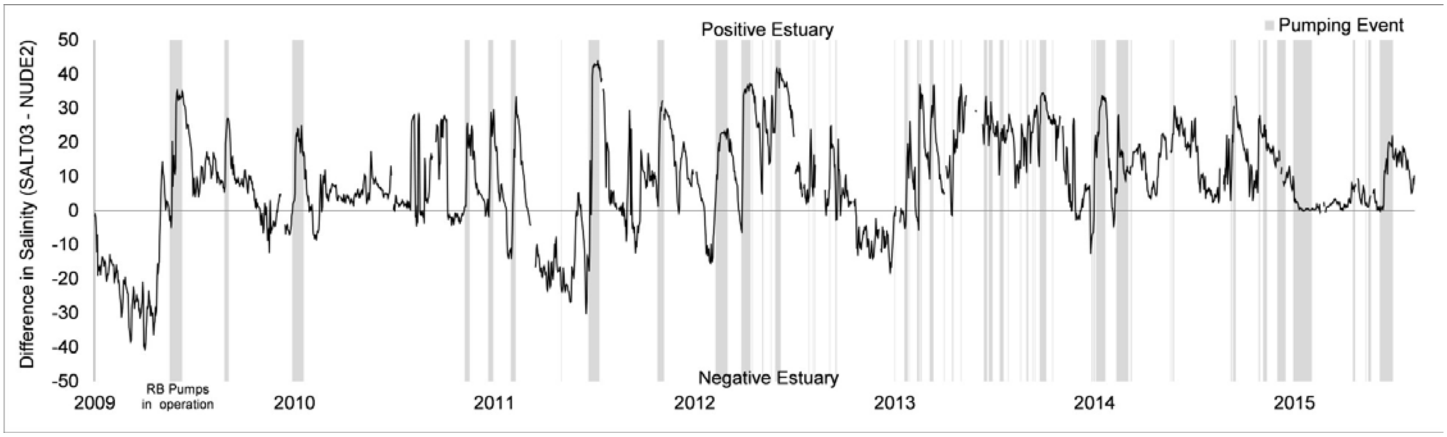

Figure 2. Salinity gradient for the Nueces Estuary (i.e., difference between downstream SALT03 and upstream NUDE2) and pumping event daily totals May 2009 to December 2015. The Rincon Bayou Pipeline became operational in September 2009 (Appendix 1). The width of the bar indicates pumping event duration.

Nueces Delta Weather Station (CBI 069-NUDEWX) located at 27.8975 °N latitude and 97.616389 °W longitude (Figure 1).

Data analysis

Data manipulation, calculations, and statistical analyses were performed using SAS 9.3 software (SAS Institute Inc. 2013). The salinity gradient was determined for Rincon Bayou by subtracting the upstream salinity (NUDE2) from the downstream salinity (SALT03). It was determined to be in a negative estuary condition when the difference was negative, i.e. the salinity at SALT03 was less than the salinity at NUDE2, and in a positive estuary condition when the difference was positive, i.e., the salinity at SALT03 was greater than the salinity at NUDE2.

Pumped inflow and gaged inflow were converted to m^3/s. Pumped inflow data were assigned pumping event numbers based on breaks in the pumping duration. The number of days of inflow and the total pumped inflow rate per pumping event number was calculated. Total inflow rate into Rincon Bayou was calculated per day by summing the pumped inflow rate and the inflow rate at the USGS Gage.

Percent occurrence is defined as how often the event has occurred in a time period. Percent occurrences were derived from histogram frequencies and converted to percent for the salinity range at NUDE2, for natural inflow (USGS Gage), and for the long-term salinity range at Station G.

Percent exceedance was calculated for natural inflow (USGS Gage), pumped inflow (RBP), and total inflow (USGS Gaged inflow + RBP). Inflows were ranked from highest to lowest. The exceedance probability (P) was calculated as:

$$P = 100 * [M / (n + 1)]$$

Where P is the probability that a given flow will be equaled or exceeded (% of time), M is the ranked position of the flow amount, and n is the number of flow events from September 2009 to December 2015.

Drought conditions data were obtained from the U.S. Drought Monitor (USDM 2017) from October 2001 to December 2015 for Lower Nueces watershed and the Texas-Gulf watershed. The Lower Nueces watershed contains the data for the following counties: Nueces, Live Oak, Bee, Duval, Jim Wells, Karnes, San Patricio, and McMullen (EPA 2017). D0 through D4 describes the drought severity classification using five key indicators (Appendix 3), drought impacts, and local reports from more than 350 expert observers around the country (USDM 2017). Drought conditions were reported as percent area of the watershed in moderate drought and above (D1-D4) and maximum monthly percent area was plotted with the monthly mean salinities at Station G. Missing salinity values were extrapolated.

RESULTS

The salinity gradient from the upper delta extending to the Nueces Bay defines whether Rincon Bayou has either positive or negative estuarine conditions. An increasing salinity gradient results in a positive estuarine condition with lower salinities upstream; a decreasing salinity gradient results in a negative estuarine condition with higher salinities upstream. The Nueces Estuary can shift between positive and negative estuarine conditions depending on the volumes of inflow and precipitation. In the five-month period prior to the Rincon Bayou Pipeline becoming operational in September of 2009, the Nueces Estuary was negative (Figure 2) with a mean daily salinity upstream at NUDE2 being higher than the mean daily salinity downstream in the Nueces Bay at SALT03. The Nueces Estuary oscillates between positive and negative conditions with pump-

Table 2. Daily means for USGS Rincon Bayou (Channel) Gage, CBI salinity stations (SALT03, NUDE2) and weather station (NUDEWX), Station C, and the Rincon Bayou Pipeline (September 2009 to December 2015). Note: 1 m^3/s = 35.31 cfs.

Sampling location	Unit	Number of observations	Mean	Std. dev.	Min. mean	Max. mean
USGS Rincon Channel Gage	m^3/s	2311	-0.02	0.32	-2.72	4.93
Rincon Bayou Pipeline (RBP)	m^3/s	457	1.71	0.97	0.03	5.04
Total inflow (Gage + RBP)	m^3/s	2311	0.31	0.79	-1.70	6.48
NUDEWX	cm	2182	1.92	7.78	0.00	142.00
SALT03	psu	2413	31.65	9.96	0.36	47.28
NUDE2	psu	2301	23.22	18.17	0.00	86.29
Station C	psu	734	6.77	6.65	0.01	34.41

Std, dev., standard deviation; Min., minimum; Max., maximum; cm, cubic meter

ing events (Figure 2). Pumping events coincided with periods of positive estuary conditions with salinities at NUDE2 rapidly decreasing when pumping begins and gradually increasing when pumping ceases. The mean pumped inflow per pumping event was 12 m^3/s with a maximum pumping rate of 126.86 m^3/s and a minimum pumping rate of 0.11 m^3/s (Appendix 1). With pumping, the mean daily salinity at NUDE2 was 23.22 psu with a maximum daily mean salinity of 86.29 psu and a minimum daily mean salinity of 0 psu (Table 2). NUDE2 salinity data began in May of 2009. Rincon Bayou has transitioned from a negative hypersaline estuary to a positive mesohaline estuary with lower salinity ranges occurring most often since pumping began (Figures 3a, 3b). Seasonal differences were accounted for by comparing salinity ranges that occurred monthly from May to September prior to pumping (2009) and after pumping began (2010–2015) (Figure 3b). Data was not available prior to May of 2009, so the other seasons were not included in the analysis. Figure 3b shows lower salinities occurring most often in the summer with pumping and higher salinities occurring most often in the summer prior to pumping.

Salinity at Station C (Figure 4) declined after each pumping event and gradually increased until the next pumped inflow with a mean daily salinity of 6.77 psu, a maximum daily mean salinity of 34.41 psu, and a minimum daily mean salinity of 0.01 psu (Table 2). The decreased gaged reading is caused by the back-flow preventer that was installed in July 2014. The increased gaged reading in July 2015 is caused by the back-flow preventer becoming inoperable. The back-flow preventer kept inflows from going both upstream into the Nueces River and downstream into Rincon Bayou.

Pumping events, rainfall, and salinity were plotted for a 2-year period (2014–2016) (Figures 5 and 6). Decreases in salinity that occurred when pumping was not occurring was likely due to rainfall (Figure 5). The magnitude and duration of Pumping events coincided with the amount of rainfall and typically occurred after or during rainfall periods (Figure 6). The mean pumped inflow was 1.71 m^3/s (60.4 cfs) with a maximum of 5.04 m^3/s (178 cfs) and a minimum pumped amount of 0.03 m^3/s (1 cfs) (Table 2).

The primary source of inflow into Rincon Bayou was from pumped inflow (Figures 7 and 8). The USGS Gage records downstream flows into Rincon Bayou as positive values and inflows back upstream into the Nueces River as negative values (Figure 7). The absence of a distinct elevation gradient in Rincon Bayou at the pumping (RBP) outfall area (Figure 1) allows pumped inflow to flow both upstream and downstream resulting in both positive inflow and negative discharge readings at the USGS Gage (Figures 4 and 7). A back-flow preventer was in place from July 2014 to July 2015, which restricted inflow and discharge at the USGS Gage (Figures 4 and 7).

A flow duration curve illustrates the percentage of time a given flow was equaled or exceeded during a specified period. From January 2009 through December 2015, positive inflow into Rincon Bayou was equaled or exceeded 40% of the time with pumped inflow accounting for most of the inflow into Rincon Bayou (Figure 8). Natural inflows into Rincon Bayou have been reduced by river impoundment to low-flow or drought-flow, with events over 5 m^3/s being equaled or exceeded < 1% of the time. Freshwater pumped into Rincon Bayou accounted for most of the high or medium flow events. The mean inflow volume from pumping was 1.71 m^3/s (60.4 cfs) with a maximum total inflow rate (pumping and Rincon gaged discharge) of 6.48 m^3/s (229 cfs) (Table 2). The percent of time that inflow from the Rincon Bayou diversion channel was

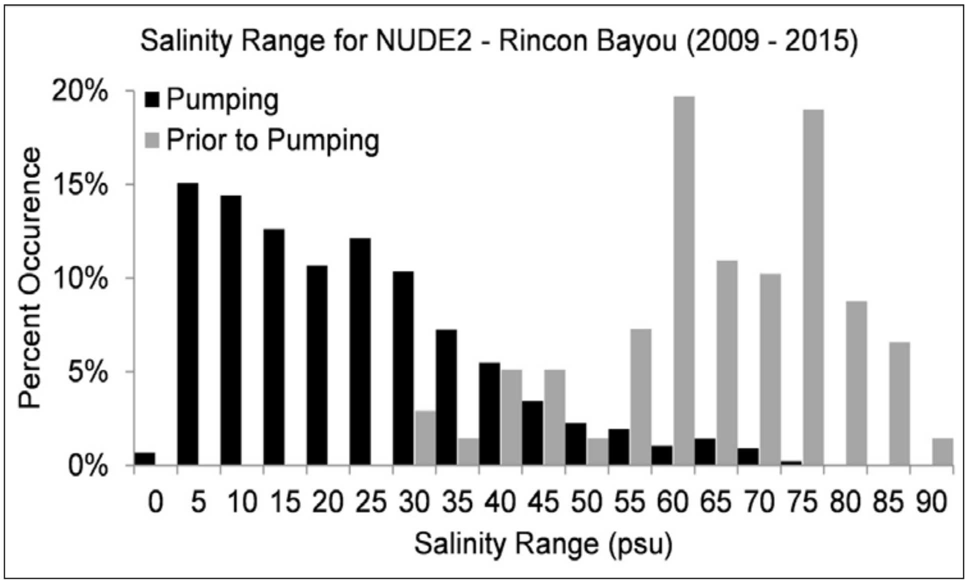

Figure 3a. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) prior to pumping (14 May 2009 to 28 September 2009) and with pumping (28 September 2009 to 31 December 2015).

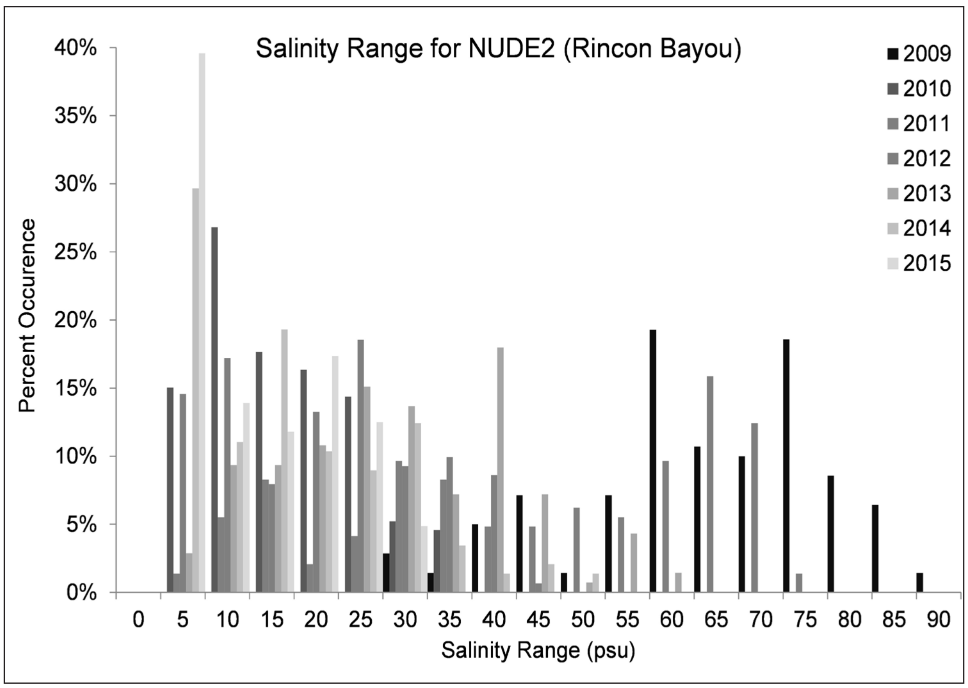

Figure 3b. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) prior to pumping May through September (2009) and with pumping from May through September (2010 to 2015).

greater than 0.2 m^3/s (7.1 cfs) was less than 10% of the time with an inflow rate between 0 and 0.1 m^3/s (3.5 cfs) occurring most often (Figure 9). The mean of daily inflow rate at the USGS Gage was -0.02 m^3/s (0.7 cfs) with a maximum daily mean discharge rate of 4.93 m^3/s (174 cfs) and a minimum daily mean rate of -2.72 m^3/s (96.8 cfs).

Drought is defined as a moisture deficit bad enough to have social, environmental, or economic effects (USDM 2017). Long duration drought conditions existed in the Lower Nueces watershed from June 2005 to September 2006, January 2008 to February 2010, and April 2011 to November 2014. The long-term salinity data for Rincon Bayou from October 2001

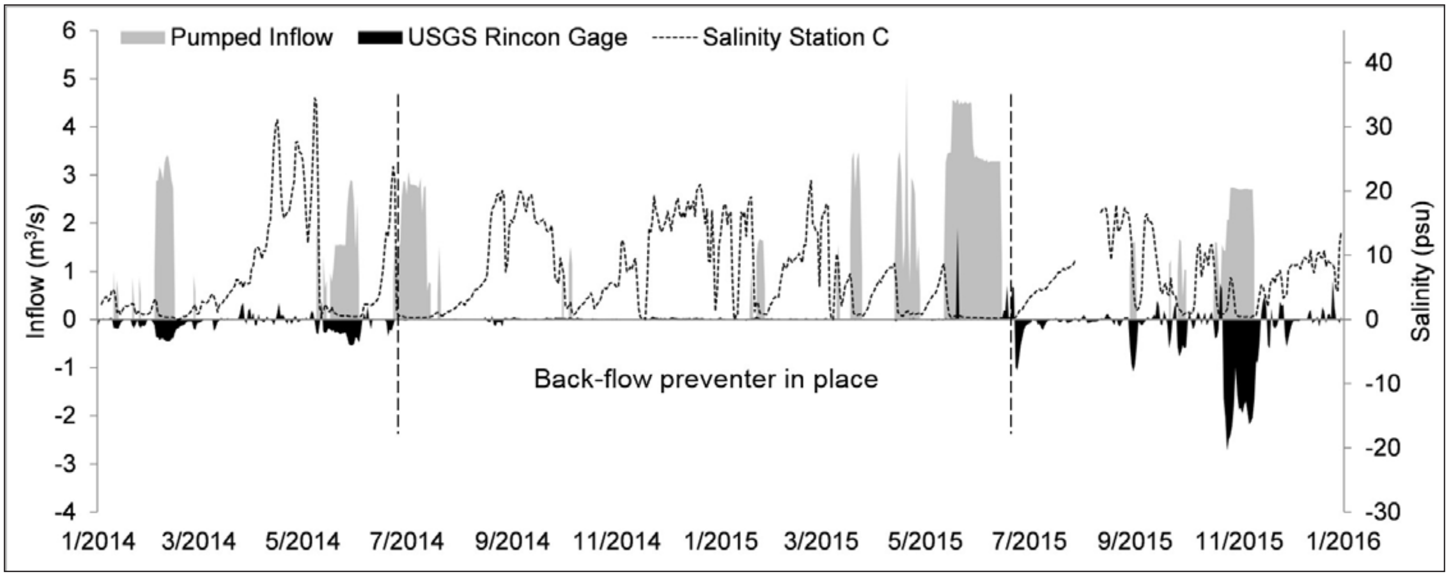

Figure 4. Salinity at Station C in Rincon Bayou, with inflow and discharge from the USGS Rincon Bayou (Channel) Gage and pumped inflow, January 2014 to December 2015.

to December 2015 shows that monthly mean salinities exceeded 35 psu in: April, June, and July of 2006; June of 2008; February, March, May, June, and July of 2009; and March and April of 2013 (Figure 10). Salinities greater than 35 psu in Rincon Bayou only occurred when drought conditions existed in the Lower Nueces watershed (Figure 11a). Percent occurrence of salinities greater than or equal to 35 psu in drought conditions has decreased from 40% (prior to pumping) to 12% (with pumping) (Figures 11b, 11c).

DISCUSSION

The downstream salinity values at SALT03 and upstream salinity values at NUDE2 were used to describe the estuary condition as positive or negative. The Nueces Estuary fluctuates between positive and negative conditions based on inflow and drought conditions, with pumped inflow decreasing the occurrence of salinities greater than 35 psu. Pumped inflow

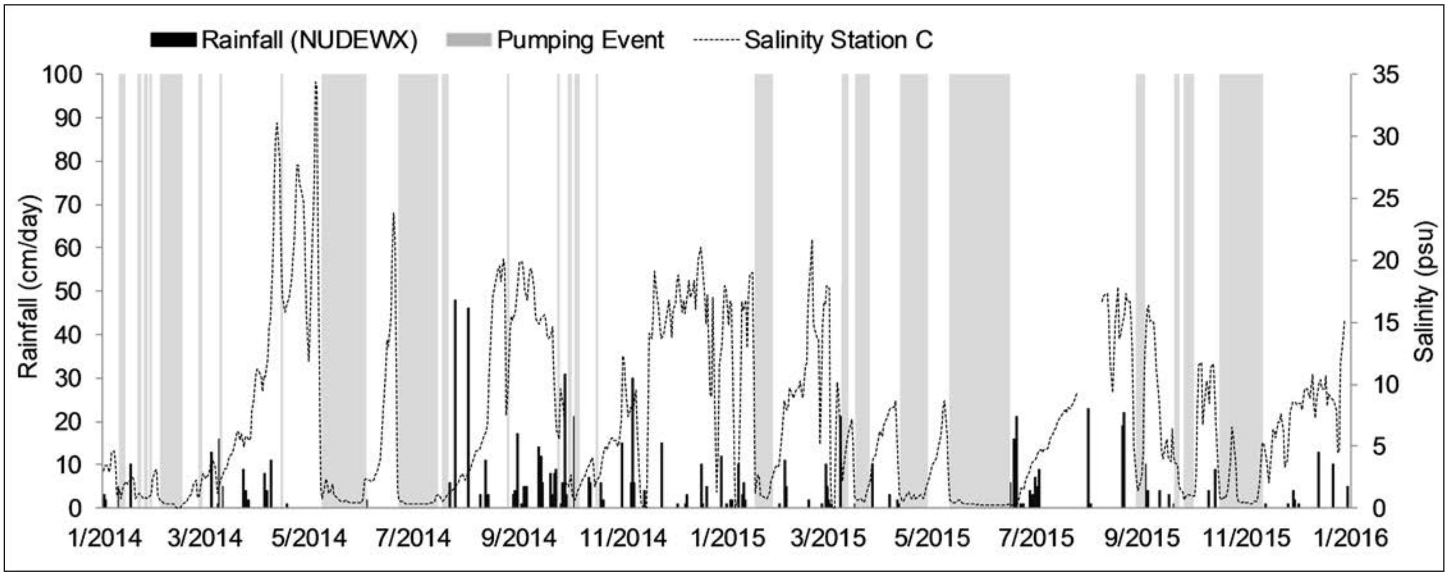

Figure 5. Salinity at Station C in Rincon Bayou, with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015.

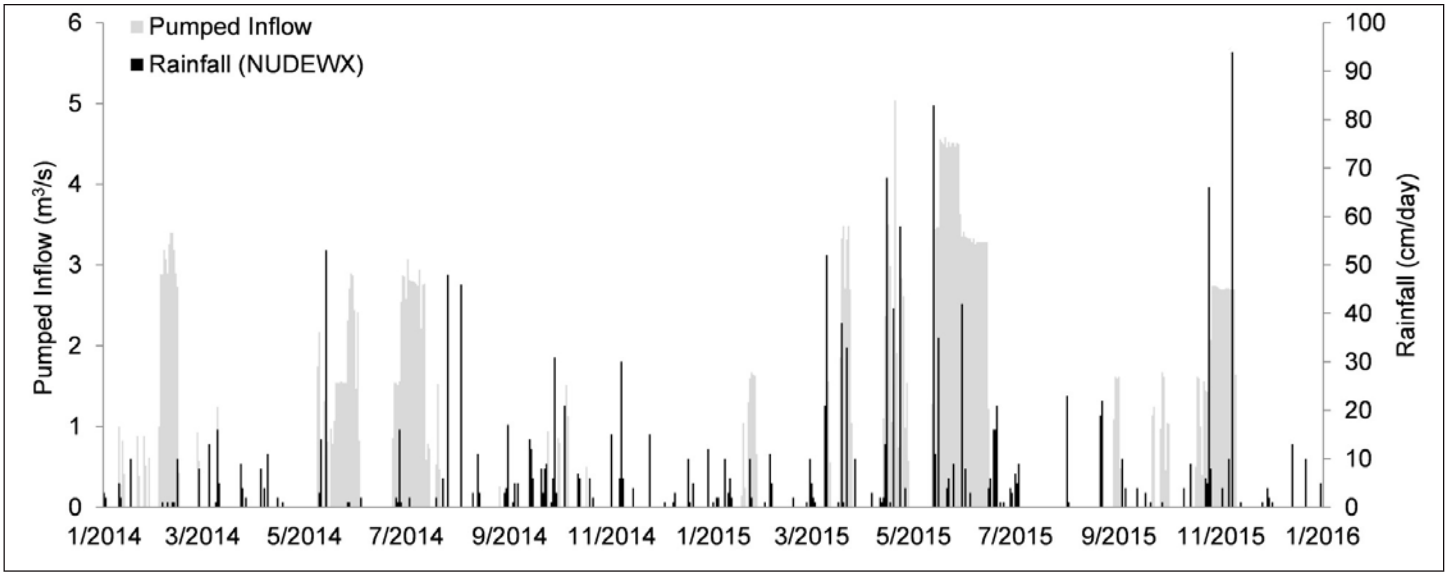

Figure 6. Pumped inflow into Rincon Bayou with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015. The width of the bar for pumping event indicates duration.

is the primary source of freshwater inflow into Rincon Bayou and has transitioned the ecosystem into a positive estuary, but this dependence can lead to reverse estuary conditions (salinity can fluctuate from fresh to hypersaline and hypersaline to fresh in very short time periods) when pumping is not occurring or occurs for short periods. Pumping has also created a distributed environment with the extreme fluctuations in salinity. The salinity tends to decrease immediately when the pumps are turned on and remain low until the pumps are turned off. The salinity will then steadily increase in Rincon Bayou, taking about 20 days to reach within 5 psu of salinity in Nueces Bay (Adams and Tunnell 2010; Tunnell and Lloyd 2011), until the pumps are turned back on. This cycle continues as the pumps are turned on and off.

A lack of an elevation gradient allows inflows to flow naturally both upstream, to the Nueces River, and downstream, to Rincon Bayou. Adams and Tunnell (2010) found that approximately 20% of pumped inflow goes upstream rather than downstream into Rincon Bayou. A weir was constructed at the pumping outfall in May 2010 to reduce the amount of pumped inflow going upstream (2016 interview with R. Kalke; unreferenced, see “Acknowledgments”). It was replaced in July

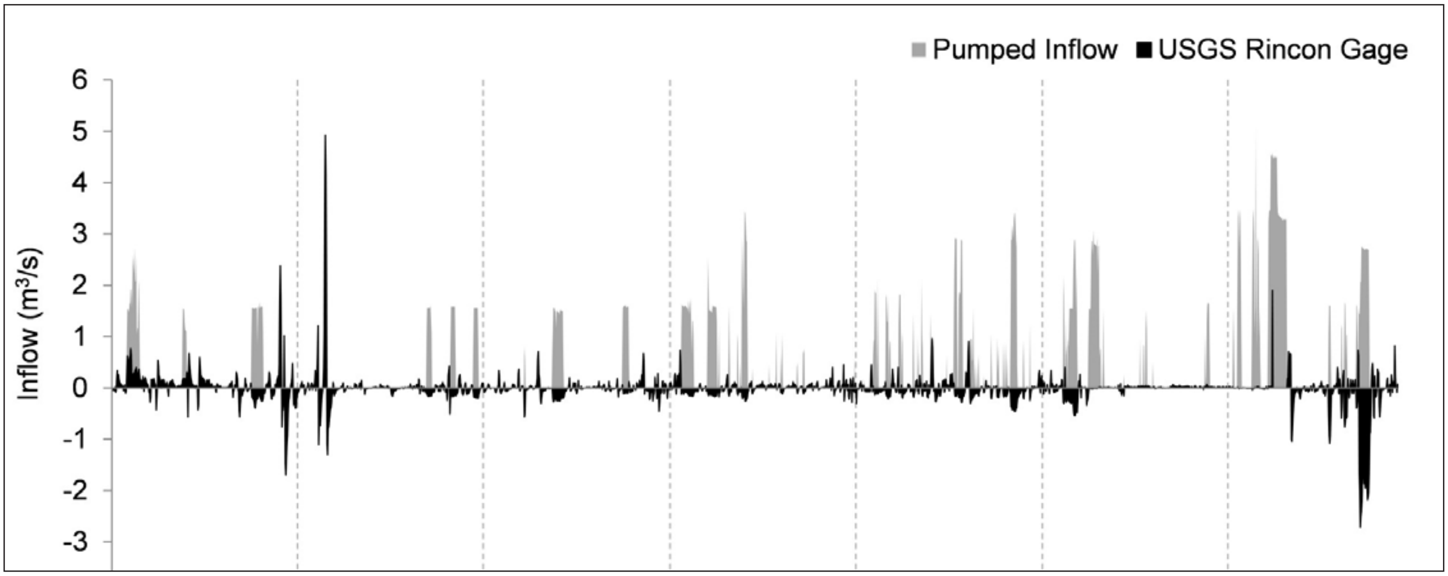

Figure 7. Inflow (+) and discharge (-) at the USGS Rincon Bayou (Channel) Gage, and pumped inflow, September 2009 to December 2015.

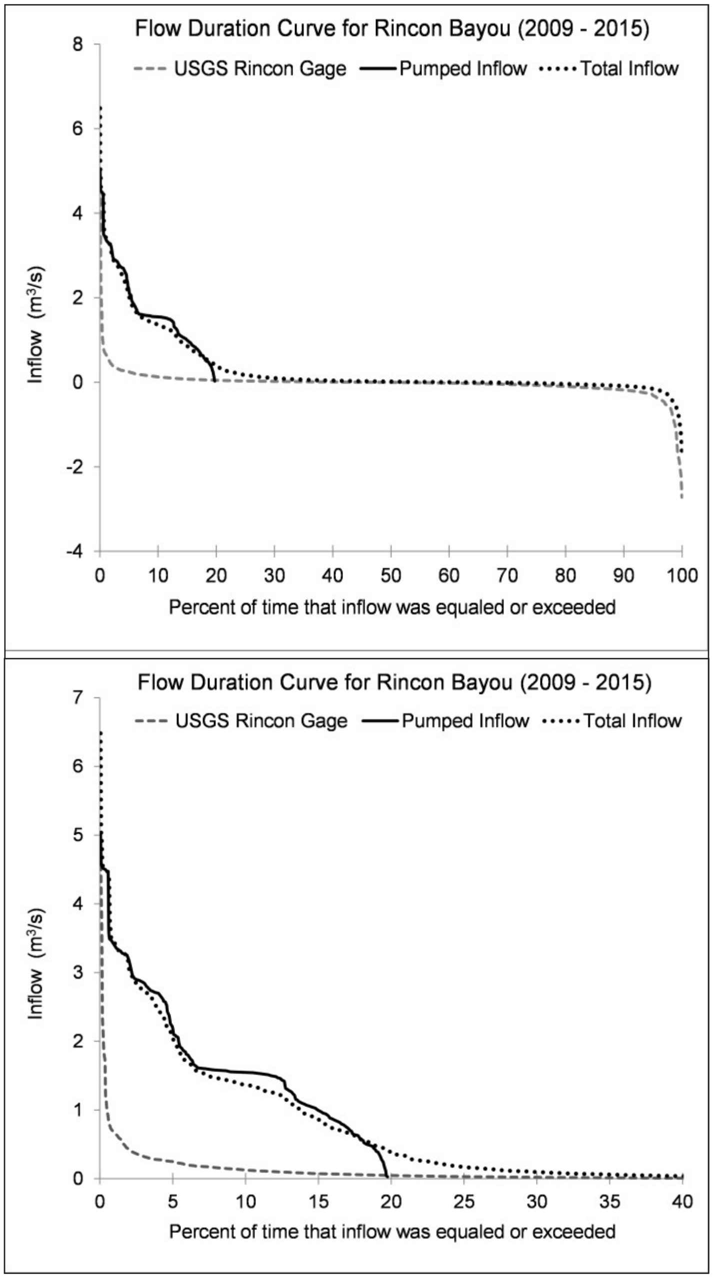

Figure 8. Flow duration curve for Nueces River inflow (+) and discharge (-) at the Rincon (Channel) Gage, September 2009 to December 2015. Top: full inflow scale. Bottom: zoomed to positive inflow values only.

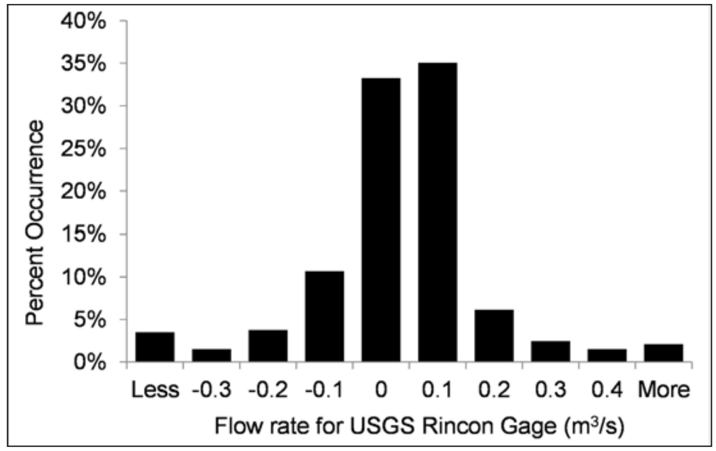

Figure 9. Percent occurrence for the natural flow rate at the USGS Rincon Bayou (Channel) Gage into Rincon Bayou from the Nueces River September 2009 to December 2015.

2014 with a freshwater inflow management structure (back-flow preventer) consisting of box culverts with gates that must be manually opened and closed (Lewis 2014; Hill et al. 2012). The gap in the USGS Gage reading in Figure 4 depicts the time in which the structure was in place. The structure was successful at reducing the amount of pumped inflow going upstream and reducing natural inflows downstream into Rincon Bayou. The back-flow preventer washed out in the July 2015 flooding (2015 interview with R. Allen and R. Mooney; unreferenced, see "Acknowledgments") resulting in increased gaged reading of natural flows both upstream and downstream.

Pumping constraints

The Rincon Bayou pump station is operated by the Wesley Seale Dam near Mathis, Texas. The Daily Reservoir System and (sic) Pass-Thru Status Report generated by the NRA (2017) is used as a guide as to what amount of water to release based on target pass-through requirements (percent full of reservoir), return flow credits (flow returned to Nueces Bay, such as treated wastewater), and salinity relief credits (low salinity in Nueces Bay) based on the 2001 Agreed Order (TNRCC 2001). Pumping events are typically activated when salinities in the Nueces Delta reach a certain threshold (> 30 psu) and when reservoir levels and rainfall events allow for pass-through conditions (Lloyd et al. 2013). The current method of pumping is based on an accounting perspective, where credits and deficits are displayed on the report and operators are given 10 days into the following month to make up deficits (TNRCC 2001). Therefore, water is often held until the end of the month and then released continuously to fulfill the deficit before the deadline (2015 interview with D. Lozano; unreferenced, see "Acknowledgments").

The pumps are often turned on during periods of rainfall because that is when water is coming into the reservoirs to trigger the pass-through requirements, and water is available for pumping. Pumping does not occur during periods of low rainfall because the requirements are not met, and water is not available for pumping. Rainfall is taken into account by the 2001 Agreed Order in which pass-through requirements call for less water to be released downstream for the estuary when there is less rainfall (TNRCC 2001). The reservoir must meet certain water content storage percent levels for pass-throughs

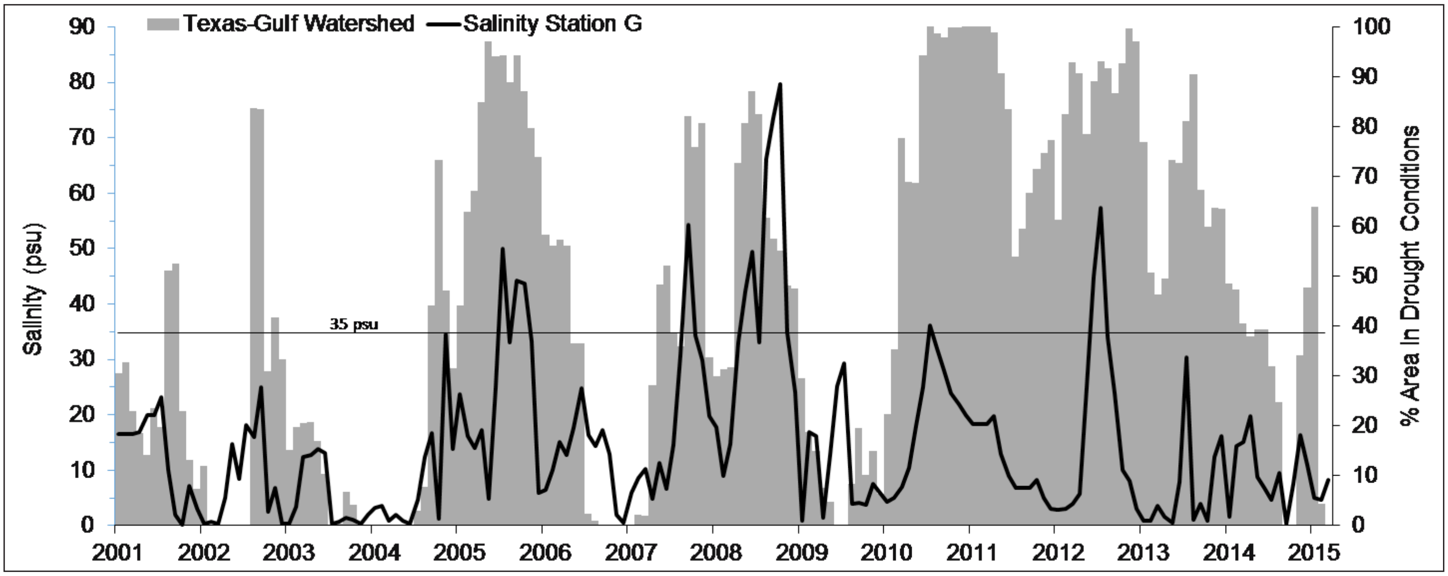

Figure 10. Long-term Rincon Bayou salinity data (Station G) with Texas-Gulf watershed drought conditions (October 2001 to December 2015).

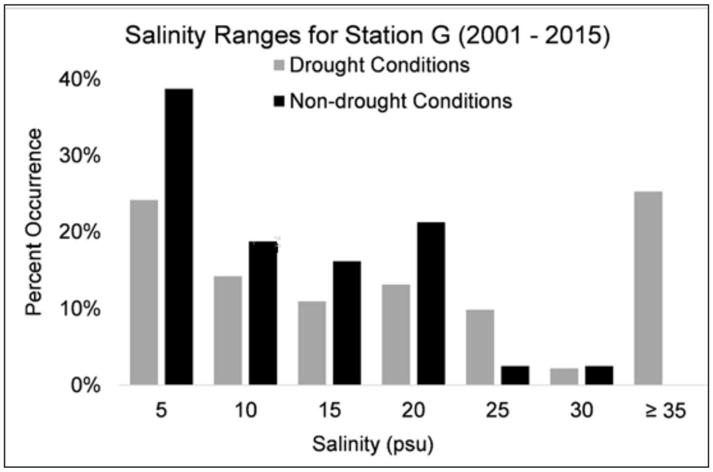

Figure 11a. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions (October 2001 to December 2015).

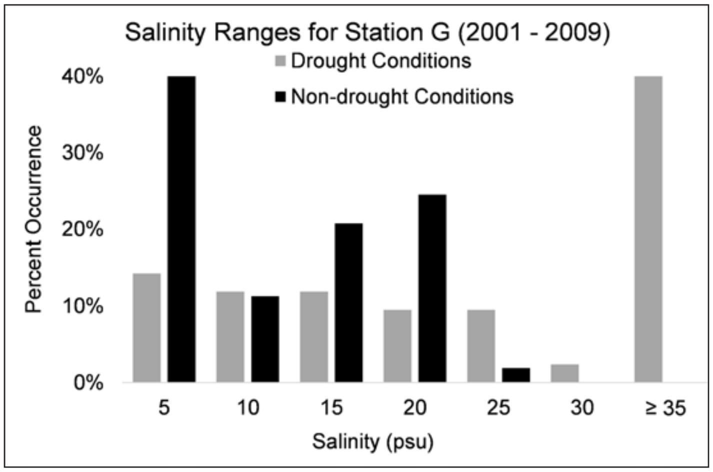

Figure 11b. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions before pumping began (October 2001 to August 2009).

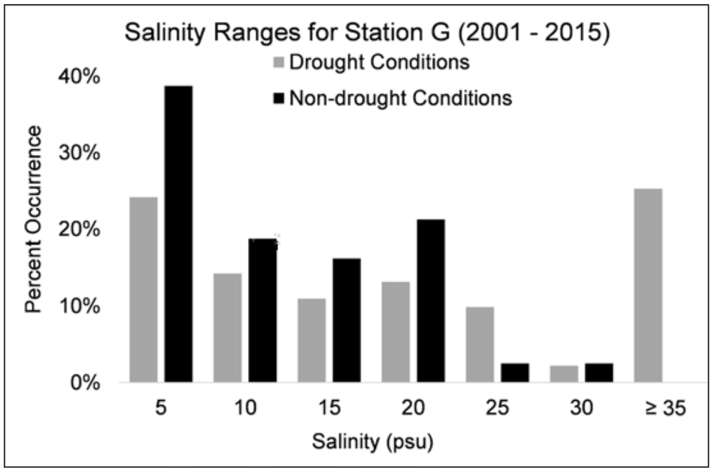

Figure 11c. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions after pumping began (September 2009 to December 2015).

to be required (Appendix 2), thus if there is not water coming into the reservoir, water does not have to be released (Lloyd et al. 2013; TNRCC 2001). This approach has established a method of providing water to the estuary during wet periods and not providing water when it is needed during dry periods. The Agreed Order reflects the natural variation in flow that would have historically been seen for inflow into the upstream reservoirs, but in practice for the downstream estuaries, adding water when water is already present and not supplying water when water is needed is not allowing for an ecologically sustainable environment.

The concept of banking water during regional wet periods for future use during regional dry periods was implemented in 2010 (Tunnell and Lloyd 2011; Lloyd et al. 2013). Water scheduled for pass-through to the Nueces Delta, based on the reservoir storage capacity level, was held and not pumped into Rincon Bayou until salinity reached a threshold (undefined) (Tunnell and Lloyd 2011). This provided the opportunity to release small quantities of water on a monthly or seasonal basis. During dry years the delta would still receive a small amount of water (~1,500 acre-feet) each month or season to keep salinity below extreme conditions (salinity > 35 psu) (Tunnell and Lloyd 2011). This was shown to be beneficial for the flora and fauna in Rincon Bayou and recommended to be a permanent management tool. However in April 2013, the Nueces Advisory Council was asked by TCEQ to suspend water banking and to continue operating under the 2001 Agreed Order allowing the scheduled monthly amount to be passed-through (Lloyd et al. 2013).

Operator constraints

Currently, the RBP pumps must be manually turned on and off from the pump station that is located next to Edward's Pump station along Interstate Highway 37 (Figure 1). At a minimum, the pumps are turned on every three months for 15 minutes resulting in pumped inflow of 56.8 m^3/s for pump maintenance. During the flooding in 2015, the pumps were left on continuously from May 12 to June 15 to keep from flooding the pump station (2015 interview with D. Lozano; unreferenced, see "Acknowledgments"). This resulted in a total of 10.96 x 106 m^3 (8,884 acre-feet) being pumped into Rincon Bayou coupled with 205 cm of rainfall recorded at NUDEWX. The USGS Rincon Bayou Channel Gage was inoperable from May 21 to June 16 (USGS 2015), so it is not known how much natural inflow entered from the Nueces River. The inflow management structure (back-flow preventer) installed in July of 2014 washed out in the July 2015 flooding and was reinstalled in spring of 2016 (2016 interview R. Kalke; unreferenced, see "Acknowledgments"). The back-flow preventer is controlled by the Coastal Bend Bays & Estuaries Program (CBBEP) and consists of three manual control gates that are to be closed when pumping is occurring and reopened when pumping stops. Due to lack of knowledge of when pumping events are going to occur, operation of the gates often does not coincide with pumping (2015 interview with R. Allen and R. Mooney; unreferenced, see "Acknowledgments")

CONCLUSION

The primary source of freshwater into Rincon Bayou is from pumped inflow, thus salinity can be altered in direct response to management actions. The current pumping regime has restored ecological function (i.e. essential habitat, assimilative capacity, and intrinsic value) to Rincon Bayou by increasing inflow and decreasing salinity but causes extreme fluctuations (Montagna et al. 2002; Alber 2002; Montagna et al. 2015). A lower magnitude, longer duration pumping strategy would create a more stable environment by providing freshwater continuously. This has been modeled to be more beneficial to the estuarine ecosystem and should be considered because of adaptive management (Montagna et al. 2015). Results of the current study demonstrate that hydrological restoration of reverse estuaries is possible.

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APPENDIX

Appendix 1. Rincon Bayou Pipeline pumping events from the Nueces River Authority. Pumped inflow data were assigned pumping event numbers based on breaks in the pumping duration. A test run was conducted in 2007 with the pipeline beginning operation in September 2009.

Pumping event number	Duration	Number of days of inflow	Total pumped inflow		
			Acre-feet/ day	ft³/s (cfs)	m³/s (cms)
0	April 17, 2007	1	36	18.15	0.51
1	Sept. 28–Oct. 21, 2009	24	2,987	1,506.05	42.65
2	Jan. 6–14, 2010	9	742	374.12	10.60
3	May 10–31, 2010	22	2,288	1,153.61	32.67
4	March 21–30, 2010	10	1,006	507.23	14.37
5	May 3–12, 2011	10	1,002	505.21	14.31
6	June 13–22, 2011	10	994	501.17	14.19
7	Sept. 13–14, 2011	2	98	49.41	1.40
8	Nov. 2–22, 2011	21	2,027	1,022.01	28.95
9	March 7–19, 2012	13	1,309	660.00	18.69
10	June 21–July 13, 2012	23	2,354	1,186.89	33.62
11	Aug. 7–24, 2012	18	2,004	1,010.42	28.62
12	Aug. 27–28, 2012	2	109	54.96	1.56
13	Sept. 14–16, 2012	3	212	106.89	3.03
14	Sept. 30–Oct. 1, 2012	2	135	68.07	1.93
15	Oct. 5, 2012	1	36	18.15	0.51
16	Oct. 8–18, 2012	11	1,981	998.82	28.29
17	Oct. 27, 2012	1	27	13.61	0.39
18	Nov. 26, 2012	1	31	15.63	0.44
19	Dec. 8–9, 2012	2	95	47.90	1.36
20	Dec. 16–20, 2012	4	159	80.17	2.27
21	Jan. 15–16, 2013	2	62	31.26	0.89
22	Jan. 26–28, 2013	3	152	76.64	2.17
23	April 29, 2013	1	40	20.17	0.57
24	May 14–15, 2013	2	15	7.56	0.21
25	June 1–10, 2013	9	847	427.06	12.10
26	June 24–July 2, 2013	8	731	368.57	10.44
27	July 17–24, 2013	8	665	335.29	9.50
28	Aug. 12–13, 2013	2	161	81.18	2.30
29	Aug. 20–22, 2013	2	124	62.52	1.77
30	Aug. 27–29, 2014	3	273	137.65	3.90
31	Sept. 12–13, 2013	2	161	81.18	2.30
32	Oct. 11, 2013	1	45	22.69	0.64
33	Oct. 21, 2013	1	27	13.61	0.39

Pumping event number	Duration	Number of days of inflow	Total pumped inflow		
			Acre-feet/ day	ft^3/s (cfs)	m^3/s (cms)
34	Oct. 24–30, 2013	7	1,131	570.25	16.15
35	Nov. 2–9, 2013	8	1,190	600.00	16.99
36	Nov. 22–Dec. 1, 2013	9	509	256.64	7.27
37	Dec. 4, 2013	1	31	15.63	0.44
38	Dec. 7–8, 2013	2	73	36.81	1.04
39	Dec. 17, 2013	1	17	8.57	0.24
40	Dec. 30–31, 2013	2	107	53.95	1.53
41	Jan. 10–13, 2014	4	177	89.24	2.53
42	Jan. 21–22, 2014	2	89	44.87	1.27
43	Jan. 25–28, 2014	3	141	71.09	2.01
44	Feb. 3–15, 2014	13	2,466	1,243.36	35.21
45	Feb. 26–27, 2014	2	105	52.94	1.50
46	March 10, 2014	1	87	43.87	1.24
47	April 15, 2014	1	8	4.03	0.11
48	May 9–June 3, 2014	24	2,736	1,379.49	39.07
49	June 23–July 15, 2014	23	3,531	1,780.33	50.42
50	July 19–21, 2014	3	177	89.24	2.53
51	Aug. 26, 2014	1	18	9.08	0.26
52	Sept. 24, 2014	1	66	33.28	0.94
53	Sept. 30–Oct. 1, 2014	2	116	58.49	1.66
54	Oct. 4–6, 2014	3	264	133.11	3.77
55	Oct. 17, 2014	1	35	17.65	0.50
56	Jan. 18–27, 2015	9	695	350.42	9.92
57	March 10–12, 2015	3	210	105.88	3.00
58	March 18–25, 2015	8	1,535	773.95	21.92
59	April 13–28, 2015	16	2,455	1,237.81	35.06
60	May 12–June 15, 2015	35	8,884	4,479.31	126.86
61	Aug. 29–Sept. 2. 2015	5	448	225.88	6.40
62	Sept. 21–22, 2015	2	167	84.20	2.38
63	Sept. 26–Oct. 1, 2015	6	475	239.50	6.78
64	Oct. 17–Nov. 10, 2015	25	3,734	1,882.68	53.32

Appendix 2. Monthly (*sic*) Pass-Thru Status Report from the Nueces River Authority (2009 to 2015) with target inflows to Nueces Bay and/or the Nueces Delta established by the 2001 Agreed Order (TNRCC 2001). Estuary inflows are reported as Rincon Bayou Pipeline plus Nueces River at Calallen, Texas. All data is reported in acre-feet (1 ac-ft = 1233.48 m^3). Target % values refer to the amount of water that is presently held in storage (% full of reservoir).

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2009	Jan	0	0	301	1,219	500	847	0	0	1,200	2,500	2,500
	Feb	0	0	555	733	500	301	0	0	1,200	2,500	2,500
	Mar	0	0	546	471	500	555	0	0	1,200	3,500	3,500
	Apr	0	0	385	559	500	546	0	0	1,200	3,500	3,500
	May	0	0	1,338	258	500	385	0	0	1,200	23,500	25,500
	Jun	0	0	313	64	500	1,338	0	0	1,200	23,500	25,500
	Jul	0	0	379	150	500	313	0	0	1,200	4,500	6,500
	Aug	0	0	204	100	500	379	0	0	1,200	5,000	6,500
	Sep	278	3	4,815	9,322	500	204	0	0	1,200	11,500	28,500
	Oct	2,709	21	6,009	5,813	500	-3,802	0	0	1,200	9,000	20,000
	Nov	0	0	3,529	4,000	500	-3,106	0	0	1,200	4,000	9,000
	Dec	0	0	1,017	1,743	500	-3,077	0	0	1,200	4,500	4,500
2010	Jan	742	9	7,626	1,875	500	-3,303	625	0	1,200	2,500	2,500
	Feb	0	0	4,698	1,250	500	0	1,250	0	1,200	2,500	2,500
	Mar	0	0	300	2,083	500	1,750	0	0	1,200	3,500	3,500
	Apr	0	0	3,856	2,625	500	0	875	0	1,200	3,500	3,500
	May	2,288	22	10,139	2,500	500	1,731	0	0	1,200	23,500	25,500
	Jun	0	0	24,866	15,500	500	-12,471	0	0	1,200	23,500	25,500
	Jul	0	0	18,552	3,250	500	-2,598	3,250	0	1,200	4,500	6,500
	Aug	0	0	312	1,805	500	3,250	0	0	1,200	5,000	6,500
	Sep	0	0	25,412	12,969	500	312	0	0	1,200	11,500	28,500
	Oct	0	0	551	414	500	0	15,000	0	1,200	9,000	20,000
	Nov	0	0	230	480	500	0	2,250	0	1,200	4,000	9,000
	Dec	0	0	309	251	500	230	0	0	1,200	4,500	4,500

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2011	Jan	0	0	1,333	1,533	500	309	0	0	1,200	2,500	2,500
	Feb	0	0	199	772	500	609	0	0	1,200	2,500	2,500
	Mar	1,006	10	1,198	984	500	199	0	0	1,200	3,500	3,500
	Apr	0	0	282	454	500	-90	0	0	1,200	3,500	3,500
	May	1,002	10	1,504	205	500	192	0	0	1,200	23,500	25,500
	Jun	994	10	1,239	167	500	502	0	0	1,200	23,500	25,500
	Jul	0	0	74	317	500	242	0	0	1,200	4,500	6,500
	Aug	0	0	184	23	500	74	0	0	1,200	5,000	6,500
	Sep	98	2	610	273	500	184	0	0	1,200	11,500	28,500
	Oct	0	0	434	7,529	500	610	0	0	1,200	9,000	20,000
	Nov	2,027	21	434	262	500	-5,984	0	0	1,200	4,000	9,000
	Dec	0	0	162	666	500	221	0	0	1,200	4,500	4,500
2012	Jan	0	0	95	279	500	162	0	0	1,200	2,500	2,500
	Feb	0	0	230	209	500	95	0	0	1,200	2,500	2,500
	Mar	1,309	13	1,372	3,500	500	230	0	0	1,200	3,500	3,500
	Apr	0	0	827	2,529	500	0	0	0	1,200	3,500	3,500
	May	0	0	1,110	23,500	500	0	0	0	1,200	23,500	25,500
	Jun	1,083	10	15,990	494	500	0	0	0	1,200	23,500	25,500
	Jul	1,271	13	2,159	297	500	0	0	0	1,200	4,500	6,500
	Aug	2,113	20	2,239	829	500	0	0	0	1,200	5,000	6,500
	Sep	286	4	399	8,156	500	0	0	0	1,200	11,500	28,500
	Oct	2,105	14	2,163	9,000	500	0	0	0	1,200	9,000	20,000
	Nov	31	1	36	686	500	0	0	0	1,200	4,000	9,000
	Dec	254	6	253	77	500	0	0	0	1,200	4,500	4,500
2013	Jan	214	5	214	1,200	500	0	0	0	1,200	2,500	2,500
	Feb	0	0	0	883	500	0	0	0	1,200	2,500	2,500
	Mar	0	0	0	164	500	0	0	0	1,200	3,500	3,500
	Apr	40	1	179	875	500	0	0	0	1,200	3,500	3,500
	May	15	2	198	1,200	500	-195	0	0	1,200	23,500	25,500
	Jun	1,452	15	1,452	1,200	500	-697	0	0	1,200	23,500	25,500
	Jul	791	10	794	1,200	500	55	0	0	1,200	4,500	6,500
	Aug	558	7	558	273	500	149	0	0	1,200	5,000	6,500
	Sep	161	2	1,579	1,200	500	558	0	0	1,200	11,500	28,500
	Oct	1,203	9	9,646	3,213	500	600	0	0	1,200	9,000	20,000
	Nov	1,664	16	7,223	4,000	500	2,000	0	0	1,200	4,000	9,000
	Dec	263	7	283	283	500	2,250	0	0	1,200	4,500	4,500

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2014	Jan	407	9	413	220	500	283	0	0	1,200	2,500	2,500
	Feb	2,571	15	2,583	143	500	0	0	0	1,200	2,500	2,500
	Mar	87	1	89	74	500	0	0	0	1,200	3,500	3,500
	Apr	8	1	11	39	500	0	0	0	1,200	3,500	3,500
	May	2,406	21	2,438	21,596	500	0	0	0	1,200	23,500	25,500
	Jun	1,400	11	18,938	14,059	500	-18,658	0	0	1,200	23,500	25,500
	Jul	2,638	18	16,418	1,839	500	-13,279	920	0	1,200	4,500	6,500
	Aug	18	1	134	134	500	600	0	0	1,200	5,000	6,500
	Sep	126	2	302	1,098	500	0	0	0	1,200	11,500	28,500
	Oct	355	5	605	836	500	-297	0	0	1,200	9,000	20,000
	Nov	0	0	433	867	500	-28	0	0	1,200	4,000	9,000
	Dec	0	0	157	150	500	0	0	0	1,200	4,500	4,500
2015	Jan	695	9	709	1,200	500	0	0	0	1,200	2,500	2,500
	Feb	0	0	26	0	500	0	0	0	1,200	2,500	2,500
	Mar	1,745	11	4,720	1,200	500	0	0	0	1,200	3,500	3,500
	Apr	2,455	16	7,039	300	500	0	900	0	1,200	3,500	3,500
	May	5,562	20	124,478	1,704	500	0	6,612	0	1,200	23,500	25,500
	Jun	3,321	15	108,377	5,750	500	0	17,250	0	1,200	23,500	25,500
	Jul	0	0	482	0	500	0	4,500	0	1,200	4,500	6,500
	Aug	302	3	522	1,092	500	0	1,250	0	1,200	5,000	6,500
	Sep	717	9	838	1,282	500	-70	0	0	1,200	11,500	28,500
	Oct	2,075	16	3,516	9,000	500	-14	0	0	1,200	9,000	20,000
	Nov	1,818	10	9,260	3,000	500	-4,998	1,000	0	1,200	4,000	9,000
	Dec	0	0	326	2,910	500	1,762	0	0	1,200	4,500	4,500

Appendix 3. Drought severity classification. U.S. Drought Monitor. D1 is the least intense level and D4 the most intense. D0 areas are not in drought, but are experiencing abnormally dry conditions that could turn into drought or are recovering from drought but are not yet back to normal. Source: http://droughtmonitor.unl.edu/AboutUSDM/DroughtClassification.aspx

Category	Description	Possible impacts	Palmer Drought Severity Index (PDSI)	CPC SoilMoisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally dry	Going into drought: short-term dryness slowing planting, growth of crops or pastures. Coming out of drought: some lingering water deficits pastures or crops not fully recovered.	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate drought	Some damage to crops, pastures. Streams, reservoirs, or wells low, some water shortages developing or imminent. Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe drought	Crop or pasture losses likely. Water shortages common. Water restrictions imposed.	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme drought	Major crop/pasture losses. Widespread water shortages or restrictions.	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional drought	Exceptional and widespread crop/pasture losses. Shortages of water in reservoirs, streams, and wells creating water emergencies.	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

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Economic valuation of groundwater in Texas

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Abstract: Groundwater is a strategic economic asset, and recent Texas Supreme Court decisions have strengthened private ownership rights in groundwater. Despite the economic and political stakes, debate on how to actually value groundwater has been sparse. In response, this article sets forth seven methods of economically valuing groundwater in Texas and uses case studies and hypotheticals informed by real data to assess the valuation techniques' strengths and weaknesses under a range of conditions. In addition, the analysis shows how in practice, multiple valuation methods can be combined to render the most credible valuation range for a particular groundwater asset. Readers will also see how to marshal a wide range of publicly available data resources—including actual water sale and lease contracts—and analytically mesh them to arrive at a defensible valuation range for water assets under various conditions. These methods can help value water more accurately, create opportunities for unlocking additional economic value, and help manage groundwater resources more effectively for the benefit of future generations.

Keywords: groundwater, valuation, resource stewardship, capitalization

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Terms used in paper

Short name or acronym	Descriptive name
ASFMRA	American Society of Farm Managers and Rural Appraisers
DCF	discounted cash flow
EBITDA	earnings before interest, taxes, depreciation, and amortization
NPV	net present value
SAWS	San Antonio Water System
TDS	total dissolved solids
TWDB	Texas Water Development Board

INTRODUCTION

Groundwater in place has real, substantial, and quantifiable economic value in Texas. One of this article's core goals is to describe and analyze the existing set of methodologies that can be used to quantify a reasonable and defensible value range for groundwater assets across the state. This analysis draws directly upon the author's recent experience serving as a valuation expert in a Montgomery County groundwater proceeding.[1] It also builds upon the analytical foundations laid by Charles Kreitler and Bruce Darling in a 1997 paper titled *Value of Groundwater*, two subsequent analyses by Darling in 2007 and 2009, and most recently, a paper written by Ed McCarthy and Charles Porter for a Continuing Legal Education course in late 2016.[2]

The groundwater valuation methodologies addressed in this analysis are globally relevant and have been employed in other jurisdictions around the world, including Australia, Namibia, and Spain. Groundwater valuation is location-specific and fact-intensive. A diverse set of tools helps evaluators choose methods most appropriate for the conditions and factual realities inherent in the asset or set of water assets they are assessing.

Multiple valuation tools also help address the reality that, in some instances, water is the final good sold, though in other cases, such as farming or industrial uses, water is an essential intermediate input. Weather, water demand, hydrogeology, and other factors vary widely across Texas. As such, parties valuing water assets must make many judgment calls and assumptions. But this should not discourage the valuable contribution of developing and promulgating a common set of frameworks for pricing water.

Being able to value water in place is the gateway to facilitating a range of commercial and financial transactions that can unlock additional economic value from Texas groundwater resources. Indeed, if sufficiently protected by tract size, correlative rights withdrawal restrictions, or lease pooling, groundwater in place that underpins a cash flow-generating project can potentially also become collateral for reserve-backed lending.

Furthermore, better groundwater valuation will facilitate fairer resolution of disputes. For instance, groundwater valuation in place is important for assessing the value at stake in cases where groundwater owners are litigating against groundwater

[1]Mr. Collins served as a groundwater valuation expert in the proceeding of *Petition of the Cities of Conroe and Magnolia, Texas Appealing Desired Future Conditions of GMA 14 Adopted by Lone Star Groundwater Conservation District*, SOAH DOCKET NO. 958-17-3121, which was settled in November 2017.

[2]Charles W. Kreitler and Bruce K. Darling, "Value of Ground Water," presented at the Seventh Annual Conference on Texas Water Law, 13-14 November 1997, Austin, TX; Bruce K. Darling, "Groundwater in Texas: Marketability and Market Value," The Water Report, 15 July 2007; Bruce K. Darling, "The Rule of Capture, Changing Perspectives on Water Management in Texas, the Tragedy of the Commons, and Developments in the Valuation of Groundwater," Conference Paper, April 2009, DOI: 10.13140/RG.2.1.1516.3047; Edmond R. McCarthy Jr. and Charles R. Porter Jr., "Valuation of Water Rights," 2016 Texas Water Law Institute, https://utcle.org/practice-areas/index/practice_area_id/26.

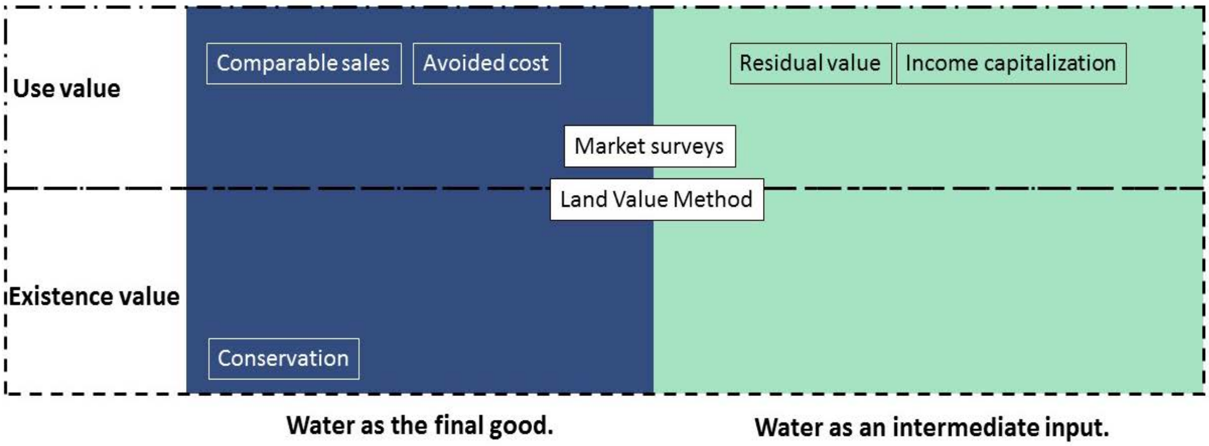

Figure 1. Overview of key groundwater valuation methods.

conservation districts, whose regulatory actions have impaired water owners' access to, and use of, their natural capital assets.[3] Texas courts are also seeing an increase in cases where one party believes that physical actions taken by another have somehow impaired its ability to access groundwater it owns.[4]

This article aims to lay down foundational methods and parameters and does so fully acknowledging that iterative improvements to the techniques discussed are inevitable as commercial transactions occur, more scholars engage the subject, and more groundwater cases wind their way through the courts.

INTRODUCTION TO PRINCIPAL VALUATION METHODS

There are seven core methods for evaluating the economic value of groundwater in Texas: (1) comparable sales (including market surveys), (2) avoided cost, (3) land value method, (4) residual value, (5) income capitalization, (6) net present value valuation, and (7) conservation value. Ultimately, useful valuations of groundwater incorporate a number of elements, each of which contributes to the asset's worth. These include, but are not limited to, (1) the capital and recurring operational costs of extracting water; (2) the costs of transporting the water to market; (3) treatment costs (when applicable); and (4) economic benefits that may be conferred simply by having a certain volume of water in place in an aquifer.

Figure 1 outlines the core methodologies and highlights their key characteristics, while the accompanying discussion very briefly outlines the fundamental parameters of each concept. Subsequently, this article will analyze each method in greater detail, offer case examples where the methods have been—or could be—applied, and evaluate the strengths and weaknesses of each.

Groundwater valuation methods summary

1. **Comparable sales.** This method entails examining transactions where groundwater was bought or sold to see what values are feasible for a water sale in the area of interest. For example, if groundwater from the Carrizo-Wilcox Aquifer in Burleson County is purchased by the San Antonio Water System (SAWS) at a royalty rate of $460 per acre-foot to supply San Antonio, water from an equally productive part of the aquifer nearby would likely be worth at least approximately as much to Austin, College Station, or another municipal consumer.
2. **Avoided cost.** This method values groundwater by seeing how much money a consumer could save by obtaining water from an alternative, cheaper source. Consider the following simplified hypothetical: if a city currently purchases water from one source for $1,000 per acre-foot but could obtain water from an alternative groundwater source for $700 per acre-foot, the avoided cost value of water from the second source would be up to $300 per acre-foot. Any avoided cost relative to the baseline supply source would be a net economic benefit to the consumer, all else held equal.

[3]See, for instance: *Edwards Aquifer Auth. v. Bragg*, 421 S.W.3d 118 (Tex. App.—San Antonio 2013, pet. denied); *Forestar [USA] Real Estate Group, Inc. v. Lost Pines Groundwater Conservation District, et al.,* No. 15,369, Texas Dist., Lee Co.; *Petition of the Cities of Conroe and Magnolia, Texas Appealing Desired Future Conditions of GMA 14 Adopted by Lone Star Groundwater Conservation District*, SOAH DOCKET NO. 958-17-3121.

[4]See, for instance: *Edwards Aquifer Auth. v. Day*, 369 S.W.3d 814 (Tex. 2012) (landowners own groundwater beneath their tract as real private property and have an interest in groundwater that is compensable under the takings clause of the Texas Constitution); *Coyote Lake Ranch, LLC v. City of Lubbock*, 498 S.W.3d 53 (Tex. 2016), reh'g denied (Sept. 23, 2016) (accommodation doctrine applied to the relationship between as owner of severed groundwater estate and surface estate).

3. **Land value method.** The land value method is an inductive approach that derives water values by comparing transactions of irrigated and non-irrigated farmland. For example, if dry cropland in an area sells for $1,000 per acre and irrigated cropland in the same zone sells for $2,000 per acre, this would suggest that the water associated with the land is worth $1,000 per surface acre. This technique often crosses over with the comparable sales method and can be combined with data on the thickness of water-bearing layers to actually develop a price per saturated foot for water in place.
4. **Residual value.** This method helps assess how much a consumer can pay for water. It looks at how much income someone makes from a water-dependent activity such as growing hay, subtracts the costs, and divides the remaining net income by the amount of water needed. If a farmer's income for growing corn is $100 after costs and she needs 1 acre-foot of water to grow that corn, then the residual value of water to her is $100 per acre-foot because in theory that's the most she could pay for the water from another supplier (or the highest extraction cost she could afford for self-produced water) and still break even.
5. **Income capitalization.** This method also examines capacity to pay for water. It converts the income generated by an asset into an estimate of its overall value. A farm whose annual net operating income is $100 with a capitalization rate of 10% would have an annual capitalized crop value of $1,000 [$100÷10%]. For water-intensive assets such as farms, it can also yield a value for the water input by taking the capitalized income value and dividing it by the volume of water needed to produce it. If the farm's crop needs 10 acre-feet of water, the water would be worth $100 per acre-foot to the farmer [$1,000 in capitalized income per year ÷ 10 acre-feet per year to generate that income].
6. **Net present value.** This method focuses on assessing an asset's current value based on its likely future cash flows. Net present value (NPV) analyses are fundamentally predicated on the time value of money—in other words, the concept that a dollar today is typically worth more than a dollar tomorrow. In practice, buyers and sellers of oilfield water supply facilities, farms, and other cash-generating water investments often use an NPV-based approach to value their assets.
7. **Conservation value.** The prior four core methods center upon the use value of water. Conservation value, in contrast, more fundamentally rests upon the "existence" value of water. Determining conservation value can require a multi-faceted analysis that considers factors such as ecosystem services value and the costs that aquifer depletion might impose. In addition, because groundwater is private property in Texas, groundwater conservation programs should compensate water owners for idling their natural capital assets.

IN-DEPTH ANALYSIS OF PRINCIPAL VALUATION METHODS

This section explores each of the seven principal groundwater valuation methods in depth, with a detailed examination of their respective strengths and weaknesses. It also demonstrates how valuation methods often "cross pollinate" in practice and how a proper valuation is frequently a multi-method, if not multi-disciplinary, endeavor. The author also shares some methods he has used to obtain transaction data and a set of adjustment factors that can help analysts compensate for differences in local conditions when assessing groundwater assets. Finally, the author also includes data from sample transactions showing how groundwater has been priced in recent years across Texas in land purchases, groundwater estate sales, and water leases.

Method 1: Comparable sales

Comparable sales valuation means examining transactions where groundwater was bought or sold and seeing what the prices were for those transactions. If available, recent sales or leases of comparably situated water rights or water resources in place typically offer the most dependable metric for determining the value of water resources in that location.

Comparable transaction valuations are predicated on the principle that the "fair market value of property" denotes "the amount that a willing buyer, who desires but is not obligated to buy, would pay a willing seller, who desires but is not obligated to sell."[5] This fundamental idea of fair market value is also enshrined in the Texas Water Code, which states in relevant part that:

> *"[w]henever the law requires the payment of fair market value for a water right, <u>fair market value shall be determined by the amount of money that a willing buyer would pay a willing seller, neither of which is under any compulsion to buy or sell, for the water in an arms-length transaction and shall not be limited to the amount of money that the owner of the water right has paid or is paying for the water</u>."*[6] *[emphasis added]*

In other words, the water right's or asset's value should be based on *actual market conditions as dictated by supply and demand and other factors* and not be determined simply on the

[5]Op. Tex. Attn'y Gen. No. LO-98-082 (1998).

[6]Tex. Water Code Ann. § 11.0275 (West).

basis of compensating a water owner based on what they themselves originally paid for the property. To yield a true "fair market value," the transaction should occur between parties that are operating under normal commercial conditions and are not facing any type of financial, regulatory, or other duress that could skew the terms of the deal.

Water valuators using comparable sales methodology are in good company. For a cross-industry comparison, consider that National Football League and National Basketball Association player contracts involve very large amounts of money, the market for talent is relatively illiquid, and precise transaction terms are often kept confidential.[7] Notwithstanding these challenges, many player agents and teams use the terms and economic parameters reflected in prior agreements as a baseline to inform new contractual negotiations for player signings each year during the free agency period where total transaction value turnover approaches $2 billion per league.[8]

On an even larger scale, reporting of comparable transaction prices—including bids and offers where a transaction was not necessarily consummated—provides the basis for indices used to price commodity contracts in markets for natural gas, petrochemicals, and crude oil.[9] Combined trade turnover in markets priced off indices from Platts, Argus, and other price providers can exceed $300 billion per year.[10] As such, using comparable sales transaction data to value and price groundwater in Texas is highly defensible and will become more so as additional data from sales and leases become publicly available.

Obtaining comparable transaction data

Water marketing in Texas is generally opaque, and deal terms are often kept private. Actual signed water supply and purchase agreements and judicial rulings and settlements, which collectively generally offer the highest fidelity source of information, can be obtained through a number of channels, including (a) open records requests to municipalities, their water suppliers (such as SAWS or Alliance Water), and other public entities that own or regulate groundwater resources; (b) discussions with private water sellers, purchasers, and parties such as county extension agents and others who may have access to deal flow information; (c) judicial decisions; and (d) for the San Antonio area, periodic water rights purchase solicitations by SAWS.[11]

In addition, surveys can be a relevant technique for helping to assess value along several portions of the groundwater value chain, including sales prices, production costs, and transport costs. The most reliable information is likely to come from parties who are already either participating in the market, such as oilfield water sellers, or farmers, who are actively preparing to do so. In a nutshell, these parties either (1) have already made the necessary capital investments in requisite physical infrastructure and permits and/or (2) are geographically situated near water demand and can credibly enter the market on short notice.

Simply asking landowners "what would you sell or buy water for?" risks placing them in a situation where their response may lack the anchoring context of knowing the value of water-dependent outputs, water extraction costs, and other important information that helps inform the ultimate value of water in a given area for a particular application.

Municipal water sourcing data tends to be more sparse than that from the oilfield but still useful. Municipalities typically do not enter into water sales and purchase transactions as frequently as oilfield parties do, but when they enter the market, the volumes of water and dollar amount of capital at stake are often enormous. Many of these agreements have terms of at least 30 years, which forces the parties to thoroughly contemplate future supply/demand conditions, hydrological risks, capital market conditions, and other factors. As such, if the water appraiser is weighing the value information transmitted from short-term oilfield supply deals in a given area versus longer-term, higher volumes, and more capital-intensive municipal deals, the municipal deals arguably hold a greater validity over a longer period for baseline valuation assessments.

Judicial rulings

While not "sales" in the traditional sense, court rulings offer a number of unique factors that can make them useful barometers of groundwater value. First, judicial opinions are matters of public record, which makes them broad and transparent benchmarks that are far more accessible than most water sales and purchase contracts. Second, each party to litigation often faces enormous financial stakes and has commensurately high incentives to provide as powerful of evidence as possible to sup-

[7]https://www.cbssports.com/nfl/news/agents-take-the-top-10-nfl-contracts-from-players-side-of-the-negotiating-table/.

[8]See, for instance: "2015 NFL salary Cap and Adjusted Team Positions," NFLPA, 24 March 2015, https://www.nflpa.com/news/all-news/2015-nfl-salary-cap-and-adjusted-team-positions#update; as well as Anthony Chiang, "NBA free agent spending spree up to $1.8 billion in total contract value," PalmBeachPost.com, 2 July 2016, http://heatzone.blog.palmbeachpost.com/2016/07/02/nba-free-agent-spending-spree-up-to-1-8-billion-in-total-contract-value/.

[9]See, for instance: "METHODOLOGY AND SPECIFICATIONS GUIDE: AMERICAS PETROCHEMICALS," S&P Global Platts, Updated April 2017, https://www.platts.com/IM.Platts.Content/MethodologyReferences/MethodologySpecs/americas-petrochemicals-methodology.pdf.

[10]Terry Macalister, "Price reporting agencies cut out of the loop," The Guardian, 8 May 2013, https://www.theguardian.com/business/2013/may/08/price-reporting-agency-boycott.

[11]McCarthy and Porter, "Valuation of Water Rights," 2016 Texas Water Law Institute, https://utcle.org/practice-areas/index/practice_area_id/26.

port their position. Third, while a judicially driven transaction is compelled, the analysis underlying it draws upon a robust debate and information discovery process that is more likely than not to render its value reasonably reflective of actual prevailing market conditions.

The body of judicial and jury decisions, along with settlements on groundwater value disputes in Texas, remains relatively small but already includes at least two prominent case examples. The first, *Bragg v. Edwards Aquifer Authority*, centered on a damage claim arising from the Edwards Aquifer Authority's decision to deny groundwater pumpage rights to a pecan farming couple in Medina County. After approximately a decade of litigation, a Medina County jury awarded the Braggs $2.5 million in damages, finding that one orchard was worth $1.67 million with full access to Edwards Aquifer groundwater but only $300,000 if water access was limited to 120 acre-feet per year, as the Edwards Aquifer Authority desired.[12] The jury also found that a second pecan orchard was worth $1.18 million with full access to the necessary water volumes but had no value as a commercial pecan farm without water rights. The *Bragg* valuation relies heavily upon the cash-generation potential of agricultural land with and without access to water.

The second case, *State of Texas v. 7KX Investments*, involved the condemnation of approximately 28 acres of property for the construction of a rest stop alongside Interstate 35 in Bell County, near Temple. The State offered to pay approximately $500,000 for the land it sought to acquire. However, this offer proved unacceptable to the owner, 7KX Investments, which had drilled six large volume groundwater supply wells on the tract and would not be able to access the water once the State built the rest stop because the aquifer could not be reached using directional drilling.[13] The jury awarded 7KX $5.8 million for the condemned land, based largely on the long-term likely sales value of the groundwater resources that lay beneath it.

The case ultimately settled for $5.5 million just prior to the commencement of oral arguments before the Third Court of Appeals, meaning the land was effectively valued at more than $196,000 per acre.[14] The settlement in *7KX Investments* was very likely predicated on the future income generation potential of the proven commercial-scale water resource under the tract taken by the State of Texas. Supporting this idea, the final settlement amount fell nearly in the middle of the 50-year total groundwater value estimate of $4.5 million and $6.2 million offered by the Plaintiff's expert witness.[15]

Adjusting comparable transaction data for specific assets

Groundwater valuations are best framed in terms of what Charles Porter and Ed McCarthy call "the most probable price."[16] Most importantly, this means that groundwater prices result from dynamic interaction between many variables and so a valuation dollar figure at any given point is a "snapshot" in time and could rise or decline meaningfully months or even weeks later.

Businesses often use a "fair value" approach intended to reflect market activity, timing, and a range of other factors to reach value estimates for water assets. For instance, Martin Marrieta—a large, publicly traded corporation with major land holdings in Texas—employs "a market approach to determine the fair value of water rights that may be associated with its properties."[17] The company specifies that it values other intangible assets using an "excess earnings" method or a replacement cost approach, but classifies water rights entirely differently, which strongly suggests that "market approach" in this context means "comparable sales."

Forestar Group, another large, publicly traded corporation whose business focuses on relatively illiquid assets such as real estate and groundwater, offers a useful three-level framework for assessing the "fair value" of property interests in water:

1. Level 1: "Quoted prices in active markets for identical assets or liabilities."[18]
2. Level 2: "Inputs other than Level 1 that are observable, either directly or indirectly, such as quoted prices for similar assets or liabilities; quoted prices in markets that are not active; or other inputs that are observable or can

[12]Jess Krochtengel, "Texas Jury Awards Pecan Farmers $2.5M In Water Takings Suit," Law 360, 23 February 2016, https://www.law360.com/articles/762833/texas-jury-awards-pecan-farmers-2-5m-in-water-takings-suit.

[13]Paul A. Romer, "Rest stop dispute finally comes to end," tdtnews.com, 1 July 2009, http://www.tdtnews.com/archive/article_ffa15658-9cc1-566f-99dc-0f0343ba804b.html.

[14]Johns Marrs Ellis & Hodge, LLP, "Trials & Appeals," State of Texas v. 7KX Investments, No. 03-10-0069, In the Third District Court of Appeals, Austin, Texas (2011), http://jmehlaw.com/trials-appeals/types-of-cases/condemnationeminent-domain/.

[15]Paul Romer, "Setting a precedent: Bell case possible landmark for eminent domain involving underground water rights," tdtnews.com, 23 August 2009, http://www.tdtnews.com/archive/article_33fbf22f-c781-53fd-811e-9a7657c55fbe.html.

[16]Charles Porter and Ed McCarthy, "Valuation of Water Rights," 2016 Texas Water Law Institute, https://utcle.org/practice-areas/index/practice_area_id/26.

[17]"Martin Marrieta Materials 2016 Annual Report," http://files.shareholder.com/downloads/MLM/5519439460x0x932416/88AB9794-3EC6-462A-AAAA-0ED16EE13FC0/Annual_Report_2016.pdf.

[18]Forestar Group, Form 10-K, 2016. Pg. 70. Available from http://investor.forestargroup.com/phoenix.zhtml?c=216546&p=irol-sec&control_symbol=&control_symbol.

Figure 2. Vista Ridge delivered water cost visualization. Source: SAWS

be corroborated by observable market data for substantially the full term of the assets or liabilities," and[19]

3. Level 3: "Unobservable inputs that are supported by little or no market activity and that are significant to the fair value of the assets or liabilities."[20]

Aside from high-activity oilfield areas, the main high-activity "market" for groundwater in Texas to date is in the Edwards Aquifer, which provides an online portal for parties wishing to sell or lease groundwater, but does not comprehensively report transaction and price data.[21] For other groundwater transactions throughout Texas, data availability is even sparser, which makes finding "apples-to-apples" transaction data upon which to price the water difficult. Accordingly, buyers and sellers must generally apply multiple adjustment factors to determine a defensible fair value range for a transaction at a given place and time.

Key variables to consider when adjusting comparable transaction valuations include the 11 criteria enumerated below. These factors are not rank-ordered because under various circumstances their relative importance may differ. For instance, a rapidly growing city in a drier part of Texas may be most concerned about a resource's drought resistance and water quality, while an oilfield or factory user may be most concerned with how quickly water can be brought online and the availability of rights of way and infrastructure to get it to market.

Factors 1-3: Water location, the existence of production and delivery infrastructure, and the cost of such infrastructure. These factors tend to be closely related to one another, hence the decision to group them in a bloc here. Take for instance the Vista Ridge project supplying water from Burleson County to San Antonio. As of February 2017, the project's expected water cost per acre-foot was $460 per acre-foot to purchase the water from Bluewater Systems, $1,146 per acre-foot to finance infrastructure costs, $191 per acre-foot in electricity costs, and $196 per acre-foot in operations and maintenance costs, for a final delivered water price of $1,993 per acre-foot.[22] In simple terms, infrastructure and debt service costs alone account for nearly 60% of the final delivered water price for the Vista Ridge project (Figure 2).

4: Market competition. Multiple parties competing for a water asset will likely drive up the price, while a lack of competition empowers a potential buyer to seek a lower price.[23]

5: Water quality. The price of water may be varied based on its quality. For instance, in agreements to supply municipal drinking water, water volumes with lower total dissolved solids (TDS) content (a proxy for salinity) can entitle producers to higher royalty payments while water volumes with higher TDS levels yield lower royalty payments.[24] Conversely, oilfield water supply agreements in Texas have been designed to incentivize the use of high-TDS non-potable water for fracturing fluid by prohibiting the production of water below a specific TDS level and requiring a lessee to effectively forfeit the gross revenues earned from any sales of water below a certain defined TDS level.[25]

6: A closely related concept is **the cost of physically extracting and treating the water**. A water seller will likely have to discount the price of water they are selling if that water has a quality impairment that requires a customer to spend on treatment. Quality-related premiums and discounts abound in the oil and gas world and provide ample precedent for parties valuing water and structuring sales and purchase agreements.

7: The intended use of the water. Agricultural users are the largest users of water per unit of economic output produced but also generally have the lowest capacity to pay, municipal users have a medium capacity to pay and contract the largest steady volumes of water for the longest periods, and specialty users such as oilfield frac'ers have much smaller volume

[19]Ibid.

[20]Ibid.

[21]"Sellers Lessors Listing," Edwards Aquifer Authority, http://data.edwardsaquifer.org/sellerslessors.

[22]Data obtained from "Project Introduction: San Antonio's Vista Ridge Regional Water Project," Nancy Belinsky, VP & General Counsel, Delivered at 59th Annual V.G. Young School for County Commissioners Courts, Austin, TX, 8 February 2017.

[23]Bruce K. Darling, "Groundwater in Texas: Marketability and Market Value," The Water Report, 15 July 2007.

[24]See, for instance: Groundwater Rights Sales Contract between the Roark interests, Winkler Land, LLC, and the Midland County Fresh Water Supply District No.1 (2015).

[25]See, for instance: the Groundwater Lease signed on 1 November 2017 between the Texas General Land Office and Layne Water Midstream, LLC.

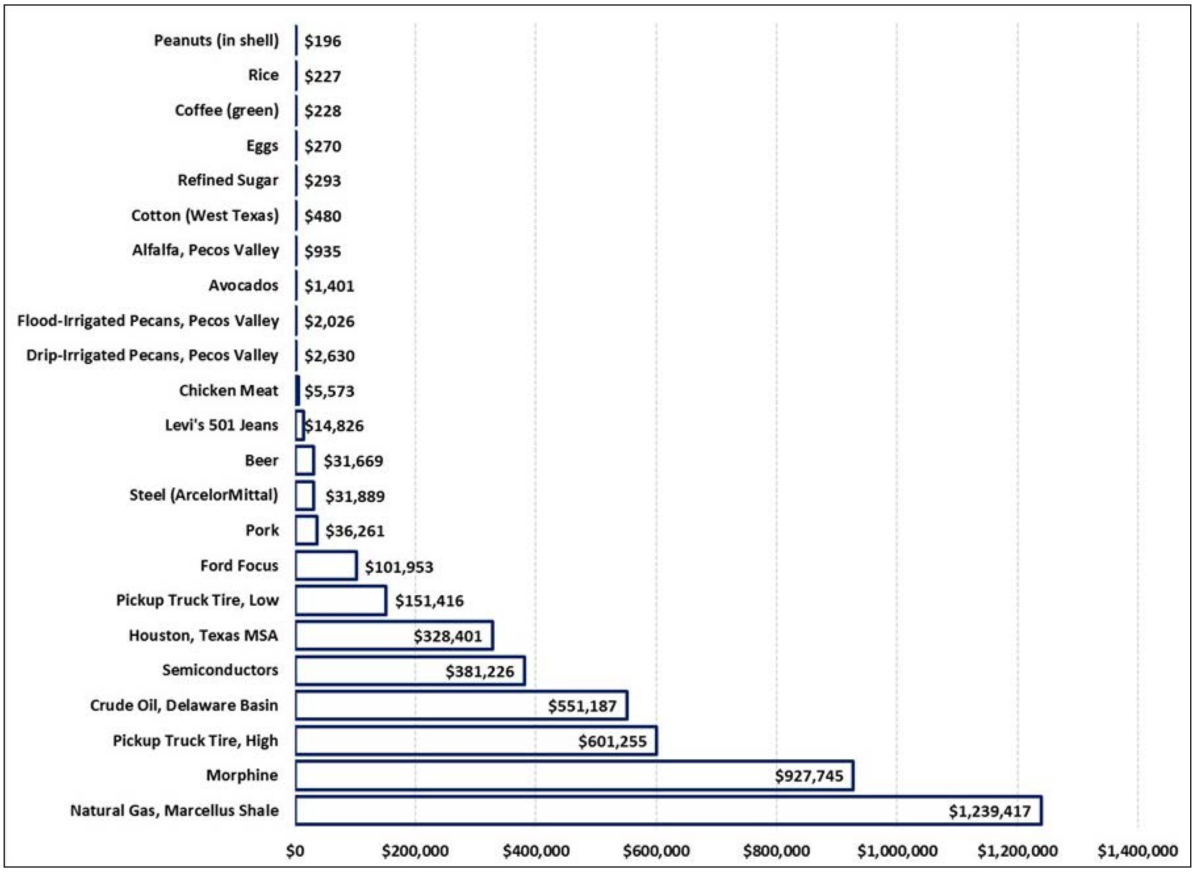

Figure 3. Economic value generated per acre-foot of water used, 2016 dollars. Source: Ag Extension Data, Company Reports, FracFocus, Mekonnen and Hoekstra, U.S. Census Bureau, USDA, Author's Estimates

requirements but can pay an order of magnitude higher than what a municipality or factory could (Figure 3).

8: Protection from drainage by neighboring pumpers. Texas currently governs groundwater under "rule of capture" principles that in practice mean water owners do not have access to a given volume of water nor do they have practical recourse to prevent themselves from being pumped out by neighboring users.[26] The practical implication is that water sourced from very large contiguous tracts or pooled leases is the most "protected" and, all else held equal, will likely command the highest valuations for groundwater in place in that particular area.

9: Political, legal, and regulatory barriers that could impede development of the resource. Developing water resources for off-tract use generally requires some—or at times all—of the following: groundwater conservation district export permits (which ideally need to cover a period of 15 years or longer to support the financing of infrastructure necessary to get the water to end users), payment of groundwater conservation district export fees, public support, the consent of third parties whose property must be crossed, and the consent of other parties who may hold a property interest in the groundwater resource in question. These "above-ground factors" often present the greatest challenge to developing a water asset and exert great influence on what a given groundwater asset is actually worth because potential investors will generally seek the highest practicable degree of regulatory certainty.

10: Time sensitivity of the end use. In practice, time sensitivity is often inversely correlated with the length of the period in which the consumer will need the water. For instance, sourcing water for hydraulic fracturing completions of oil and gas wells is the epitome of a "time-is-of-the-essence" transaction, but such purchases often occur on an irregular schedule and energy companies are generally unwilling to enter into longer-term or take-or-pay water procurement agreements. In contrast, cities that need water for the next 30 to 50 years will not pay as much as a frac'er and will not move as quickly to seal up a deal, but when a purchase agreement is executed, it typically spans multiple decades. The most rapidly implemented municipal water development and acquisition transactions typically occur when a city already owns an anchor water property—such as Midland's T-Bar Ranch—and then patches satel-

[26]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, 463 (2015).

lite properties such as the Roark and Clearwater Ranches into the supply corridor.

11: Resource dependability (i.e. drought resistance and available volumes). The value of a groundwater resource will be affected by how much water is available at a given time as well as by whether or not the aquifer is "mined" or recharges (such as the Edwards Aquifer in Central Texas).[27] Groundwater resources are generally much more insulated from drought than surface water sources. As such, access to groundwater can help cities and other water users hedge against a drought by offering them an alternative water source that replaces supplies lost from surface water sources and helps buy time for demand-side reforms aimed at optimizing water conservation.

Oilfield water assets, an important subset of the market in the Permian Basin and parts of South Texas, generally require analysts to apply a number of additional criteria to properly evaluate their potential economic value. First, how close is the asset to a state-owned highway that offers a potential right of way for pipelines or layflat hoses to be laid in the bar ditch? Second, how many drilling permits have been approved for the next six-12 months forward within a 20-mile radius of the asset? Third, how intense is the competition from other water suppliers in the area? Is there a larger supplier whose "zone of influence" curtails the potential market opportunities that the asset under evaluation might otherwise enjoy?[28]

Comparable transaction pricing has, to date, been the preferred method of valuing groundwater sold in Texas. But income-based value approaches are likely to become more prominent if institutional investors become more interested in Texas water assets, whether they are businesses directly selling water or those using water as a critical intermediate input (like farms). In Australia, the executive director of BDO, a prominent firm representing institutional buyers of agricultural assets, noted in a 2014 interview that "The comparable sales methodology is not the valuation methodology expected to be used by sophisticated investors…Instead, they are more likely to adopt an income approach when valuing agricultural businesses for acquisition, divestment and general reporting."[29]

Nevertheless, the comparable transactions method is likely to continue serving as a core groundwater valuation tool in Texas for at least two reasons. First, the final sale price of a given groundwater asset is likely to incorporate the influence of income-based valuation methods, particularly in cases where the water renders the land its value and drives its income generation potential. Second, basic human psychology makes it such that buyers and sellers of an asset will want to see what "similar" assets fetched on the market. And in turn, this information in many cases will "anchor" their own subsequent value perceptions and expectations.

How has groundwater actually been priced in Texas to date?

Data from actual sales shows three fundamental pathways in which buyers acquire access to groundwater in Texas (Figure 4). One method is to purchase the groundwater in place outright. The second method involves purchasing surface acreage to acquire the accompanying groundwater. The third method is to lease groundwater rights. The following section will offer case examples of each method and discuss how they price groundwater resources relative to one another.

Leasing and Sale of the Groundwater Estate in Texas

Texas law recognizes a separate groundwater estate that can be severed from the surface land and bought and sold as an independent asset. In its landmark *Coyote Lake Ranch* decision in May 2016, the Texas Supreme Court affirmed that the groundwater estate is not only a stand-alone real property interest, but that it is also dominant relative to the surface estate. Without specific contractual provisions to the contrary, a surface owner now generally cannot prevent a groundwater estate owner from making reasonable use of the surface in order to develop her asset.[30]

Coyote Lake Ranch reinforces the property rights underlying an approximately 50-year history of groundwater estate transactions in Texas. For example, in 1969 University Lands leased for up to 50 years all groundwater rights down to 1,200 feet depth on an 11,500-acre tract in Ward County to an entity called Duval Corporation, which subsequently transferred its interest to the Colorado River Municipal Water District.[31] Furthermore, in a 1986 transaction, University Lands leased all groundwater that was potable or capable of being rendered potable under a 1,319-acre tract in Upton County to the

[27]Bruce K. Darling, "The Rule of Capture, Changing Perspectives on Water Management in Texas, the Tragedy of the Commons, and Developments in the Valuation of Groundwater," Conference Paper, April 2009, DOI: 10.13140/RG.2.1.1516.3047.

[28]For these points, I am indebted to the insights shared with me in October 2017 by a large Delaware Basin frac water supplier.

[29]Matthew Cranston, "Earnings call for farm value," FarmOnline National, 17 March 2014, http://www.farmonline.com.au/story/3578573/earnings-call-for-farm-value/.

[30]*Coyote Lake Ranch, LLC v. City of Lubbock*, 498 S.W.3d 53, 65 (Tex. 2016), reh'g denied (Sept. 23, 2016). (The principle, absent an agreement to the contrary, that a severed mineral estate's implied right to use the surface must be exercised with due regard for the surface estate's rights, and the rules common to mineral and groundwater estates, compel the conclusion that the accommodation doctrine extends to groundwater estates.)

[31]Agreement available upon request.

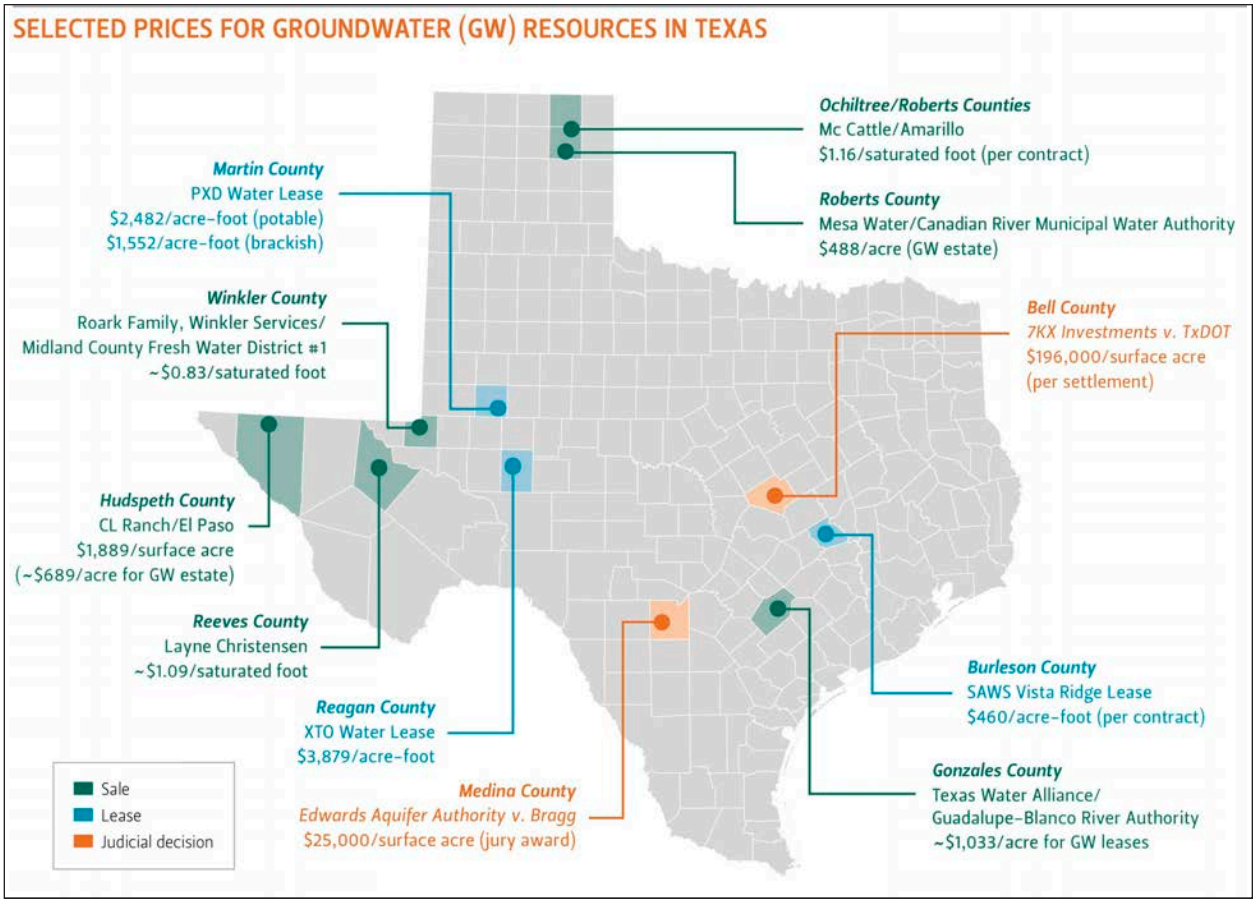

Figure 4. Selected valuations for groundwater resources in Texas, $/acre-foot (flow values), $/saturated foot (groundwater estate values), $/surface acre (judicial values). Note: In sales tranactions listed, seller is listed first followed by the buyer (i.e., seller/buyer) where applicable. Source: Baker Institute for Public Policy, CRMWA, Water Supply Agreements, Company Reports, Local Newspapers, Author's Model (Layne Christensen asset).

Upton County Water District.[32] Like the Ward County agreement discussed above, the Upton County contract also used a total potential lease life of 50 years.

Moving to recent transactions, the Vista Ridge project is perhaps the signature groundwater lease project in Texas at present. Vista Ridge aims to begin supplying water to San Antonio in 2020 through a 142-mile pipeline from Burleson County. SAWS will purchase groundwater from a trust controlled by Blue Water VR at a price of $460 per acre-foot.[33] This groundwater is sourced from a pool of 1,312 individual groundwater leases covering a total of 50,000 surface acres.[34]

Metropolitan Water Company, L.P. amassed these leases over a period of approximately 15 years as part of its Porter's Branch Groundwater Project, which the company claims "was the first large-scale Groundwater Lease Project in the State of Texas."[35] Met Water then transferred a portion of the total lease pool to Blue Water, which in turn marketed them to the Vista Ridge project. Landowners who leased their water receive a royalty equal to 10% of the water purchase price, or $46 for each acre-foot produced.[36]

The author has also located two examples of agreements to sell groundwater in place.[37] One contract specified a price based on the thickness of water-saturated strata underneath the

[32] Agreement available upon request.

[33] Conformed Version of SAWS Vista Ridge Water Transmission and Purchase Agreement, as revised by the Third Amendment dated April 5, 2017, http://www.saws.org/your_water/waterresources/projects/vistaridge/download.cfm. Pg. 601.

[34] "Groundwater Leases of Metropolitan Water Company, L.P." http://www.metwater.com/landleases/index.html.

[35] Ibid.

[36] http://www.hillcountryalliance.org/wp-content/uploads/2015/12/Vista-Ridge-Project-Financial-Questions-Answered-Nov-18-2015-3.pdf.

[37] There are almost certainly many more such agreements, but most are confidential and kept inaccessible to the public. The agreements cited by the author involved a municipal entity and were thus accessible via a request under the Texas Open Records Act.

tract of interest, while the second agreement entailed the payment of a fixed price for the groundwater estate under a tract.

In the first instance, the City of Amarillo agreed in 2015 to purchase the groundwater estate from the base of the Ogallala Aquifer upwards under the lands of the Mc Cattle Company in Roberts and Ochiltree counties northwest of Amarillo. The City priced the water resource based on the feet of saturated water available under each acre in the surface tract and attached a value premium to those acres underlain by the thickest saturated layer. It paid $250 per surface acre for acreage underlain by a saturated layer with an average thickness less than 200 feet, $300 per acre for acreage with an average saturated thickness between 200 and 257 feet, and $1.16 per average saturated foot for each acre with saturated aquifer strata with an average thickness of 258 feet or more.[38]

In the second instance, the Midland County Fresh Water Supply District No. 1 paid $3.2 million to Winkler Services and members of the Roark family to purchase the groundwater rights underneath approximately 4,500 acres of the Roark Ranch.[39] Data from the Texas Water Development Board (TWDB) show that the average thickness of the Pecos Valley Aquifer under the tract is approximately 850 feet.[40] This suggests a groundwater estate purchase value of approximately $0.83 per water-bearing foot per acre.

Parties seeking water may also purchase an entire tract of land in order to access the water underneath. This is more likely to occur with sales of farmland, where property owners may be reluctant to sever the groundwater estate, since doing so impairs the land's farming value.[41] Accordingly, "unbundling" the value of the surface alone can shed light on the likely value of the groundwater beneath. This is important to parties considering agricultural investments where the water "renders the land its value," as well as to parties such as municipalities, water export project developers, or oilfield water suppliers that only seek access to the groundwater estate but may have to purchase the surface tract to obtain the water underneath.[42] Unbundling opens the door for a direct "apples-to-apples" comparison of the implied price paid for groundwater in a land purchase transaction and the price paid for an explicit agreement to acquire only the groundwater estate beneath a tract.

The value-unbundling process proceeds as follows:

1. Take the entire capital investment amount. In addition to the land and groundwater, this can also include the value of fixtures or improvements to the land, if relevant.
2. Subtract the cost of infrastructure, labor, and other non-land expenditures (which may have to be estimated) from the total capital investment amount.
3. Take the remaining dollar figure, which reflects the implied value paid for the land and divide by the number of acres in the tract to find the implied total cost per acre for the land and the water beneath.
4. Find data that reflect the value of the land per acre in its "most recent prior use" (farming, for instance).
5. Subtract the most recent prior-use value from the total value paid per acre of land. This reveals the implied "premium" paid for the groundwater.
6. Divide the premium by the average saturated thickness of the groundwater underlying the land to derive the implied value paid per saturated foot per acre.[43]

The author's recent work offers an example of how to develop in-place groundwater valuations by combining total purchase price or capital investment data and baseline land value data for a specific region of Texas, as outlined below.[44]

Finding the value

First, the author developed an input cost model based on technical and other data, then refined the model based on conversations with knowledgeable industry sources. Next, the estimated input cost figure ($15.2 million) was subtracted from the total reported project capital investment of $18 million, leaving an implied land cost just over $2.7 million. Dividing

[38]See Contract of Sale, Groundwater Rights between Mc Cattle Company and M&D McLain Family (sellers) and City of Amarillo (purchaser).

[39]Winkler Services also retained a royalty interest in water sold, with a scaled system that premium priced water from the ranch based on its quality as measured by total dissolved solids content.

[40]This figure was calculated by taking a shapefile of the Pecos Valley Aquifer from the Texas Water Development Board containing approximately 6800 data points, including thickness of the water-saturated strata, finding the 14 cells that completely or partially underlay the relevant sections of the Roark Ranch in Winkler County, and then averaging the thickness of those cells and using that number as the denominator to calculate the price paid for the groundwater estate.

[41]That said, in wetter areas near the Texas Triangle where high-value, large-volume water sales to municipalities are a real possibility, some landowners now wish to retain groundwater ownership interests in case water leasing occurs in the future. A groundwater conservation district official in Central Texas that the author spoke with in September 2017 noted that in that area, landowners increasingly seek to retain all or part of the groundwater estate associated with the tract they are selling.

[42]There can be exceptions. Consider, for instance, the hypothetical of a developer who purchases the entirety of the surface estate of a 1,000-acre tract for $1,000 per acre, then re-sells the surface rights for the same $1,000 per acre, but severs and retains the groundwater estate. Such situations are less likely now that more parties in Texas recognize the value of groundwater—especially for large tracts where farming, water sales to cities and the oilfield, and other such activities are feasible and may actually be a core reason for purchasing that particular piece of land.

[43]Derived from Gabriel Collins, "Valuation of Groundwater In Place at a Texas Frac Water Supplier," Baker Institute Issue Brief, 7 December 2017, https://www.bakerinstitute.org/media/files/research-document/c96199a5/bi-brief-120717-ces-groundwatervalue.pdf.

[44]Ibid.

Table 1. Estimating the likely value for the groundwater estate at Layne's Hermosa Oilfield Water Supply Asset. Source: Company reports, author's interviews of relevant providers of goods and services.

Item	Units	Number	Unit cost	Subtotal
Wells (new drill)	-	2	$127,250	$254,500
Wells (refurbish)		4	$65,000	$260,000
Storage ponds (built and lined)	bbl	750,000	$1.25	$937,500
Pumps (200 HP)	-	4	$25,000	$100,000
Booster pumps on pipeline		3	$10,000	$30,000
22-in high-density polyethylene pipeline	feet	107,000	$90.20	$9,651,400
Pipe fusion	joint welds	2,112	$150.00	$316,800
Trencher operation (Vermeer T1155)	feet	107,000	$7.50	$802,500
Right-of-Way	miles	20	$71,680	$1,433,600
Riser stations for water offtake		13	$15,000	$195,000
Labor	days	90	$8,400	$756,000
Branch lines linking wells to central pits	feet	21,000	$12	$252,000
Electronics on wells		6	$10,000	$60,000
Electrification		1	$50,000	$50,000
Concrete	tonnes	500	$167	$83,250
Rebar	tonnes	16	$600	$9,494
Roads	miles	1.50	$50,000	$75,000
Total, ex-land				$15,267,044
Total estimated CAPEX				$18,000,000
Implied land cost				$2,732,956
Acreage				1,000
Implied land value per acre				$2,733
Est. value of "farming only" farmland in trans-Pecos region ($/acre)				$750
Implied value premium for water, $/acre				$1,983
Average available aquifer thickness under tract				1,825
Implied price paid for groundwater estate ($/available foot)				$1.09

that number by 1,000 acres delivers a land cost of $2,733 per acre. Land sales value data from the Texas Chapter of the American Society of Farm Managers and Rural Appraisers (ASFMRA) indicate that irrigated cropland in the Trans-Pecos region of Texas sold for an average price of between $500 and $750 per acre in 2016.[45]

To be conservative, the high end of the ASFMRA value range ($750 per acre) was subtracted from the implied land valuation of $2,733 per acre, leaving an implied value premium

[45] "Texas Rural Land Value Trends for 2016" (report presented at the 27th Annual Outlook for Texas Land Markets, April 20, 2017), 23.

Cost of water City is forced to purchase from High Cost Water Authority	$1,000 per acre-foot
-	
New cost of self-sourced water if City deepens wells and taps Farmer Joe's deep aquifer.	$600 per acre-foot
=	
Implied maximum price City would be willing to pay for Farmer Joe's water	**$400 per acre-foot**

Figure 5. Avoided cost valuation in action—valuing Farmer Joe's deep aquifer rights.

of $1,983 per acre for groundwater. The Pecos Valley Aquifer shapefile from the TWDB was then laid over the approximate location of the Layne tract using QGIS software. The cells where the two layers overlapped were selected, and the thickness of each cell was used to calculate the average thickness of the water-bearing strata under the tract area (1,825 feet). Finally, the $1,983 implied water premium per acre was divided by 1,825 feet of potentially water-bearing thickness shown in the TWDB model data, yielding an implied groundwater estate valuation of $1.09 per saturated foot per acre (Table 1).

The price paid for water in place can become a basis for analyzing other groundwater transactions across the state, subject to adjustment factors.

Method 2: Avoided cost

Groundwater can also be valued relative to the savings realized by procuring water from a lower-cost supplier, since avoiding a cost effectively yields an economic benefit.[46] Other authors have called this concept "replacement cost," but the concepts are essentially alike, as both measure the cost of self-sourcing water to either compensate for a supply disruption or avoid procuring water from more expensive sources.[47] It is an especially relevant methodology in cases where an entity such as a city or farm owns the water wells and supporting infrastructure necessary to produce and deliver water but is subjected to a politically motivated requirement that it procure water from an alternative higher cost source (Figure 5).

Consider the following simplified hypothetical example:

Burdened City supplies its residents from a well whose water costs $100 per acre-foot to pump to the surface, $200 per acre-foot to treat, and $300 per acre-foot to distribute. Despite Burdened City having access to a relatively shallow aquifer, Acme Water Conservation District amends its ruleset to require all large-scale groundwater pumpers to reduce withdrawals by 50% and instead purchase water from an alternative supply source (the High Cost Water Authority) costing $1,000 per acre-foot.

Taking High Cost Water's price of $1,000 per acre-foot and subtracting the likely cost of self-sourced groundwater of $600 per acre-foot [$100 per acre-foot lifting cost + $200 per acre-foot treatment cost + $300 per acre-foot distribution cost] leaves a difference of $400 per acre-foot.

Under serious budgetary pressure from the cost of paying over 60% more for its water, Burdened City searches for alternative options. It decides to tap a deeper aquifer layer exempted from the groundwater pumping restrictions, whose rights are owned by Farmer Joe. The Farmer hasn't used the deeper water to date because it costs too much to pump for agricultural use. But the City has run its numbers and realizes that it can deepen its wells and use its existing infrastructure to produce, treat, and distribute Farmer Joe's water to municipal customers at the final cost of $600 per acre-foot described above.

So how much would the City potentially be willing to pay Farmer Joe for his water? The likely solution is up to $400 per acre-foot. Any amount between that figure and zero would represent a net economic gain for the City, as it would allow it to avoid the existing cost it must bear for supplies from High Cost Water Authority.

Avoided cost valuation will likely prove especially important to medium-sized and smaller cities as well as farmers and industrial water users. Such parties generally cannot take on

[46]"Assessing the Value of Groundwater," UK Environment Agency, Science Report—SC040016/SR1, http://www2.aueb.gr/users/koundouri/resees/uploads/Econ%20Val%20GW.pdf.

[47]Charles Porter and Ed McCarthy, "Valuation of Water Rights," 2016 Texas Water Law Institute, https://utcle.org/practice-areas/index/practice_area_id/26.

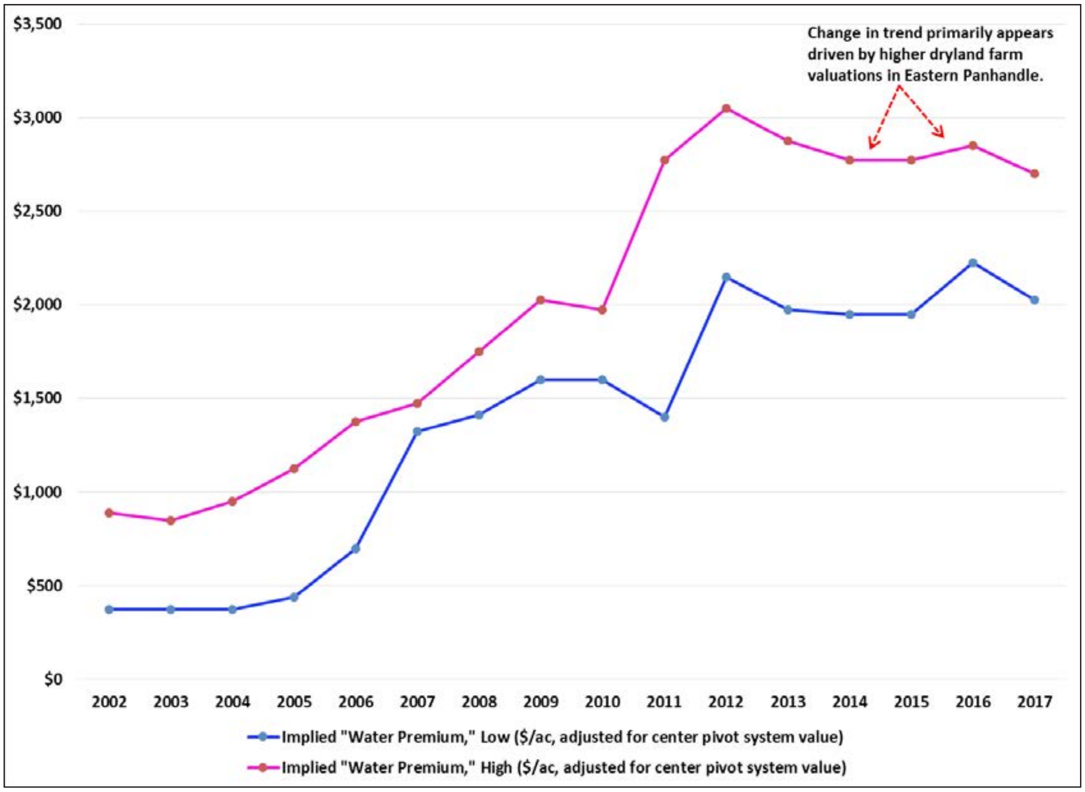

Figure 6. Implied water value in North Texas Panhandle based on land value method, $/acre. Source: ASFMRA, author's analysis.

the hefty financial risk of multibillion-dollar water supply projects like the Vista Ridge pipeline. Accordingly, they will likely seek to augment their water resources by acquiring groundwater-bearing tracts near their existing wellfields and pipelines, using a strategy of incremental expansion. This in turn is likely to drive ongoing market activity in the form of such cities/governmental entities and certain large private consumers leasing or purchasing entire land tracts or, at the very least, the groundwater estate beneath them.

Method 3: The land value method

The land value method is an inductive approach, which derives water values by comparing transactions of irrigated and non-irrigated farmland. For instance, if dry cropland in an area sells for $1,000 per acre and irrigated cropland in the same zone sells for $2,000 per acre, this would suggest that the water associated with the land is worth $1,000 per surface acre. The method is simple and provides a "starting-point" value for a broader assessment. Yet with proper adjustments for the capital costs of accessing and using the water (center pivot sprinklers, for instance), useful basic valuations can be rapidly obtained and used as reference points.

Data from the annual Texas Rural Land Value Trends report offer insights into the implied value of water per acre of farmland sold. The instant analysis focuses on the Northern Texas Panhandle. This region, consisting of Carson, Dallam, Gray, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Potter, Roberts, and Sherman counties, is one of the most intensively farmed in Texas *and* relies almost exclusively on groundwater for irrigation. As such, the difference in value per acre between dryland and irrigated farm tracts offers a relatively "pure" indicator of how much value the water renders to the land. The land value method's utility in a farming-centric area such as Northwest Texas is reinforced by the fact that buyers and sellers of land in the area are typically sophisticated parties who understand the land's potential to yield income through agricultural production and how water is an integral component of that process.

To calculate the value of water on Northern Panhandle farmland, this author employs a three-step process. First, take the reported value range of "irrigated cropland good water," which in 2016 was $3,000–$4,000 per acre, based on reported transactions that year. Second, subtract the value of dry cropland in the eastern portion of the northern Panhandle ($750–$1,200 per acre) from the value of the irrigated land. This yields a difference of $2,250 per acre [$3,000–$750] on the low end and $2,800 per acre [$4,000–$1,200 per acre] on the high end. Third, these numbers should then be adjusted for the value per acre of center pivot sprinkler systems, which are the primary mode of irrigation in the northern Texas Panhandle.

Data from Texas A&M University suggest a cost range of $325–$375 per acre for a quarter-mile center pivot capable of watering 120 acres and $200–$250 per acre for a half-mile center pivot system capable of watering a 500-acre area, not including the costs of drilling water wells and installing pump equipment.[48] Since farm tracts vary in size but tend to be larger than 500 acres in the area of interest, this analysis assumes a cost of $225 per acre for center pivot systems, which we apply as an "adjustment factor." That step yields final implied water values in 2017 of $2,025 per acre on the low end [$2,250–$225] and $2,700 per acre on the high end [$2,925–$225] (Figure 6).

To "cross-check" the theoretical valuation outlined above, the author compares it to the price Amarillo paid for the Mc Cattle Company's groundwater estate in southern Roberts and northern Ochiltree counties, which, like the farmland discussed above, is located in the Northern Panhandle.

Under eight sample tracts of farmland listed for sale in the Northern Texas Panhandle as of late October 2017, the average thickness of the High Plains Aquifer averaged between 450 to 710 feet, depending on the tract. Amarillo paid $1.16 per saturated foot in 2015 for the thickest portions of the Mc Cattle groundwater estate. If we assume that there are 500 feet of saturated layer under a farm whose adjusted water value is $2,500 per acre using the land value method, this would suggest a value for water in-place of $5.00 per saturated foot.

The improvements made to land for farming can increase the surface tract's value and implicitly reduce the "groundwater premium" but even those adjustments would still likely leave groundwater estate values more than twice as high as those paid by Amarillo in its 2015 purchase. One possible explanation for the disparity is that a farm typically pumps and consumes water close to the wellhead, while supplying water from a distant asset—Mc Cattle's tracts are located roughly 90 miles from Amarillo—requires expensive infrastructure whose cost must also be borne by the end users of that water. The fact that a final delivered water price includes all costs necessary to pay back capital investments and cover operating expenses—from pumping, to treatment, to delivery—potentially limits the actual price that can be paid for the groundwater itself, lest the final delivered water become unaffordable for customers.

Method 4: Income capitalization

The income capitalization method is most appropriate for valuing groundwater in contexts where money is invested in a water-focused asset to generate cash flow. This happens when direct sales of water are occurring or where the water is a critical input to a broader industrial or agricultural process that generates cash flow *and* water's contribution to the final value of the product can be clearly attributed. As a general proposition, income capitalization should be employed as a valuation technique "only when actual income from the property can be established in a continuing on-going business."[49]

The income capitalization method fundamentally hinges on the perceived risk of an investment, as this is a key determinant of the discount rate applied to an income stream.[50] Water sales transactions often involve significant risks that can arise from timing, climate factors, and, perhaps most of all, legal, political, and regulatory barriers that prevent an owner from monetizing groundwater resources. Returns-focused investors generally want to pay back the original capital as quickly as possible and then begin garnering returns on the original capital employed. This reality has two immediate implications for prospective Texas water investments and the valuation of the underlying water.

First, as McCarthy and Porter point out, municipal and industrial water sourcing agreements generally specify prices, minimum offtake volumes, and a multi-year (often decades long) timetable over which the deal plays out. Each of these factors, generally speaking, "de-risks" a transaction and suggests capitalization rates should be lower than those that an appraiser would apply to more speculative water transactions. Second, oilfield water supply deals, which bear a high degree of risk from commodity price volatility and which are generally spot market or short-term deal structures without take-or-pay conditions, will usually entail much higher capitalization rates.

A capitalization rate of between 20% and 30% represents the level of returns that would likely be needed to entice capital into an oilfield water supply deal without long-term minimum volume commitments, as well as to offset the opportunity costs of putting capital to work in competing investments in real estate, oil and gas, and other sectors. Valuation estimates for municipal supply projects could likely be defensibly capitalized at lower rates.

Consider the Table 2 example, which compares the capitalized value of water used in the Trans-Pecos region of Texas as an intermediate input for growing alfalfa and as hydraulic fractur-

[48]"Center Pivot Irrigation," Texas Agricultural Extension Service," B-6096 4-00, http://aglifesciences.tamu.edu/baen/wp-content/uploads/sites/24/2017/01/B-6096-Center-Pivot-Irrigation.pdf.

[49]Foster v. United States, 2 Cl. Ct. 426, 448 (1983); The Texas Property Code further notes that when a governmental entity condemns land that includes groundwater rights and the rights may be developed or used for a public purpose, the resulting condemnation proceeding should use methodologies prescribed in Chapter 23 of the Texas Tax Code, which includes income capitalization Tex. Prop. Code Ann. § 21.0421 (West)(b); Tex. Tax Code Ann. § 23.012 (West).

[50]A broadly accepted "risk-free rate" is the annual interest rate paid on 10-year United States Treasury notes (commonly known as "T-Bills"). Investors generally seek to put their capital to work in exchange for returns that would be a multiple of the risk-free rate.

Table 2. Sample valuations of water using the income capitalization method.

	Alfalfa farm	Alfalfa farm, high	Municipal water sales	Intermittent frac water sales	Contract frac water sales
Acreage	640	640	N/A	N/A	N/A
Commodity Units Sold	6.8	6.8	15,000	1,500,000	9,000,000
	Tonnes	*Tonnes*	*Acre-Feet*	*Barrels*	*Barrels*
Unit Price	$196	$245	$500	$0.50	$0.50
	Per Tonne	*Per Tonne*	*Per Acre-Foot*	*Per Barrel*	*Per Barrel*
Gross Income	$854,400	$1,068,000	$7,500,000	$750,000	$4,500,000
Total Costs	$644,480	$644,480	$1,500,000	$60,000	$360,000
Net Income	$209,920	$423,520	$6,000,000	$690,000	$4,140,000
Capitalization Rate	16%	16%	10%	30%	15%
Implied Payback Time of Investment, Years	6.3	6.3	10.0	3.3	6.7
Capitalized Income	$1,312,000	$2,647,000	$60,000,000	$2,300,000	$27,600,000
Water Used Annually, acre-foot	1,626	2,033	15,000	193	1,160
Indicated value of groundwater used / sold, ($ / acre-foot)	**$807**	**$1,302**	**$4,000**	**$11,896**	**$23,791**
High leverage to commodity price changes	**A price increase of only 25% boosts the indicated value of the groundwater used by 160%.**			Significant, but lesser leverage to changes in Capitalization Rate	**A 50% reduction in the capitalization rate doubles the indicated value of groundwater sold.**

Source: Harry F. Blaney and Eldon G. Hanson, "Consumptive Use and Water Requirements in New Mexico," Technical Report 32, New Mexico State Engineer, Pg.19; "Period of Record Monthly Climate Summary: Pecos, TX," Western Regional Climate Center, http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?tx6892; Yonts et.al, "Water Loss from Above-Canopy and In-Canopy Sprinklers," University of Nebraska Extension, http://extensionpublications.unl.edu/assets/html/g1328/build/g1328.htm; Laurialt et.al, "The 2015 New Mexico Alfalfa Variety Test Report," New Mexico State University, http://aces.nmsu.edu/pubs/variety_trials/AVT15.pdf; Texas District 6 Alfalfa Crop Budget, 2017, TAMU Extension, https://agecoext.tamu.edu/resources/crop-livestock-budgets/budgets-by-extension-district/district-6-far-west/2017-district-6-texas-crop-and-livestock-budgets/, Texas District 6 Center Pivot Cotton Crop Budget, 2017, TAMU Extension, https://agecoext.tamu.edu/files/2017/02/2017D6TPCottonPivot.pdf; Author's Interview of Permian Basin-focused oilfield water investors, October 2017.

ing fluid. Two things quickly become apparent. First, changing the underlying commodity price massively shifts indicated water value when using the income capitalization method. Alfalfa that costs $196 per ton under normal conditions implies a water value of $807 per acre-foot. If we assume that alfalfa prices and water use each rise 25% due to drought, the indicated value of the groundwater used rises by 160%, leverage of more than six-fold. Second, changing the capitalization rate (i.e. the risk profile of an asset) also exerts substantial, although much less dramatic impacts on underlying water values.

To further test the data in Table 2, we analyzed a sales listing from an irrigated corn farm in Sunray, Texas, located approximately 50 miles north/northeast of Amarillo. The 480-acre center pivot-irrigated farm was listed as of early November 2017 on Lands of Texas for $1,488,000.[51] U.S. Department of Agriculture National Agricultural Statistics Service census data from 2013 indicate that statewide, Texas corn producers using pressure irrigation enjoyed a yield of 202 bushels per acre (~5 metric tons per acre). Crop budget data for the North Panhandle from Texas A&M suggest that growers in that area—where the Sunray farm is located—could potentially reap closer to 225 bushels per acre.[52] At a realized price of $3.80 per bushel, the farm could thus produce $855 per acre in revenue. Using data from the same crop budget, corn grown on land owned by the farmer would incur costs of approximately $748.56 per acre, yielding a net income of $106.44 per acre and $51,091.20 for the entire farm [$106.44 per acre X 480 acres]. At a capitalization rate of 16%, the capitalized net income would be $319,320.

So how does this translate into a value for water? Data from the TWDB show that between 1999 and 2007, farmers in the North Plains region applied an average of 14.44 inches of irrigation water to their crops per year—roughly 1.2 feet.[53] A farm like Sunray would thus likely require about 576 acre-feet of water per year to maintain its corn production, suggesting the water has an indicated value of approximately $554 per acre-foot [$319,320 of capitalized income ÷ 576 acre-feet of water]. Using a corn price of $5 per bushel would drive the implied water value up to nearly $1,961 per acre-foot; a 2.5-fold increase in implied water value driven by an increase of only 32% in the value of the underlying commodity being produced with the water.

It is interesting to consider how water valuations reached via the income capitalization method compare to alternative business valuations using multiples of cash flow or earnings. For instance, the hypothetical intermittent fracturing sales business shown in Table 2 has a capitalized income value of $2.3 million when valued with a 30% capitalization rate (indicating a volatile, high-risk business). Oilfield water investors the author has spoken with generally examine cash flow when evaluating such an asset. In doing so, they would typically use a rule of thumb that a water sales business is worth two to three times earnings before interest, taxes, depreciation, and amortization (EBITDA).[54] With annual net income of $690,000 in the example below, plus fixtures (wells, catchment pit, etc.) that are likely worth at least $500,000, this would suggest a business valuation of $1.9 million [$690,000 EBITDA X 2 + $500,000 in fixtures] on the lower end and $2.6 million on the upper end [$690,00 EBITDA X 3 + $500,000 in fixtures]. The capitalized income value suggested by the simple model above falls almost squarely in the middle of that range, which indicates it can be valid as a "quick-and-dirty" method for assessing possible values of a water-centric business.

Method 5: Residual Value

The concept of calculating a residual value (or "shadow price") for water is rooted in the idea that a profit-maximizing enterprise will only use water to the point at which the net revenue generated by using that additional unit of water is equal to the marginal cost of obtaining it.[55] Residual value analysis is appropriate for valuing water for agricultural or industrial use if comparable transaction data cannot be found or if water is an input that is not explicitly priced. Many of these circumstances would involve parties with their own water supply infrastructure, in which case "cost of substitute" valuation methods could also be used.

Crop budget residual valuation has been utilized to assess the value of water in multiple locations globally, including the High Plains region of the United States along with Spain, and Namibia.[56] At its core, this technique takes the total value of output from growing a specific crop or conducting a specif-

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[51]https://www.landsoftexas.com/property/480-acres-in-Sherman-County-Texas/3440331.

[52]District 1 Crop Budget for Bt corn, sprinkler irrigated, Texas A&M AgriLife Extension, 2018, https://agecoext.tamu.edu/resources/crop-livestock-budgets/budgets-by-extension-district/district-1-panhandle/2018-district-1-texas-crop-and-livestock-budgets/.

[53]http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R378_IrrigationMetering.pdf.

[54]Broadly similar businesses such as manufacturing or construction firms might be evaluated using a multiple of 3-4 times "seller's discretionary earnings," a measure analogous to cash flow, as commonly defined. Barbara Taylor, "Determining Your Company's Value: Multiples and Rules of Thumb," The New York Times, 15 July 2010, https://boss.blogs.nytimes.com/2010/07/15/determining-your-companys-value-multiples-and-rules-of-thumb/.

[55]Mesa-Jurado, M.A. et. al., Irrigation Water Value Scenarios for 2015: Application to Guadalquivir River," Paper prepared for presentation at the 107th EAAE Seminar "Modelling of Agricultural and Rural Development Policies". Seville, Spain, January 29th -February 1st, 2008, https://ageconsearch.umn.edu/bitstream/6450/2/pp08me20.pdf.

[56]Concept drawn from Jadwiga R. Ziolkowska, "Shadow price of water for irrigation—A case of the High Plains", In Agricultural Water Management, Volume 153, 2015, Pages 20-31, ISSN 0378-3774, https://doi.org/10.1016/j.agwat.2015.01.024. See also: J. Berbel, M.A. Mesa-Jurado, J.M. Piston, "Value of irrigation water in Guadalquivir Basin (Spain) by residual value method," Water Resour. Manage., 25 (6) (2011), pp. 1565-1579 and "Case studies of water valuation in Namibia's commercial farming areas, G.M. Lange, R. Hassam (Eds.), The Economics of Water Management in Southern Africa: An Environmental Accounting Approach, Edward Elgar Publishing, Chelthenham (2006), pp. 237-255, and finally, James Macgregor, et.al., "Estimating the Economic Value of Water in Namibia," paper prepared for 1st WARFSA/Waternet Symposium: Sustainable Use of Water Resources; Maputo; 1-2 November 2000.

ic industrial activity under a specified set of conditions and subtracts the operational costs incurred under those conditions. Expenses include seed, fertilizer, labor, fuel, equipment depreciation, and importantly, the capital and operating costs associated with providing necessary irrigation water to the crop. Including the costs of accessing groundwater is essential because it helps bring the analysis closer to what the water could potentially be worth while still in the ground.

The sum left over is then divided by the volume of water needed to grow the crop under the specified conditions, and the quotient shows the theoretical maximum amount a farmer could pay for the water and still break even.

Consider the following simple hypothetical:

Residual Value Simplified Example

Revenue From Hay Cultivation 50 acres X 10 tons per acre X $100 per ton = $50,000

Costs of Hay Cultivation 50 acres X $500 per acre = $25,000

Net Revenue = $25,000

Water Needed = 100 acre-feet

Net Revenue/Water Needed= Residual water value of $250 per acre-foot

Method 6: Net present value valuation

Net present value (NPV) analysis entails examining the amount of money an investment is expected to make and discounting it based on anticipated risks in order to translate expected investment returns into "today's dollars."[57] As such, NPV analysis offers some advantages to those seeking to value groundwater assets in a place such as Texas, where groundwater is owned as real private property. NPV analysis can help translate specific activities into the common language of financial value anchored along a timeline and providing transparent assumptions of the risks used to determine the requisite discount factors. This makes it a tool for conducting "apples-to-apples" value comparisons between disparate uses of the surface that might affect access to groundwater beneath.

For instance, a 1,000-acre tract of land in the Midland or Pecos area could have valuable groundwater underneath but might also be the subject of competition between various business interests. An oilfield water sales company might want to purchase the surface as a means to access the water beneath, leading it to seek a farmland-level price for the land to minimize the relative price it is paying for the underlying water, so as to maximize its returns on that natural capital asset. In contrast, a pipeline operator seeking to build a tank farm might be willing to pay a surface price far in excess of the implied "farmland value." This is because the pipeline company would be investing many tens of millions of dollars to install infrastructure intended to yield cash flow for decades and would presumably not seek to make a primary business of extracting and selling groundwater from under its tract.

Under this type of circumstance, using a "land value method" valuation approach like that employed in the Layne Christiansen example above could yield a highly distorted view of groundwater value. A bulk water seller might be willing to pay $2,500 per surface acre for the entire tract, but the pipeline operator might be willing to pay five or more times that much for subdivided portions of the tract. NPV analysis can potentially help bridge the valuation gaps by quantifying the economic returns each party expects relative to its anticipated investment outlay for the land.

Similarly, NPV analysis is also useful in environmental and water security contexts because it can provide insights into competing water users' willingness to accept payment to *forego* water use.[58] Such foregone use could take the form of spot market sales, longer-term supply agreements whereby a lower value user (like a cotton farm) fallows fields to supply water to a higher paying user (like oilfield frac'ers), and/or investment in technology that creates a more durable surplus of water available for alternative, higher-value uses. NPV analysis can potentially help backstop insights provided by sporadic local market transactions and potentially guide water owners in making more nuanced long-term allocation and investment decisions.

NPV analysis also has downsides. First, the calculation's mathematical structure is enormously sensitive to input assumptions. Commodity prices matter. For instance, a fracturing water project with an $18 million initial project investment that sells 100 thousand barrels per day (kbd) of water at an average water sales price of $0.35 per barrel (bbl) yields a net present value of approximately $70 per acre-foot of water, assuming a 15-year project life. Changing the water price to $0.40/bbl lifts the 15-year NPV to $121 per acre-foot. In other words, a 14% increase in the water sales price yielded a roughly 70% increase in the underlying groundwater resource's implied value.

Discount rate assumptions also matter. The discount rate for a water project typically consists of a baseline risk-free rate (typically the 10-Year T-Bill rate) and then a discretionary discount factor applied on top of that. In determining this rate, the borrower's company-level situation matters (how good of a credit is it in lenders' eyes?) and the global commodity price situation will also greatly influence the discount rate. Herein

[57]Amy Gallo, "A Refresher on Net Present Value," Harvard Business Review, 19 November 2014, https://hbr.org/2014/11/a-refresher-on-net-present-value.

[58]Qureshi, M. E., Ranjan, R. and Qureshi, S. E. (2010), An empirical assessment of the value of irrigation water: the case study of Murrumbidgee catchment*. Australian Journal of Agricultural and Resource Economics, 54: 99–118. doi:10.1111/j.1467-8489.2009.00476.x.

problems arise because a 10-year time horizon in the oil and gas or farming sectors exposes projects to potentially huge commodity price risks whose timing is very difficult to predict. Furthermore, there are currently no direct hedges a pure-play water seller can use to mitigate its exposure to oil and gas price fluctuations, particularly since energy producers in the Permian Basin generally avoid signing firmly binding take-or-pay contracts for water supplies.

The current NPV approach of making essentially straight-line risk projections will likely need to give way to methodologies that incorporate more probabilistic assessments and better reflect the complex realities of risk in the modern global economy. As two experienced risk assessment practitioners put it in late 2016: "*Valuation methods—not only for infrastructure projects but in general—should start by accepting that cash flows are uncertain and treat them accordingly. That is, relying on a branch of mathematics (probability and statistics) that knows how to deal with uncertainty*."[59] The same reasoning applies to water-oriented investment projects.

Method 7: Conservation Value

In certain instances, water may also have a "conservation value," in essence, an existence or preservation value. Since groundwater is owned as real private property in Texas, a regulatory regime aiming to preserve groundwater in place should compensate property owners for idling their natural capital assets. For surface lands, conservation easement values in Texas often range between 35% and 65% of the tract's market value.[60] Such a range could help anchor the determination of what property owners should be paid for groundwater assets that they forego developing for a certain time period.

CONCLUSION

Groundwater valuation is—and will remain—an exercise requiring analysts to make judgment calls for each specific asset and aquifer location being evaluated. But this is true of markets for many illiquid assets whose combined transaction volume is in the hundreds of billions of dollars per year globally, including other forms of real property such as residential and commercial properties as well as athletic talent, energy commodities, and intangible assets such as financial derivatives.

As long as those appraising water values provide a clear and transparent accounting of their assumptions and analytical inputs, defensible values are eminently achievable. Actionable valuations for water assets can unlock many billions of dollars in currently constrained economic potential, including reserve-backed lending, more sales and leases of water reserves in-situ, and potentially, enabling equity markets to price in the potentially significant water holdings of multiple publicly traded companies with substantial land footprints in Texas.

This analysis is akin to a "beta version software." It seeks to lay the foundation for more groundwater property holders to systematically value their assets, scrutinize the methodologies presented here, and, ideally, find ways to improve upon them. As the process of iterative improvement proceeds, the groundwater value data points developed can guide the creation of economic opportunities and the resolution of disputes alike. The author also hopes that more groundwater valuation data can be made publicly available. The TWDB already does an admirable job of making a substantial—and growing—repository of geospatial and hydrogeological data available to the public. Augmenting this dataset with greater disclosure of groundwater transaction prices and valuations can help property owners, policy-makers, and the voting public more effectively collaborate and craft policy approaches to protect private property and optimally manage our great state's groundwater resource base.

[59] Arturo Cifuentes and David Espinoza, "Infrastructure investing and the peril of discounted cash flow," The Financial Times, 2 November 2016, https://www.ft.com/content/c9257c6c-a0db-11e6-891e-abe238dee8e2.

[60] "FAQ Page: What amount can I expect to receive from a conservation easement?," Texas Agricultural Land Trust," http://www.txaglandtrust.org/faq-page/.

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Seasonal changes of groundwater quality in the Ogallala Aquifer

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Abstract: The Ogallala Aquifer extends beneath eight states in the Great Plains region of North America. It stretches from Texas to South Dakota and is among the largest aquifers in the world. In Texas, extraction of groundwater, primarily for cropland irrigation, far exceeds recharge resulting in a significant decline of the water table. In the Texas High Plains, this decline prompted restrictions set by a local water conservation agency in 2009 stating that in 50 years about 50% of the saturated thickness of the Ogallala Aquifer should be preserved. However, this restriction only addressed the quantity and not the quality of the remaining water. The quality of water extracted from the Ogallala Aquifer has been observed to change over time, especially over the length of a crop's growing season. We measured water quality over a three-year period using an electrical conductivity sensor and measured depth to water at 20 locations across five counties in the Texas High Plains. Results show that when wells are actively pumping, water quality can change in complex and unpredictable ways. In some cases, water quality declined and in others water quality improved. This result has prompted us to further investigate the mechanisms involved in observed seasonal water quality changes.

Keywords: Ogallala Aquifer, water quality, groundwater, irrigation, conductivity

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Terms used in paper

Short name or acronym	Descriptive name
ARS	Agricultural Research Service
CP	center pivot
°C	degrees Celsius
EC	electrical conductivity
km^2	square kilometers
m	meter
mg/L	milligrams per liter
mL	milliliter
SDI	subsurface drip irrigation
THP	Texas High Plains
TDS	total dissolved solids
USDA	U.S. Department of Agriculture
µS/cm	micro-Siemens per centimeter

INTRODUCTION

The Ogallala Aquifer extends across an area of approximately 450,000 square kilometers (km^2) (173,746 square miles) and is among the largest aquifers in the world (http://water.usgs.gov/ogw/aquiferbasics/ext_hpaq.html). This vast aquifer extends across portions of eight states where it is the primary source of irrigation water for various crops, accounting for 27% of the irrigated land in the United States (Darton 1898; Gollehon and Winston 2013). In the Southern High Plains, the Ogallala formation was deposited by ancient rivers that once flowed west to east from the mountains of New Mexico. Remnant paleo-valleys such as the Winkler, Simanola, and Portales valleys have been identified and mapped by geologists that have studied the area (Holliday 1995). These valleys were sequentially abandoned as the Pecos Valley formed and provided a new path to the Rio Grande and ultimately to the Gulf of Mexico. The waters contained within the Ogallala sands and gravels deposited by these ancient streams were subsequently covered and preserved by aeolian deposits, such as the Blackwater Draw formation (Robbins 1941).

Today, the Ogallala Aquifer is being depleted at a rapid rate. Changes in the saturated thickness of an aquifer respond to changes in the balance between recharge and discharge. On the High Plains of the Llano Estacado, the only significant source of recharge is precipitation; however, hydrogeological studies have shown for decades that groundwater withdrawals exceed the amount of recharge by a large margin (Cronin 1969; McGuire 2014). Thus, despite its critical importance to irrigated agriculture, the Ogallala Aquifer is being depleted at a rapid rate (Dutton et al. 2001; Custodio 2002; Whitehead 2007; McGuire 2014). Depth-to-water measurements obtained each year by the High Plains Underground Water Conservation District indicated that the saturated thickness of the aquifer has dropped at an average rate of 0.3 meters (m), or 1 foot, per year since 1985 (McCain 1996; HPWD 2014). During drought conditions, the depletion of the aquifer can accelerate to nearly twice this long-term rate (Mullican 2013).

While conservation of the quantity of groundwater is important, the quality of the remaining groundwater is equally important (Chaudhuri and Ale 2014; Ledbetter 2014). It has been suggested that the impact of increased salinization of freshwater is a significant threat to global water resources (Williams 2001). Aqueous salinity is a measure of the dissolved mineral content of water and is reported in units of milligrams per liter (mg/L) total dissolved solids (TDS). The quality of water produced from the Ogallala Aquifer generally falls into the category of brackish (1,000–10,000 mg/L TDS) (Hanor 1994). The Dockum Aquifer, a second aquifer that underlies the Ogallala Aquifer, and is categorized as saline, typically has TDS values exceeding 10,000 mg/L (Hanor 1994). In general, water quality decreases in the lower sections of the saturated thickness of an aquifer (Hanor 1994; Druhan et al. 2008). This phenomenon is one of the causes of increased salinization of aquifers over time in agricultural regions above the Ogallala Aquifer, pumping of available groundwater for irrigation creates a situation where this common mechanism for groundwater salinization occurs (Druhan et al. 2008). Typically, there would be a diffuse mixing layer of variable thickness that would separate areas of higher and lower salinity. Pumping of groundwater induces the migration of poorer quality water (such as that in the Dockum), and if pumping rates are high enough, the saline water can enter the well's capture zone resulting in increased salinity of irrigation water (Kreitler 1993).

While it is commonly accepted that the deeper water in an aquifer is more saline (Hanor 1994; Druhan et al. 2008), of interest to agricultural producers in the Texas High Plains (THP) is the quality of the deeper and more saline water and its suitability for irrigation, which would be accessed in the later months of the growing season. On the THP and during the growing season there is a need for irrigation during the dry period from the end of July to early September. Irrigation wells are generally running at full capacity to compensate for the lack of rain during this critical period. The objective of this study was to sample the quality of the water in a number of irrigation wells across several counties in the THP during the growing season (1 April to 1 October) (Howell et al. 1996; Lascano 2000; Bordovsky et al. 2012; TAWC 2013). We hypothesized that as the cone of depression, caused by water extraction, expanded to deeper depths the water pumped for irrigation would become more saline. This assessment is needed to understand the long-term impact of lower quality water on crop irrigation.

METHODS

Well Sampling

Water samples were taken from all sites at approximately two-week intervals starting in spring of 2014 and continuing through 2016. When the wells were in operation, water samples were obtained from spigots on wells. If the wells were inactive, then pencil bailers (EcoBailer, ECOPVC 703, Mississauga, Ontario, Canada[1]) were used to obtain water samples. Water samples were placed in 60 milliliter (mL) vials (Thomas Scientific, pre-cleaned clear vial with 0.1 SEPTA cap, 9-093-2, Swedesboro, New Jersey). When the wells were not active, depth-to-water measurements were obtained with an "electric line" water level sensor (Solinst, Model 102, Georgetown, Ontario, Canada). Water samples were then filtered through a 0.2-millimeter filter and tested for pH (Mettler Toledo, MA235 pH/Ion Analyzer with InLab 413 pH Probe, Columbus, Ohio) and electrical conductivity (EC) was measured with a conductivity sensor (Thermo Orion, Model 105A with 011050 conductivity cell, Waltham, Massachusetts). Thereafter, remaining water samples were placed in a 20 mL vial (National EPA Vial Kit) and stored at 4 degrees Celsius (°C) (39 degrees Fahrenheit).

[1]Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Site Description

A total of 20 irrigation wells were selected for sampling. The selected wells spanned five counties of the THP, which from south to north included Terry, Lubbock, Hockley, Cochran, and Lamb counties (Figure 1). Permission was obtained from producers to access the irrigation wells at sites shown on the map (Figure 2). Due to privacy and agreement with the landowners, the specific location of each irrigation well remains

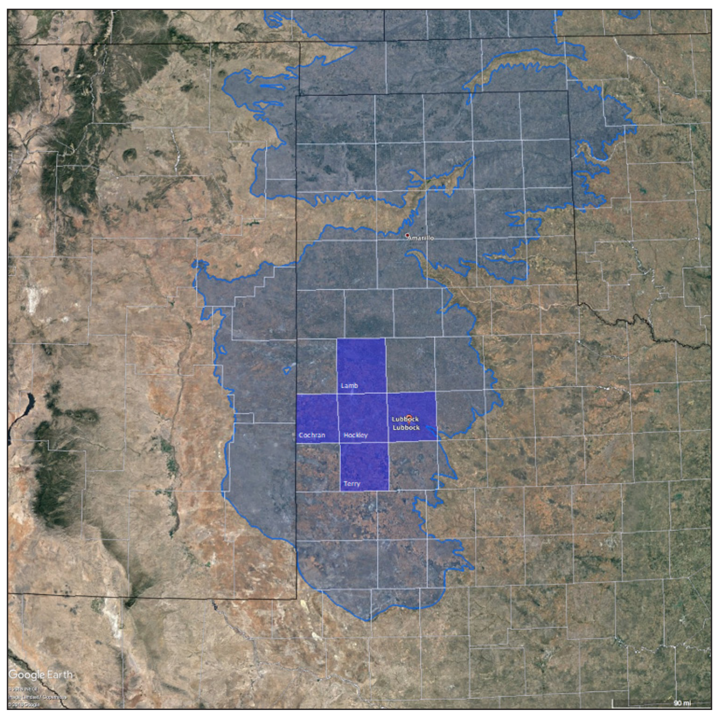

Figure 1. Location of the five counties where study was conducted with respect to the Texas border and the underlying Ogallala Aquifer (courtesy of Google Earth® using data from the USGA National Atlas).

Table 1. General description of the 20 irrigation wells located in five counties of the THP and used for sampling in our study.

County	Well #	General Use	Well Depth in Meters (feet)	Irrigation System	Crops Irrigated	Soil Series	Sampling Period
Lubbock	1	Irrigation	51 (167)	SDI & CP[1]	Cotton, Sorghum & Peanuts	Amarillo	Nov 2012–Sep 2016
	2	Abandoned	49 (161)				
Terry	1	Residential	52 (171)				Nov 2013–Dec 2016
	2	Residential	50 (164)				
	3	Irrigation	50 (164)	CP	Cotton & Peanuts	Patricia & Amarillo	
	4	Irrigation	52 (171)	CP	Cotton & Peanuts	Patricia & Amarillo	
Hockley	1	Irrigation	46 (151)	SDI	Cotton	Amarillo & Ranco	Nov 2013–Dec 2016
	2	Irrigation	45 (148)	CP	Cotton	Amarillo & Ranco	
	3	Irrigation	47 (154)	CP	Cotton	Amarillo & Ranco	
	4	Irrigation	76 (249)	CP	Cotton	Amarillo & Ranco	
	5	Irrigation	65 (213)	CP	Cotton	Amarillo & Ranco	
Lamb	1	Irrigation	53 (174)	SDI	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	June 2014–Dec 2016
	2	Irrigation	62 (203)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
	3	Irrigation	52 (171)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
	4	Irrigation	51 (167)	CP	Cotton, Sorghum & Wheat	Amarillo, Midessa & Olton	
Cochran	1	Storage – Fracking	N/A			Patricia & Amarillo	July 2014–Dec 2016
	2	Irrigation	73 (240)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	3	Irrigation	76 (249)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	4	Irrigation	75 (246)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	
	5	Irrigation	71 (233)	SDI & CP	Cotton, Sorghum & Peanuts	Patricia & Amarillo	

[1]Subsurface drip irrigation (SDI) and center pivot (CP) irrigation.

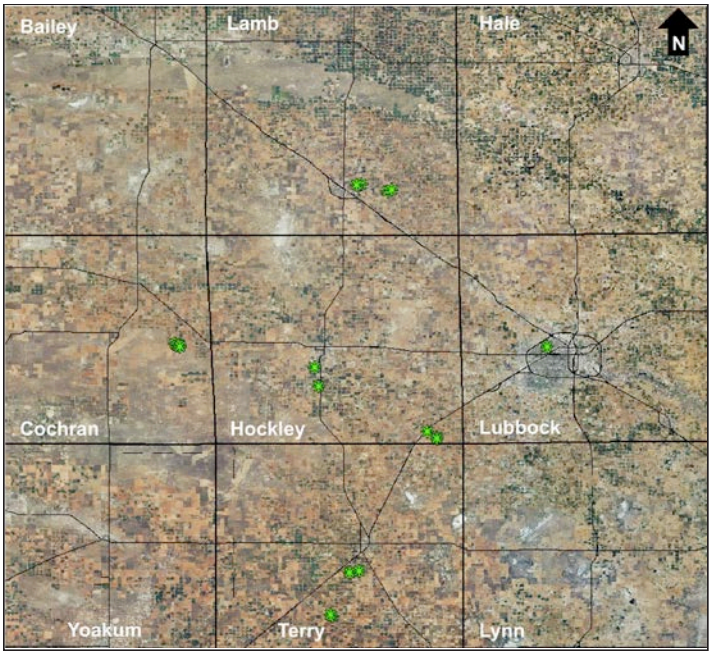

Figure 2. Location of 20 irrigation wells sampled in Terry, Hockley, Lubbock, Cochran, and Lamb counties in the Texas High Plains. (From: Esri®ArcMap™10.2.0.3348).

confidential. A general description of the irrigation wells used in our study is provided in Table 1.

Lubbock County

Two wells were located in Lubbock County separated by approximately 100 m (328 feet) (Figure 2). One well is actively used for irrigation while the other is an abandoned well that was converted to an observation well. The well that is actively used for crop irrigation is located at the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Plant Stress and Water Conservation Laboratory and is used to irrigate several different crops including cotton (*Gossypium hirsutum* L.), sorghum (*Sorghum bicolor* L.), and peanuts (*Arachis hypogaea* L.) using subsurface drip irrigation (SDI) as well as a two-span center pivot (CP) irrigation system. The soil type is classified as Amarillo soil series (fine-loamy, mixed, thermic Aridic Paleustalf). These wells were part of our initial assessment and they have been sampled since November 2012.

Terry County

Four irrigation wells were selected in Terry County (Figure 2). Two of these wells are for residential use only and were permanently in operation while the other two were used to irrigate cotton and peanuts using CP irrigation. The soil types are Patricia (fine-loamy, mixed, superactive, thermic Aridic Paleustalf) and Amarillo loamy fine sands. These wells were sampled starting in November 2013.

Hockley County

We sampled five irrigation wells in Hockley County (Figure 2). All of these wells were used to irrigate a cotton crop. One well supplied water to a SDI and the other four fed into CP irrigation systems. The soil types being irrigated were Amarillo fine sandy loam and Ranco (very-fine, smectitic, thermic Ustic Epiaquerts) clay. These wells were sampled starting in November 2013.

Lamb County

Four irrigation wells were sampled in Lamb County (Figure 2). All of these wells were used for irrigation of crops including cotton, sorghum, and winter wheat (*Triticum aestivum* L.). Three wells were used for SDI and one well was used for CP irrigation. The soil types being irrigated were Amarillo fine sandy loam, Midessa (fine-loamy, mixed, superactive, thermic Aridic Calciustepts) fine sandy loam, and Olton (fine, mixed, superactive, thermic Aridic Paleustolls) loam. These wells were sampled starting in June 2014.

Cochran County

A total of five irrigation wells were sampled in Cochran County (Figure 2). These wells are part of a corporate farm that, in addition to using water for agricultural irrigation, was also selling water for oil-field operations, such as hydraulic fracturing. The result was that while most irrigation wells were not in operation during the winter some of the wells were operational to provide water to a storage tank (~75,000 liters, or ~19,800 gallons) until it was transported off site. The first irrigation well on this site was taken from a valve on the above-mentioned storage tank. The rest of the irrigation wells fed both CP as well as SDI systems. The irrigated crops are primarily cotton, sorghum, and peanuts. The surface soil types in this area include Patricia and Amarillo loamy fine sands. These wells were sampled starting in July 2014.

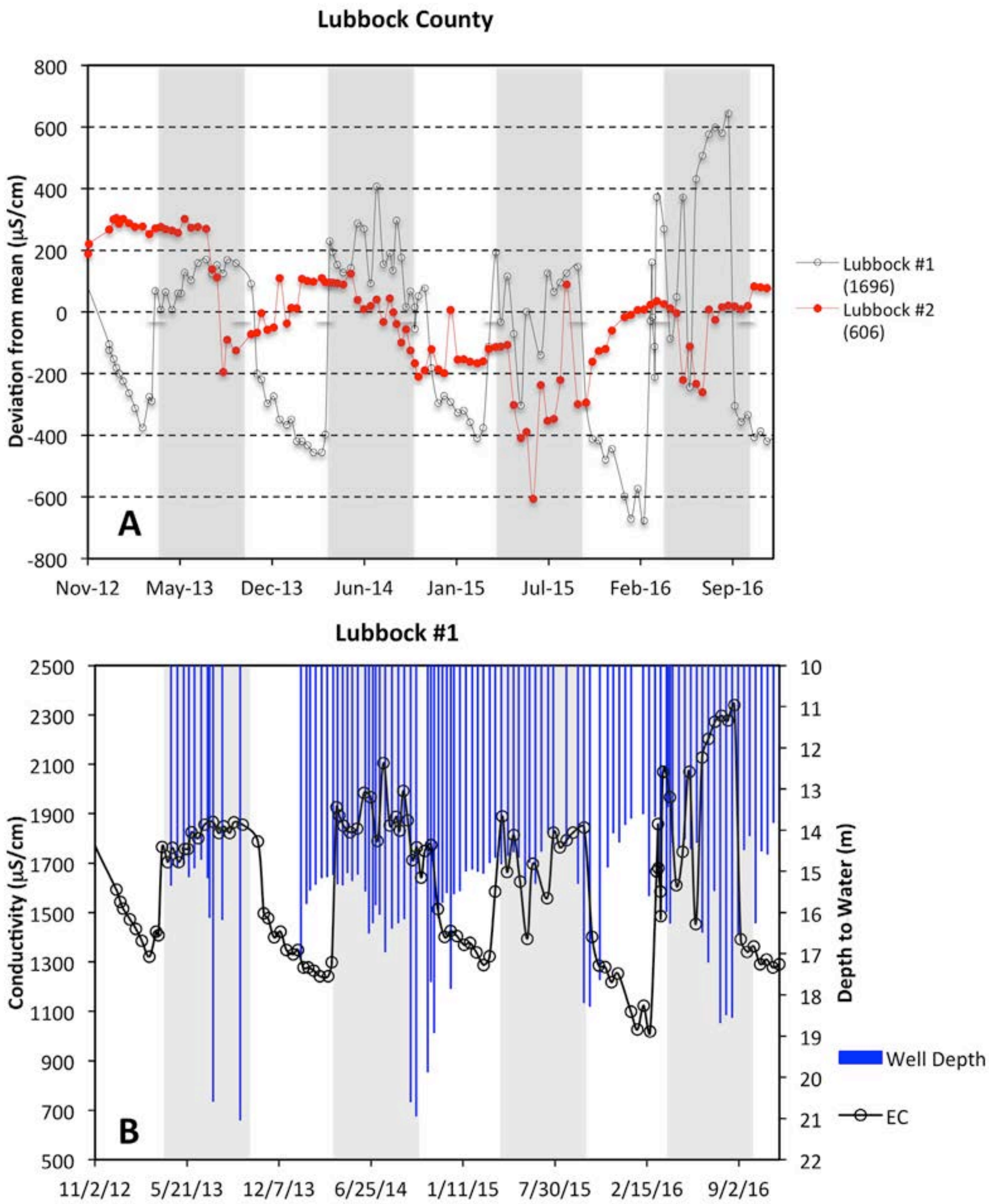

Figure 3. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Lubbock County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #1 in Lubbock County. The shaded area denotes the crop-growing season for the year.

RESULTS AND DISCUSSION

Lubbock County

The initial phase of our investigation focused on the quality of irrigation water within two wells located at the Plant Stress and Water Conservation Laboratory in Lubbock County (Figure 2). During the first two years, seasonal changes in EC (peak to trough) was as high as 30% (Figure 3a), and it was this unexpected result that led us to further investigate possible seasonal variations of groundwater water quality. We wanted to evaluate if the seasonal change in water quality was common on the high plains of Texas or if this was simply a local anomaly. The measured EC of the water in these two irrigation wells was quite different (Figure 3a) considering that these wells were spaced only 100 m (328 feet) from each other. The values of EC are shown as a deviation from the mean EC for all sampled wells and this comparison reveals significant seasonal changes

Table 2. The mean electrical conductivity (μS/cm) of the water sampled at each of the 20 irrigation wells in Lubbock, Terry, Hockley, Lamb, and Cochran counties in the THP. Also given is the calculated average slope over time.

County	Well #	Slope	Mean Electrical Conductivity (μS/cm)
Lubbock	1	–0.57	1,696
	2	–1.34	606
Terry	1	–0.18	2,037
	2	0.15	1,346
	3	–0.42	2,788
	4	–0.76	2,423
Hockley	1	0.71	1,044
	2	0.38	1,249
	3	0.79	1,329
	4	–0.80	1,011
	5	0.37	1,167
Lamb	1	–0.27	2,884
	2	–0.02	3,528
	3	–0.41	1,183
	4	0.10	1,503
Cochran	1	–0.18	1,348
	2	–0.01	1,344
	3	–0.01	1,767
	4	–0.03	1,761
	5	–0.04	1,201

in EC (Figure 3a). The mean EC, over a five-year span, was 1,696 micro-Siemens per centimeter (μS/cm) at the active irrigation well identified as Lubbock #1 and 606 μS/cm at the inactive observation well (Lubbock #2), and this difference of 1,090 μS/cm represents an increase of 180% (Table 2). Irrigation Well #1 showed an increase in EC during the growing season when it was actively pumping (Figure 3a). Both of the wells trended toward improved water quality, i.e., lower EC over the course of five years, and more noticeably towards the end of each growing seasons. For these particular two irrigation wells, the results suggest that this trend repeats each year; however, the extent of the increase of EC within the growing season and decrease thereafter is not well defined.

Also shown in Figure 3b is the measured depth to the water table for Lubbock Well #1. Note that depth to water increased toward the end of each growing season, e.g., 20 m (66 feet) in 2013 and 2014 and 18 m (59 feet) in 2015 and 2016. In between growing seasons, the depth to water stabilized at around 15 m (49 feet).

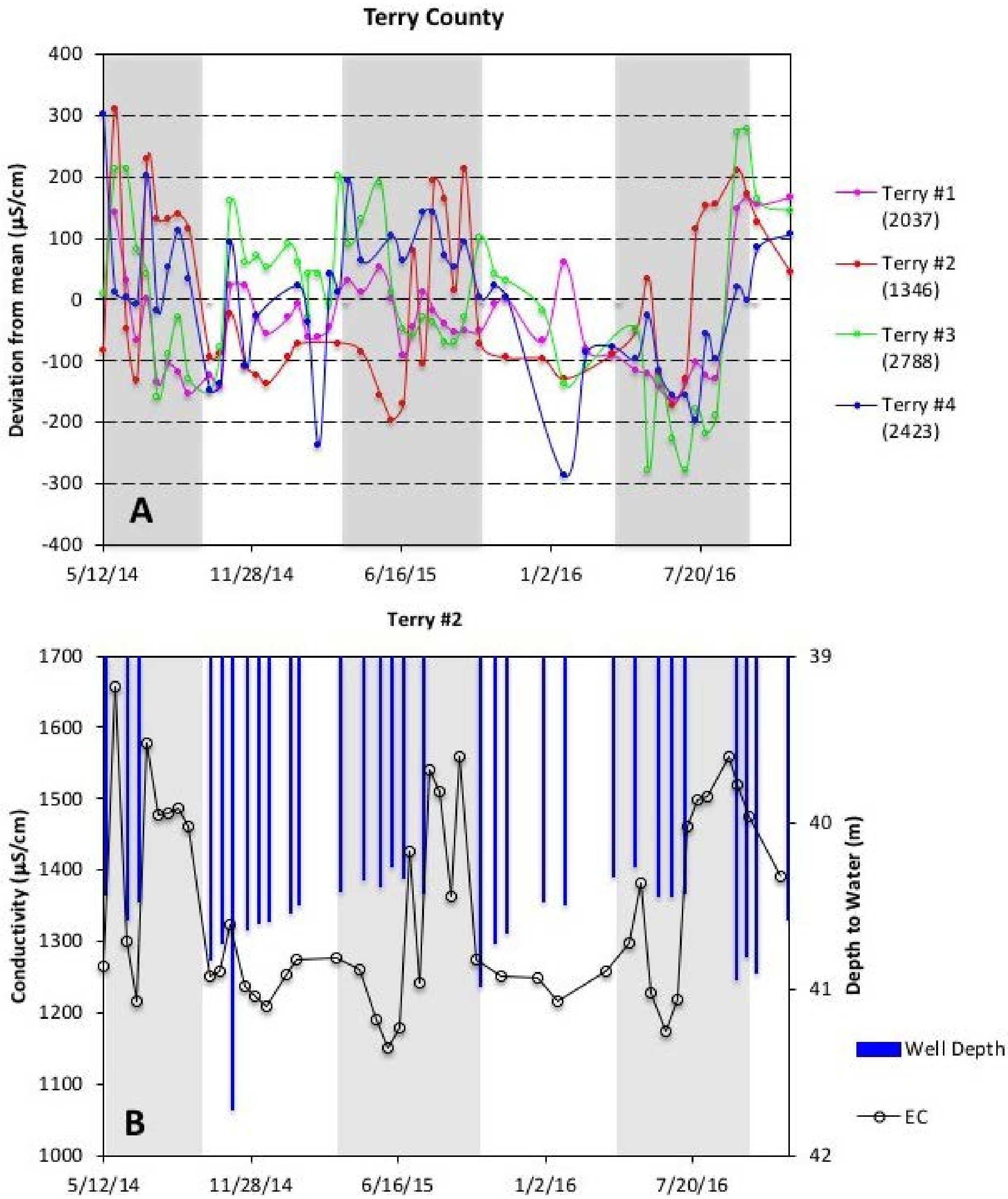

Figure 4. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Terry County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #2 in Terry County. The shaded area denotes the crop-growing season for the year.

Terry County

In general, the four sampled irrigation wells in Terry County did show some evidence of changes in EC relative to the mean value during the growing season (Figure 4a), and three of the four wells tended to show improved water quality, i.e., a negative slope, over the course of the three growing seasons (Table 2). In fact, irrigation well Terry #2 showed an increase in EC from 1,150 µS/cm to 1,560 µS/cm during the active irrigation period in 2015 (Figure 4b). Observations made at irrigation well Terry #2 showed that in each growing season, when the wells were actively pumped, EC increased by as much as 28%. The depth to the water table for Terry #2 showed a value of 41 ± 1 m (135 ± 3.3 feet) over the three growing seasons (Figure 4b).

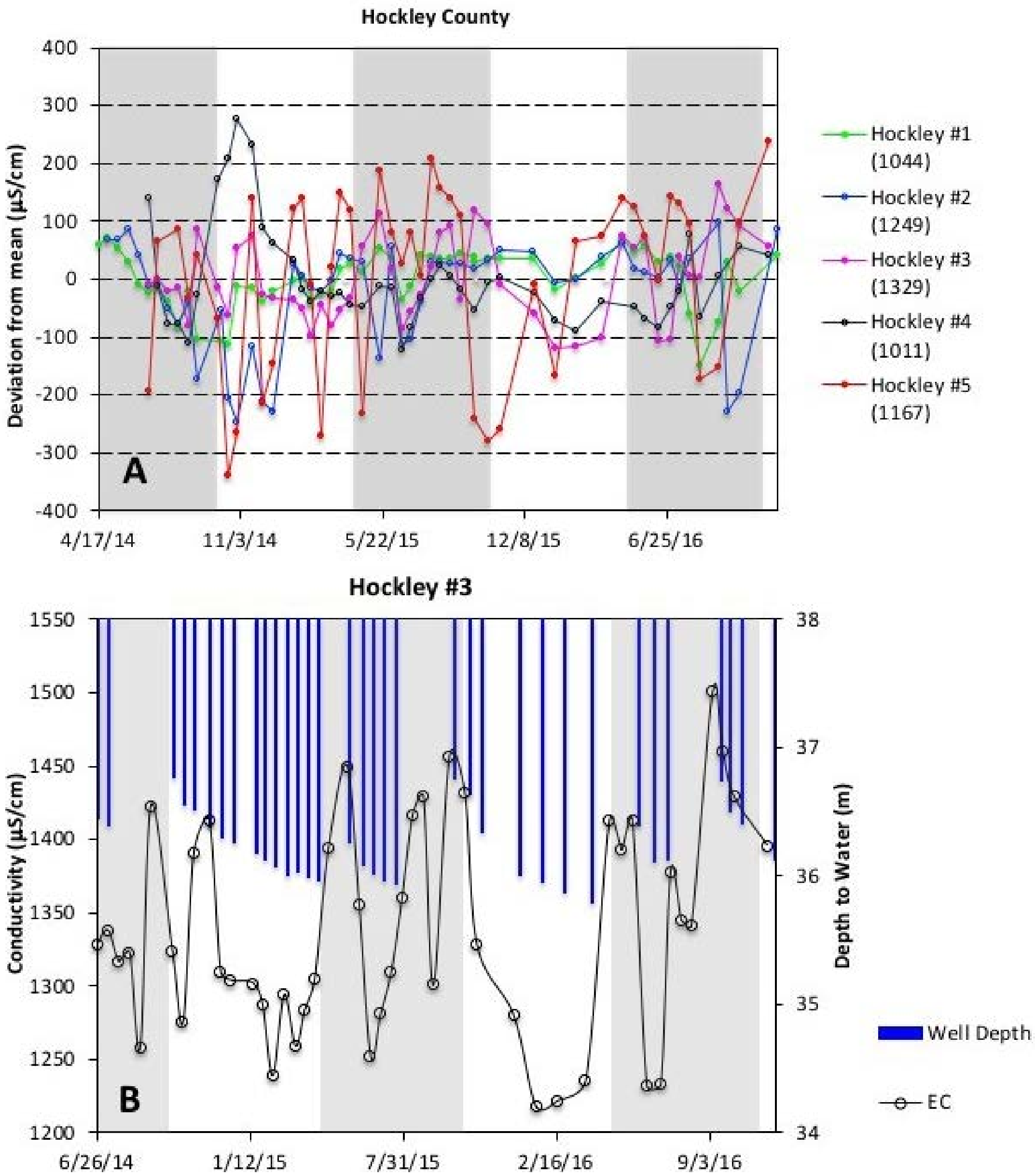

Figure 5. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for five irrigation wells in Hockley County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #3 in Hockley County. The shaded area denotes the crop-growing season for the year.

Hockley County

The EC of the five-sampled irrigation wells over three growing seasons for Hockley County is shown in Figure 5a. The values of EC are shown as a deviation from the mean EC for all sampled wells, and this comparison reveals significant seasonal changes in EC (Figure 5a). Four of the five wells trended toward higher EC over the three-year period (Table 2). One well, Hockley #3, did show some response to active pumping during the growing season where in the off-season the EC would gradually drift to lower values, ultimately changing as much as 17% (peak to trough) (Figure 5b). During the growing season, it would quickly become more saline and recover within two to four weeks after the wells were turned off due to rain. The depth-to-water values showed a consistent pattern of increasing about 1 m (3.3 feet) from the start to the end of the irrigation period for each of the growing seasons (Figure 5b).

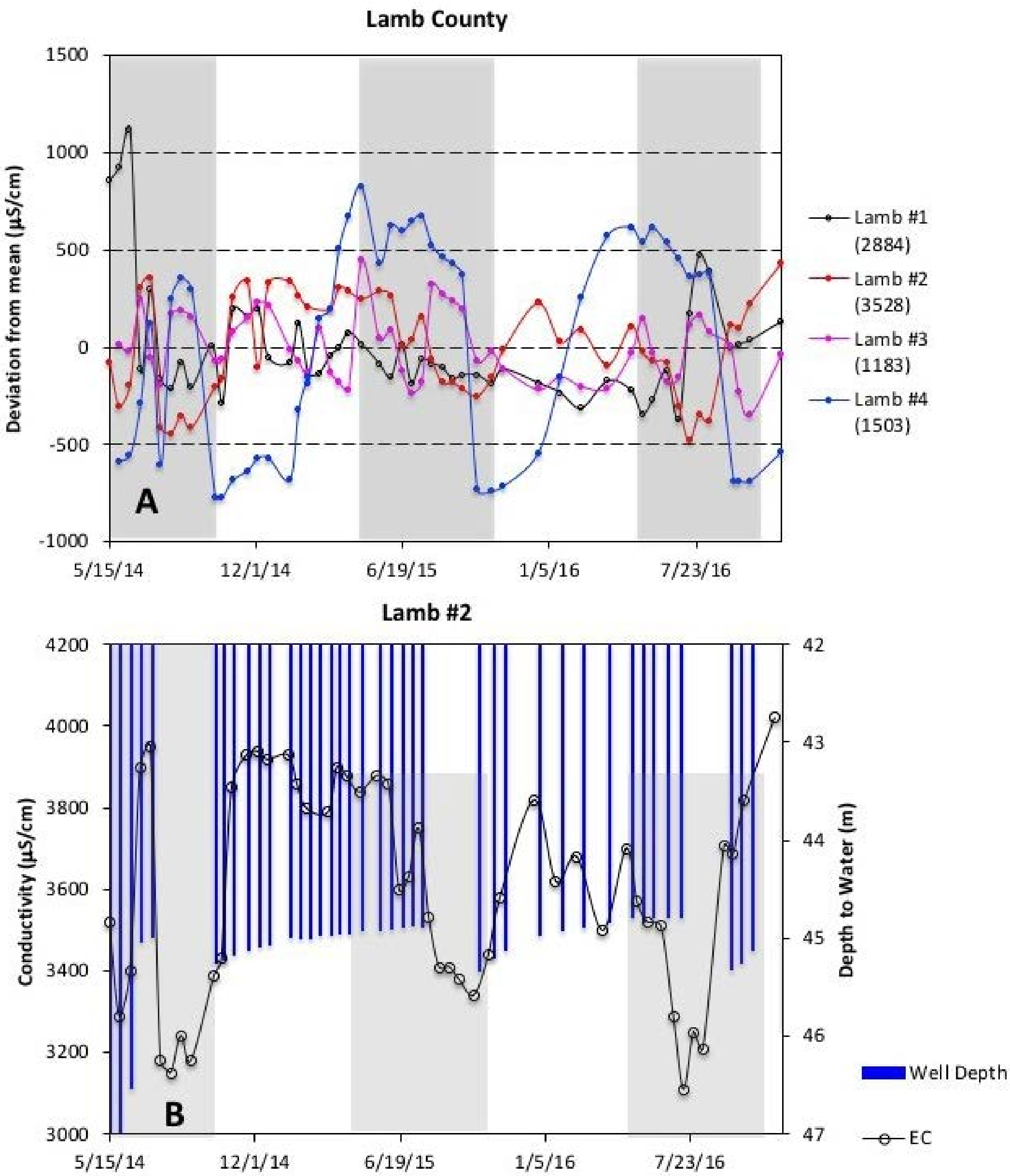

Figure 6. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for four irrigation wells in Lamb County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #2 in Lamb County. The shaded area denotes the crop-growing season for the year.

Lamb County

In Lamb County two of the four wells showed a seasonal change in EC while the other two wells did not (Figure 6a). In addition, three of the irrigation wells trended to lower values of EC over the three-year period while one well drifted in the opposite direction of increasing EC (Table 2). Lamb #4 showed a response similar to that of other wells in other counties, i.e., an increase in EC when the wells were actively pumping during the growing season. However, Lamb #2 responded to active pumping in the opposite direction (Figure 6b). For example, in 2014 EC decreased to 3,200 µS/cm during the irrigation period and increased to about 4,000 µS/cm in the winter. The same trend was measured during the 2015 growing season, with an EC of 3.400 µS/cm during the growing season and increasing to about 3.800 µS/cm thereafter (Figure 6b). There was no discernible pattern on the measured values of depth to water (Figure 6b).

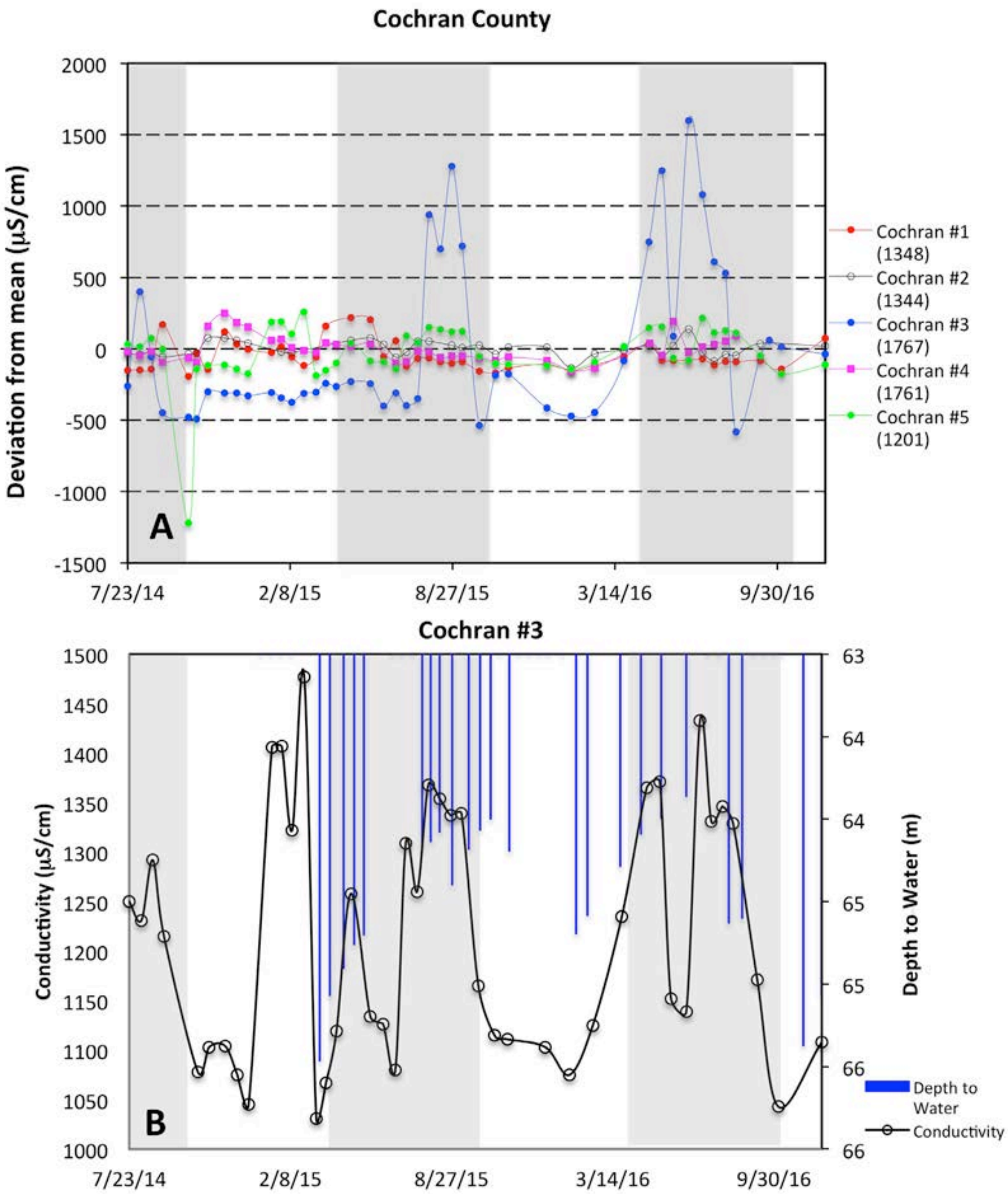

Figure 7. (a) Deviation from the mean value of electrical conductivity (µS/cm) measured throughout the sampling period for five irrigation wells in Cochran County. (b) Electrical conductivity (µS/cm) and depth (m) to water table of Well #3 in Cochran County. The shaded area denotes the crop-growing season for the year.

Cochran County

In Cochran County most of the irrigation wells showed small deviations from the mean value of EC, except for Cochran Well #3 (Figure 7a). All of the sampled irrigation wells trended toward improved water quality (lower EC values) over the course of the study (Table 2). Cochran #3 is used for irrigation and showed variation with the growing season. The largest variation in EC was 17% (Figure 7b). To supply water for oil-field operations, the well was often operating outside of the growing season, as shown in Figure 7b. Of the sampled wells in our study, Cochran Well #3 had the deepest depth-to-water of 66 m (217 feet) (Figure 7b).

CONCLUSIONS

While it is common for water deeper in an aquifer to have a higher salinity, the pressure of irrigation during the growing season has not caused a marked increase in salinity for most of the wells sampled in this study. Over the course of the study, the EC for roughly half of the sampled wells increased and the other half decreased. At least one well per county did have a change in water quality when the wells were actively pumped. Four of those wells showed an increase in EC while the wells were active, suggesting the possibility that more saline water from the depths of the aquifer were being drawn upward. In one case in Lamb County, the water quality actually improved when the well was actively pumped. This specific case does not follow the trend that is normally seen and is likely due to a unique local geologic condition at that location. The results presented here suggest that in the short term, a change in water quality over the growing season does not present a significant challenge to producers in this region. However, some wells are responding to the continued extraction of water from the aquifer, and likely the rest of the wells will begin to show similar trends at some point in the future as the aquifer continues to be depleted and more of the deeper, more saline water is accessed. This study will continue and future attempts will be made to better define possible salinity gradients within our observation wells so that we may ultimately reach a better understanding of possible future water quality conditions.

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Systems-level thermodynamic and economic analysis of a seawater reverse osmosis desalination plant integrated with a combined cycle power plant

Andrew S. Reimers[1]*, Michael E. Webber[1]

Abstract: This study includes thermodynamic and economic analyses of a seawater reverse osmosis (RO) plant integrated with a small-scale combined cycle natural gas (CCGT) plant ranging from 36–71 megawatts (MW). These analyses model electricity produced by the CCGT plant as power for the RO plant or for sale to the power grid. These analyses consider the coolant flow rate, carbon intensity, and capital and operating costs of the CCGT plant. For a case where the RO plant is sized according to the rated capacity of the CCGT plant, the maximum flow rate of coolant for the CCGT plant is only 8–10% of the total rate of seawater intake for the RO plant. Thus, no additional intake capacity is needed for the CCGT plant. The carbon intensity of the CCGT plant varies from 802-885 pounds per megawatt-hour (lb/MWh) compared to an average carbon intensity of 1285 lb/MWh for the Texas power grid. The economics of the integrated facility are evaluated using a levelized cost of water (LCOW) framework, which accounts for the capital cost associated with the CCGT plant and electricity sales to the grid. Results indicate that integrating an RO plant with a CCGT plant reduces LCOW by 8–10% compared to an RO plant powered by electricity from the Texas power grid.

Keywords: integrated power generation, desalination

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Terms used in paper

Short name or acronym	Descriptive name
C_{cap}	levelized capital cost for integrated power generation and desalination plants [$/kgal]
CCGT	combined cycle natural gas turbine power plant
CF	capacity factor for the desalination plant
CI	carbon intensity [lb/MWh]
C_{power}	cost of powering the desalination plant [$/kgal]
CRF	capital recovery factor
C_{RO}	unit cost of reverse osmosis desalination [$/kgal]
DAM	day-ahead market for electricity sales
DEEP	Desalination Economic Evaluation Program
DT	down time for the desalination plant [hr]
EIA	Energy Information Administration
ERCOT	Electric Reliability Council of Texas
E_{RO}	specific energy consumption for reverse osmosis [kWh/kgal
$F_{O\&M}$	fixed operation and maintenance cost for the power plant [$/kW-yr]
HHV	higher heating value, measurement of energy content in fuel
IWPP	independent water and power project
kgal	one thousand gallons
LCOW	levelized cost of water [$/kgal]
MED	multiple effect distillation
MSF	multiple stage flash
MW	megawatts
MWh	megawatt-hour
OCC	overnight capital cost [$/kgal per day for desalination or $/kW for power]
P_{elec}	cost of purchasing of electricity from the grid [$/MWh]
$P_{elec,\ sell}$	price at which electricity can be sold to the grid [$/MWh]
P_{ng}	price of natural gas [$/MWth]
R_{elec}	revenue from electricity sales [$]
RO	reverse osmosis
RR	recovery ratio of clean water out versus seawater into the RO plant
SGT	Siemens Gas Turbine
T	number of hours in a year
t	independent variable for an hour in a year
$T_{GT,out}$	gas turbine exhaust temperature [°C]
$\dot{V}_{in}$	maximum seawater intake flow rate [kgal/hr]
$V_{O\&M}$	variable operation and maintenance cost of the power plant [$/MWh]
V_{RO}	desalination plant output [kgal]
$\dot{V}_{RO,\ max}$	maximum desalination plant capacity [kgal/hr]
W_{gen}	electrical energy generated by the CCGT plant [MWh]
$\dot{W}_{max}$	maximum power plant output [MW]
W_{RO}	energy consumption by the desalination plant [MWh]
W_{sell}	electricity sold to the grid [MWh]
x_{RO}	on/off variable for the desalination plant
η_{HHV}	power plant efficiency [MWe/MWth]

INTRODUCTION

This study includes thermodynamic and economic analyses of a seawater reverse osmosis (RO) desalination plant integrated with a small-scale combined cycle natural gas turbine (CCGT) power plant. Approximately 27% of the global population lives within 100 kilometers of the coast and less than 100 meters above sea level, making seawater desalination a viable alternative to conventional freshwater sources for much of the population (Kummu et al. 2016). At the same time, demand for both water and electricity is increasing, and an integrated power generation and desalination facility can help address both needs simultaneously (OECD 2012, EIA 2016a). There are several motivations for integrating a desalination plant with a power plant. Depending on the specific arrangement of the desalination and power plants, an integrated facility might benefit from a variety of different features, including shared site permits and intake infrastructure and greater utilization of waste energy streams, which can reduce the cost and environmental impact caused by two separate facilities. Desalination is more energy intensive and has a greater "carbon footprint" than conventional water treatment, but an RO plant integrated with a CCGT plant can be less carbon intensive than an RO plant that uses electricity from a grid reliant on generation from coal or oil-fired power plants (Shrestha et al. 2011; Liu et al. 2015). Additionally, the facility's operation and participation in both electricity and water markets can be optimized to maximize profitability while meeting demand for electricity and water.

There are numerous desalination plants worlmaxidwide that are integrated or co-located with power plants. For example, the Tuaspring Reverse Osmosis desalination plant in Singapore has a capacity of 70 million gallons per day (MGD) that is integrated with a 411 megawatts (MW) combined cycle natural gas plant (Water Technology [no date]). In the United States, the Tampa Bay Seawater Desalination plant has a capacity of 25 MGD and shares intake infrastructure with Tampa Electric's Big Bend Power Station, a 1700 MW coal plant (Tampa Bay Water [no date]; TECO [no date]). By sharing intake infrastructure, the feedwater for the RO plant can be preheated by using it as the coolant for the condenser of the power plant, and preheating the feedwater decreases the specific energy consumption of desalination (Davis and Cappelle 2013).

This study seeks to answer several questions about the technical and economic tradeoffs of integrating a seawater RO plant with a small-scale CCGT plant. First, this analysis includes an estimation of the flow rate of seawater required for the cooling system of a small-scale CCGT plant compared to the feedwater flow rate of seawater going into a seawater RO plant. If the flow rate of coolant is less than the flow rate of feedwater for the RO plant, the CCGT plant can share a seawater intake with the RO plant. Otherwise, the CCGT plant would require additional seawater intake capacity or have to use a recirculating cooling system with a cooling tower. Regulations on intakes for power plant cooling systems such as section 316(b) of the Clean Water Act in the United States tend to restrict the use of open cycle cooling systems (EPA 2015). A downside of recirculating cooling systems with a cooling tower is that they consume more water than open-loop systems (Stillwell 2010). Cooling towers can use saltwater instead of freshwater, but using saltwater increases the maintenance cost and decreases the performance of the cooling tower (Sharqawy et al. 2010). Second, this study includes an estimation of the carbon intensity of a small-scale CCGT plant compared to the average carbon intensity of electricity purchased from the Texas power grid. Even though a natural gas fueled power plant will generate carbon emissions, the carbon intensity might be less than electricity purchased from a power grid that is still heavily reliant on coal-burning power plants.

Lastly, an optimization analysis and levelized cost of water (LCOW) framework is used to estimate the cost of an RO plant integrated with a small-scale CCGT plant compared to a stand-alone RO plant. This framework takes into account the capital and operating costs associated with a seawater RO plant, the cost of powering an RO plant with electricity generated by a small-scale CCGT plant or purchasing electricity from the grid, the capital and fixed costs associated with a small-scale CCGT plant, and the revenues that can be earned by selling electricity to the grid. This kind of cost analysis is called a credit method because the revenues that can be earned by selling electricity to the grid are credited against the costs of desalinating water (Mussati et al. 2003). This analysis considers the hourly wholesale price of electricity, and an optimization model is used to schedule the operation of an integrated CCGT-RO so as to maximize revenues from electricity sales while also achieving a prescribed capacity factor for the RO plant. This analysis differs from other cost analyses that only consider the average price at which electricity can be sold to the grid, such as the International Atomic Energy Agency's Desalination Economic Evaluation Program (DEEP) (IAEA 2014).

This study builds on the body of research on integrated power generation and desalination plants and relies on existing reports for the cost and specific energy consumption of desalination. A wide range of real-world costs and cost estimates for desalination has been reported in the literature (Blank et al. 2007; Reddy and Ghaffour 2007; Akgul et al. 2008; Karagiannis and Soldatos 2008; Ghaffour et al. 2013). The cost of desalination has tended to decrease over time, particularly with improvements to RO technology in recent decades. The cost of desalination depends on a number of factors, including the type of desalination technology, the capacity and availability of the desalination plant, and the cost of energy. The cost of desalination varies based on site-specific factors such as feedwater quality and the cost of intake and outfall systems (Ghaffour et al. 2013). The cost of energy depends on the specific energy consumption of the desalination plant and the cost of electricity used to power the desalination plant. The specific energy consumption of a desalination plant depends on a number of factors including the type of desalination technology, the quality and temperature of feedwater, the length of intake, the recovery ratio, and the use of energy recovery devices such as pressure exchangers (Stover 2007; Semiat 2008; Stillwell and Webber 2016). In general, the specific energy consumption of RO is lower than for thermal desalination technologies such as multiple stage flash (MSF) or multiple effect distillation (MED).

Much of the literature on integrating desalination plants with power plants focuses on fossil fuel-burning cogeneration or "dual-purpose" power and desalination plants wherein low-pressure steam is removed from the power cycle and used as the heat source for a thermal desalination plant (Mussati et al. 2003; Kamal 2005; Nisan and Benzarti 2008; Mabrouk et al. 2010; Wu et al. 2013, 2014). This kind of arrangement is common in the Persian Gulf countries because of its reliability and the availability of cheap energy (Reddy and Ghaffour 2007). There are also numerous studies that consider or focus on fossil fuel power plants integrated with a RO plant (Bouhelal et al. 2004; Kamal 2005; Nisan and Benzarti 2008; Wu et al. 2013, 2014). These studies include in-depth analysis of the thermodynamic efficiency and economics of cogeneration power and desalination plants. Some of these studies also include an optimization analysis to determine the optimal design of a cogeneration plant with constraints on water and electricity production (Mussati et al. 2003; Wu et al. 2013, 2014). Several of these studies use the International Atomic Energy Agency's DEEP cost-estimating tool, which can estimate the cost of desalination for different technologies based on a variety of parameters including feedwater quality, fuel cost, and power plant availability (Bouhelal et al. 2004; Nisan and Benzarti 2008; IAEA 2014). The DEEP cost-estimating tool also estimates revenues earned from electricity sales based on an average price of electricity.

There are also many articles focused on integrating desalination plants with nuclear power plants (Nisan and Dardour 2007; Nisan and Benzarti 2008; Khamis 2010; Khamis et al 2011; Alonso et al. 2012; Khamis and El-Emam 2016). These studies consider the prospects for integrating desalination systems, both thermal and RO, with existing nuclear power plants as well as the potential for integrating desalination plants with next generation nuclear technologies. There are both economic and environmental motivations for these studies to focus on integrating desalination systems with nuclear power plants instead of fossil fuel-burning power plants. Nuclear power plants do not emit carbon dioxide, and nuclear power plants are cheaper to operate than fossil fuel-burning power plants in terms of fuel and variable operation and maintenance cost per unit of electricity generated (Lazard 2017). Some of these analyses also take advantage of the DEEP cost-estimating tool and estimate that the cost of desalination with nuclear power is lower than the cost of desalination with fossil-fueled power plants, particularly when the cost of environmental externalities are also taken into consideration (Nisan and Dardour 2007; Nisan and Benzarti, 2008). However, these studies do not account for the capital cost associated with building new nuclear plants.

Much of the research on integrating desalination plants with fossil fuel and nuclear power plants focuses on large, commercial-scale power plants. The focus on commercial-scale plants can be explained by the fact that many large power plants have already been built and are operating worldwide, so integrating desalination plants into these existing systems does not require investment in new power generation capacity. Commercial-scale power plants also tend to be more efficient than smaller power plants, resulting in lower energy costs for desalination. What these analyses fail to address, however, is whether it is cost effective to build new power generation capacity specifically for powering a desalination plant. A major technical difference between large- and small-scale power plants is the flow rate of water needed for a once-through cooling system. While a large power plant may need a much higher flow rate of cooling water than can be processed by a desalination plant, a small-scale power plant needs a much lower flow rate of cooling water and may be able to share an intake with a desalination plant.

In addition to fossil fuel and nuclear power plants, there have also been many studies focused on integrating desalination plants with renewable energy sources such as wind, solar, and geothermal energy (Al-Karaghouli et al. 2009; Charcosset 2009; Eltawil et al. 2009; Al-Karaghouli and Kazmerski 2013; Gold and Webber 2015). As with nuclear plants, one of the motivations for integrating desalination systems with renewable energy sources is that they do not emit carbon dioxide. Another benefit of renewable energy systems is that they may be better suited than large power plants for providing energy in remote locales that aren't connected to a power grid. However, the intermittency of renewable energy sources like wind and solar results in a lower capacity factor for the RO plant, which results in a higher LCOW. For example, the capital cost for a 1000 MGD RO plant with a capacity factor of 50% is twice as much as a 500 MGD RO plant with a capacity factor of 100%, even though both plants produce the same amount of water on average.

With the exception of Gold and Webber (2015), the existing literature lacks much consideration on the time-dependency of electricity demand and the price of electricity). Such time-dependent factors have a significant effect on how an integrated power generation and desalination plant would optimally operate with the objective of minimizing operating costs and maximizing revenues from electricity sales. In general, an integrated power generation and desalination facility would tend to schedule the operation of the desalination plant around peak electricity demand and sell electricity to the grid instead.

While the analytical framework presented in this manuscript is generalized in nature, it is illustrated for a site in Texas for several reasons. Texas' annual water demand is projected to grow by more than 17% from 2020–2070, while Texas' electricity demand is projected to grow by almost 14% by as early as 2025 (ERCOT 2017; TWDB 2017). Thus, there is a need for additional water and electric power capacity. Since 2003, the Texas Water Development Board has had a mandate to research the feasibility of investing in desalination as a means of increasing the state water supply (Texas House of Representatives 2003). Even though the high cost and specific energy consumption for desalination has historically made it an unattractive water supply option compared to conservation or treating water from other sources, the availability of relatively affordable natural gas and ability to participate in a competitive power market might improve the economic viability of a desalination plant integrated with a CCGT power plant in a state expecting severe water stress (Sturdivant et al. 2007; TWDB 2017). This analysis focuses on the power market managed by the Electric Reliability Council of Texas (ERCOT), which accounts for about 90% of the state's electric load (ERCOT [no date]). ERCOT is responsible for managing the grid and settling the buying and selling of electricity on a wholesale market. Retail electric providers who purchase electricity on one of the ERCOT wholesale markets can then sell the electricity to end-users at a contracted rate.

Table 1. Cost and performance specifications for the CCGT plants considered in this analysis.

SGT Model	W_{max}[MW_e]	η_{HHV}	OCC [$/kW]
600	35.9	0.45	1359
700	45.2	0.47	1277
800	71.4	0.5	1091

METHODS

Integrated CCGT-RO plant specifications

A schematic of an RO plant integrated with a CCGT plant is shown in Figure 1. The CCGT plants considered for this analysis are based on the Siemens Gas Turbine (SGT) line—SGT 600, 700, and 800, specifically—because of the suitability of these gas turbines for combined cycle applications, the availability of performance and cost-related data, and a range of sizes capable of running a large-scale seawater RO plant (Siemens [no date]). The maximum power output ($\dot{W}_{max}$), higher heating value (HHV) efficiency (η_{HHV}), and overnight capital cost (OCC) of the CCGT plants were taken from the Gas Turbine World Handbook (GTW 2015). Higher heating value is a measure of the energy content of the fuel, and power plant efficiency is a measure of the electricity generated per unit of fuel energy consumed by the plant. These specifications are shown in Table 1.

The maximum power output of the CCGT was used to determine the maximum RO capacity, $\dot{V}_{RO,max}$, that could be powered by the CCGT, as shown in Equation 1:

$$\dot{V}_{RO,max} = \frac{\dot{W}_{max}}{E_{RO}} \quad (1)$$

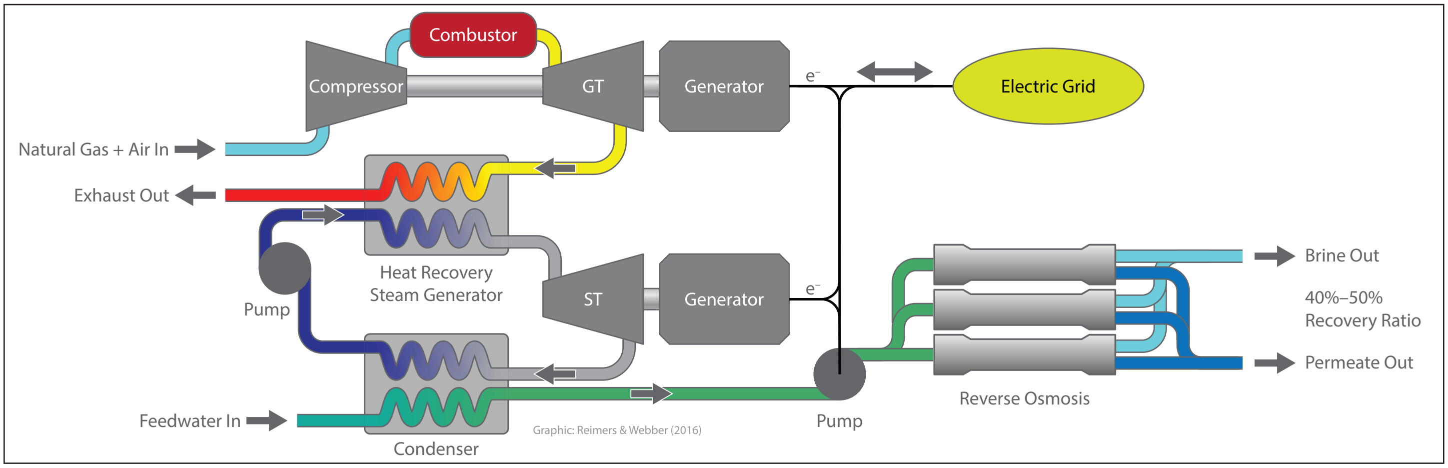

Figure 1. For an RO plant integrated with a CCGT plant, electricity generated on site can be used to power the RO plant or sold to the grid. (GT = gas turbine; ST = steam turbine)

where E_{RO} is the specific energy consumption of the RO plant. Note that the units for flow rates in the model are in thousand gallons per hour. This analysis assumes a specific energy consumption of 13.75 kWh per thousand gallons (kgal) for both the stand-alone RO plant and CCGT-RO plant (Semiat 2008). Note that the specific energy consumption of the integrated CCGT-RO plant could be slightly lower because of the feedwater being preheated with waste heat from the CCGT condenser (Davis and Cappelle 2013). This effect is assumed to be negligible because of the significantly lower cooling water flow rates compared to the overall flow rate of feedwater for the RO plant.

This analysis assumes that the RO plant would have a recovery ratio, RR, between 40-50%, i.e., 40-50% of seawater intake is output as freshwater permeate, as indicated in Figure 1 (ADC [no date]; Al-Zahrani et al. 2012). The recovery ratio is used to calculate the intake size needed to accommodate the maximum RO capacity as shown in Equation 2:

(2) $$\dot{V}_{in} = \frac{\dot{V}_{RO,max}}{RR}$$

where $\dot{V}_{in}$ is the maximum seawater intake flow rate.

Coolant flow rate and carbon emissions

The coolant flow rate for the CCGT plant was estimated using a thermodynamic model built in Thermoflex, a commercial software package for modeling thermal systems (Thermoflow [no date]). Thermoflex includes numerous sample models of thermal systems, including a model of a basic CCGT plant. Thermoflex also has a gas turbine library that includes performance specifications for many of the gas turbines on the market. The basic CCGT model was modified to include the Siemens gas turbines described in Table 1 and to include an open cycle cooling system rather than a cooling tower. Site conditions based on typical weather data for the Texas Gulf Coast region were also used as inputs to the Thermoflex model. These inputs include ambient temperature, 21°C, seawater temperature, 20°C, and relative humidity, 75% (NOAA [no date]; NREL [no date]). A detailed image and description of the Thermoflex model is included in the appendix. After selecting a gas turbine and setting the site conditions, the model was run to determine the flow rate of coolant into the CCGT plant. The coolant flow rate for the CCGT plant was compared to the total flow rate of seawater into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO.

Table 2. Operating cost components for RO desalination in $/kgal.

Component	Unit Cost $/kgal
Chemicals	0.27
Labor	0.25
Parts	0.11
Membranes	0.11
Total	**0.75**

The carbon intensity of the CCGT plant, CI_{CCGT}, that is, the mass of CO2 released per unit of electricity generated in lb/MWh, was estimated using Energy Information Administration (EIA)'s reported values for the carbon intensity of natural gas, CI_{ng}, approximately 117 lb/MMBtu, and the efficiency of the CCGT plant as shown in Equation 3 (EIA 2016b).

(3) $$CI_{CCGT} = \frac{3.412\ MWh}{MMBtu}\frac{CI_{ng}}{\eta_{HHV}}$$

For a stand-alone RO plant, the carbon emission intensity of electricity purchased from ERCOT was estimated to be approximately 1285 lb/MWh based on EIA's estimated emissions associated with power generation in the state of Texas averaged from 2011–2015 (EIA 2018a). Note that marginal emissions associated with a new RO plant in Texas would depend on the dispatch of power plants to meet the RO plant load and not just the fleet average emissions for ERCOT.

Economic analysis

An optimization analysis was used to determine how an integrated CCGT-RO plant would operate on an hourly basis with the objective of minimizing the net cost of desalination. The results of this optimization analysis were used to estimate the LCOW for an integrated CCGT-RO plant compared to a stand-alone RO plant. Data from Global Water Intelligence's DesalData.com were used to estimate the operating cost of a seawater RO plant, C_{RO}, which includes the cost of chemicals, labor, replacement parts, and membranes as shown in Table 2 (GWI 2016).

As for the cost associated with powering an RO plant, this analysis assumes that a small-scale CCGT plant could be used to power an RO plant or sell electricity into the wholesale electricity market. Conversely, a stand-alone RO plant would have to purchase electricity from a retail electric provider. Texas-specific energy prices were used for this study, but this analysis could be repeated using any electricity price data derived from an auction-based wholesale market and associated retail rates for fuel and electricity. The cost of powering a stand-alone (sa) RO plant, $C_{power,sa}$ is defined by Equation 4:

$$C_{power,sa}(t) = P_{elec,buy}(t) \times W_{RO,sa}(t) \tag{4}$$

where $W_{RO,sa}$ is the hourly electrical energy consumed by a stand-alone RO plant, and the retail price for electricity, $P_{elec,buy}$ is taken from EIA's monthly average prices for industrial customers in Texas for 2011–2015 (EIA 2016c). The hourly electricity consumed by a stand-alone RO plant is the product of the volume of water desalinated, V_{RO}, and the specific energy consumption of desalination as shown in Equation 5.

$$W_{RO,sa}(t) = V_{RO}(t) \times E_{RO} \tag{5}$$

The cost of powering an integrated (int) CCGT-RO, $C_{power,int}$, is defined by Equation 6, and the revenues from electricity sales, R_{elec}, are defined by Equation 7:

$$C_{power,int}(t) = \left(\frac{P_{ng}(t)}{\eta_{HHV}} + V_{O\&M}\right) \times W_{gen}(t) \tag{6}$$

$$R_{elec}(t) = P_{elec,sell} \times W_{sell}(t) \tag{7}$$

where W_{gen} is the hourly electrical energy generated by the CCGT, and W_{sell} is the hourly electrical energy sold to the grid. The retail price for natural gas, P_{ng}, is taken from EIA's monthly average prices for industrial customers in Texas, and the wholesale electricity prices, $P_{elec,sell}$, are based on ERCOT's day-ahead-market (DAM) settlement prices from 2011–2015 (EIA 2018b; ERCOT 2018). The variable operation and maintenance cost of the CCGT plant, $V_{O\&M}$, is 3.6 \$/MWh according to EIA (EIA 2013). All of the costs associated with operating an integrated CCGT-RO plant or stand-alone RO plant are included in the objective function defined by Equation 8:

$$min\sum_{t\epsilon T}\left[C_{power,j}(t) + C_{RO} \times V_{RO}(t) - R_{elec}(t)\right] \tag{8}$$

where the subscript *j* refers to either an integrated CCGT-RO (int) or stand-alone RO plant (sa). This optimization model includes several constraints on the RO and CCGT plants. The constraint on the maximum hourly output of the RO plant is defined by Equation 9, and the minimum desalination output is defined as 40% of the maximum output as shown in Equation 10 (Egozy and Faigon 2013):

$$V_{RO}(t) \le x_{RO}(t) \times \dot{V}_{RO,max} \tag{9}$$

$$V_{RO}(t) \ge 0.4 \times x_{RO}(t) \times \dot{V}_{RO,max} \tag{10}$$

where x_{RO} is a binary variable that describes whether the RO plant is on or off. The minimum down time (DT) of the RO plant, set as five hours for this analysis, is defined by Equations 11 and 12. The minimum annual capacity factor (CF) of the RO plant, set as 95% for this analysis, is defined by Equation 13.

$$\sum_{n=k}^{k+DT-1}\left[1 - x_{RO}(n)\right] \ge DT\left[x_{RO}(k-1) - x_{RO}(k)\right] \quad \forall k - 1 \cdots T - DT + 1 \tag{11}$$

$$\sum_{n=k}^{T}\left\{1 - x_{RO}(n) - \left[x_{RO}(k-1) - x_{RO}(k)\right]\right\} \ge 0 \quad \forall k = T - DT + 2 \cdots T \tag{12}$$

$$\sum_{t\epsilon T} V_{RO}(t) = \dot{V}_{RO,max} \times T \times CF \tag{13}$$

where T is the number of hours in a year. The RO plant integrated with a CCGT plant can only run when the CCGT plant is also running as shown in Equation 14:

$$x_{RO} \le x_{gen} \tag{14}$$

where x_{gen} is a binary variable that describes whether the CCGT plant is on or off. The maximum hourly electricity generation from the CCGT plant, W_{gen}, is defined by Equation 15, and hourly electrical energy consumed by the RO plant, $W_{RO,int}$, is defined by Equation 16.

$$W_{gen}(t) \le x_{gen}(t) \times \dot{W}_{max} \tag{15}$$

$$W_{RO,int}(t) = V_{RO}(t) \times E_{RO} \tag{16}$$

Lastly, the hourly electricity generated has to be used to run the RO plant or sold to the grid as defined by Equation 17.

$$W_{gen}(t) = W_{sell}(t) + W_{RO,int}(t) \tag{17}$$

This optimization analysis used fuel and electricity price data from 2011–2015 to determine whether the lower operating costs associated with generating electricity on site and the revenues associated with electricity sales are sufficient to justify the additional capital cost for integrating the CCGT plant with the RO plant. For a stand-alone RO plant, the amortized capital cost, $C_{cap,s.a.}$, is a function of the OCC of the RO plant, the annual capacity factor of the RO plant, and the capital recovery factor, CRF, as shown in Equation 18.

$$C_{cap,s.a.} = \frac{OCC_{RO} \times CRF}{365 \times CF} \tag{18}$$

The OCC of the RO plant is defined as 4280 \$/kgal per day per the cost-estimating tool on Global Water Intelligence's DesalData.com. The CRF was calculated using Equation 19 and assuming an interest rate, i, of 8% and a project lifetime, n, of 20 years. Note that these values were chosen for illustrative purposes and that this analysis can be done using any values for the interest rate and project lifetime. A higher interest rate or lower project lifetime would increase the capital cost.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{19}$$

For the integrated CCGT-RO, the OCC and fixed operation and maintenance cost, $F_{O\&M}$, of the CCGT plant were normalized by the specific energy consumption of desalination to be in \$/kgal as shown in Equations 20 and 21. The OCC of the CCGT plant is shown in Table 1, and the fixed operation and maintenance cost for the CCGT plant is 13.2 \$/kW-yr according to EIA (EIA 2013). The sum of amortized capital and fixed costs for the integrated CCGT-RO plant, $C_{cap,int}$, is shown in Equation 22.

$$OCC_{CCGT,norm} = \frac{OCC_{CCGT} \times E_{RO}}{24\frac{hr}{d}} \tag{20}$$

$$F_{O\&M,norm} = \frac{F_{O\&M} \times E_{RO}}{24\frac{hr}{d}} \tag{21}$$

$$C_{cap,int} = \frac{(OCC_{RO} + OCC_{CCGT,norm}) \times CRF + F_{O\&M,norm}}{365 \times CF_{desal}} \tag{22}$$

The average cost of powering an integrated CCGT-RO or stand-alone RO plant, $\overline{C_{power,j}}$, is defined as the sum of hourly power costs divided by the sum of hourly desalination volume as shown in Equation 23. Similarly, the average revenues earned from electricity sales for the integrated CCGT-RO plant, $\overline{R_{elec}}$, are defined as the sum of hourly electricity revenues divided by the sum of hourly desalination volume as shown in Equation 24.

$$\overline{C_{power,j}} = \sum_{t\epsilon T} C_{power,j}(t) / \sum_{t\epsilon T} V_{RO}(t) \tag{23}$$

$$\overline{R_{elec}} = \sum_{t\epsilon T} R_{elec}(t) / \sum_{t\epsilon T} V_{RO}(t) \tag{24}$$

The LCOW is defined as the sum of the operating cost of the RO plant, the amortized capital cost, and the average cost of power minus the average revenues earned from electricity sales as shown in Equation 25.

$$LCOW_j = C_{RO} + C_{cap,j} + \overline{C_{power,j}} - \overline{R_{elec}} \tag{25}$$

In summary, a simple Thermoflex model of a CCGT plant based on the power plant specifications (Table 1) and site conditions considered for this analysis was used to estimate the flow rate of water needed for the cooling system of a small-scale CCGT plant. This flow rate was compared with the total flow rate of seawater coming into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO plant. The carbon emission intensity of the CCGT plant was estimated based on the reported carbon emission intensity of natural gas and the efficiency of the CCGT plant as shown in Equation 3. The carbon intensity of the CCGT plant was compared to the fleet average carbon intensity of the ERCOT power grid.

An optimization analysis was used to estimate the LCOW of an integrated CCGT-RO compared to a stand-alone RO plant. The decision variables used in this analysis include binary variables, x_{RO} and x_{gen}, that describe whether the RO plant and CCGT are on or off. The decision variables also include continuous variables for the hourly volume of water desalinated, V_{RO}, hourly electricity generation, W_{gen}, and the hourly electricity sold to the power grid, W_{sell}. Dependent variables include the hourly electricity consumed by the RO plant, W_{RO}, the hourly cost of powering the integrated CCGT-RO or stand-alone RO plant, C_{power}, and the hourly revenue earned from electricity sales, R_{elec}. These values, along with the operating costs associated with an RO plant and the amortized capital cost of an integrated CCGT-RO or stand-alone RO plant, were used to calculate the LCOW with Equation 24.

RESULTS

For small-scale CCGT plants ranging from approximately 36–71 MW, the cooling water flow rate ranges from 13 to 24 MGD, and the maximum desalination capacity ($\dot{V}_{RO,max}$) ranges from approximately 63 to 125 MGD (3-6 million gallons per hour) as shown in Figure 2. For context, Sorek, the largest seawater RO plant in the world, has a capacity of 165 MGD (IDE [no date). Assuming a recovery ratio of 40–50%, the necessary flow rate of seawater intake would range from 125–312 MGD. Thus, only 8–10% of the seawater intake for the RO plant would be needed to cool the power plant. The carbon intensity of the CCGT plant varies from 802-885 lb/MWh, 33–39% less than the average carbon intensity of 1285 lb/MWh for electricity purchased from ERCOT as shown in Figure 3. Electricity purchased from ERCOT has a higher carbon intensity because coal accounted for 27-36% of ERCOT's generation mix from 2011–2015 (EIA 2018a).

Compared to a stand-alone RO plant with the same desalination capacity, an integrated CCGT-RO has higher amortization costs but lower power costs. Subtracting the amortized capital cost of a stand-alone RO plant, Equation 18, from the amortized capital cost of an integrated CCGT-RO plant, Equation 22, the additional capital cost associated with the power plant is approximately 0.17-0.21 \$/kgal as shown in Figure 4.

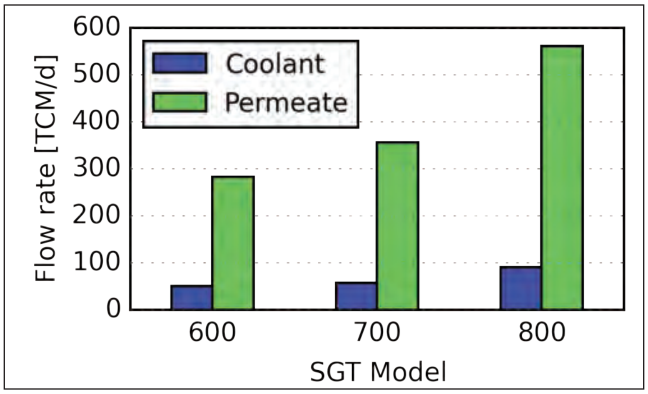

Figure 2. The flow rates [TCM/d] of power plant coolant are only 8–10% of the total flow rate of seawater intake for the RO plant assuming a 40 – 50% recovery ratio.

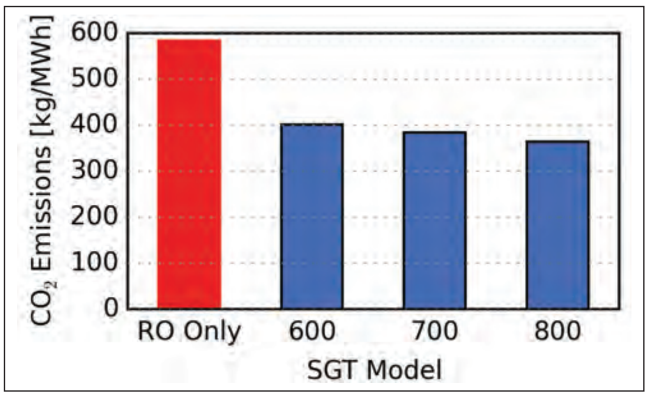

Figure 3. The average carbon intensity associated with electricity purchased from ERCOT is approximately 1285 lb/MWh compared to 802-885 lb/MWh for a range of small-scale CCGT plants that could supply power to an RO plant.

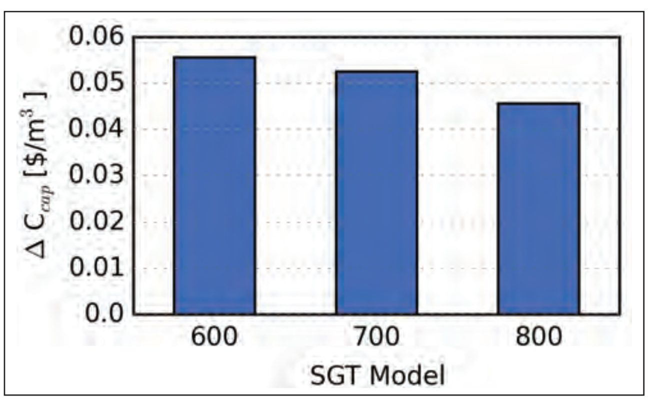

Figure 4. The additional capital cost associated with the power plant for the integrated CCGT-RO is approximately 0.17-0.21 $/kgal.

From Equation 23, the average cost of powering a stand-alone RO plant is approximately 0.68 $/kgal compared to 0.31-0.34 $/kgal for an integrated CCGT-RO plant as shown in Figure 5. An integrated CCGT-RO plant also earns approximately

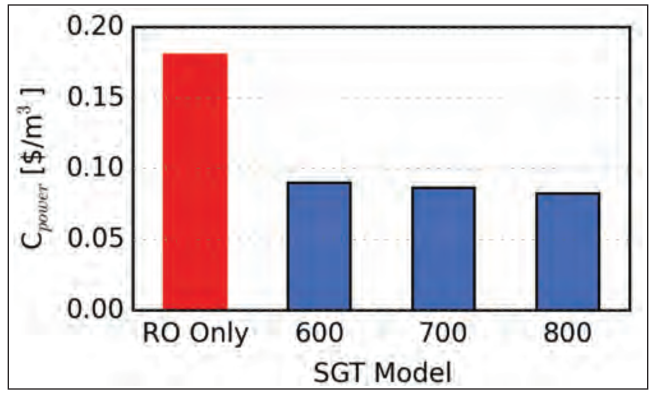

Figure 5. The power cost for a stand-alone RO plant is approximately 0.68 $/kgal compared to 0.31-0.34 $/kgal for an integrated CCGT-RO plant. An integrated CCGT-RO plant also earns approximately 0.08 $/kgal in revenues from electricity sales.

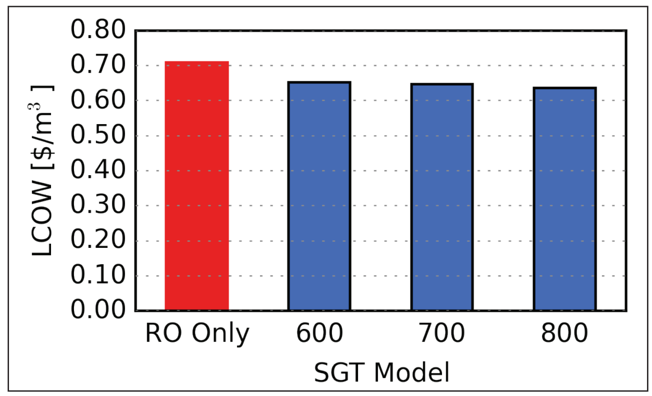

Figure 6. The LCOW for a stand-alone RO plant is approximately 2.69 $/kgal compared to 2.40-2.47 $/kgal for an integrated RO plant, a decrease of 8–10%.

0.08 $/kgal in revenues from electricity sales. From Equation 25, the LCOW for a stand-alone RO plant is approximately 2.69 $/kgal compared to 2.40-2.47 $/kgal for an integrated RO plant, a decrease of 8–10%, as shown in Figure 6. As would be expected from the decreasing amortization and power costs in Figures 4 and 5, the LCOW tends to decrease when the RO plant is integrated with a bigger, more efficient CCGT plant.

DISCUSSION

This study focused on the implications of integrating a seawater RO plant with a CCGT plant much smaller than what is typically built to be competitive in the electric power market. There were several motivations for considering such a small-scale CCGT plant. For example, even though it may make sense to integrate an RO plant with an existing large-scale power plant, it may not make as much sense to construct a new large-scale power plant just to power an RO plant. One dimension in which a small-scale CCGT plant might be preferable to a larger plant is that the cooling system of a small plant needs only a fraction of the total flow rate of seawater coming into the RO plant, and so no additional intake capacity is needed. A once-through cooling system for a 500 MW CCGT plant, on the other hand, would need an intake of more than 130 MGD, i.e., approximately 30% more than the intake for the Carlsbad RO plant outside San Diego, California, the largest seawater desalination plant in the Western hemisphere (Poseidon Water 2017).

Even though a small-scale CCGT plant is less efficient and has a higher overnight capital cost than a large-scale CCGT plant, an RO plant integrated with a small-scale CCGT plant still outperforms a stand-alone RO plant thermodynamically and economically. The carbon intensity of electricity produced by a small-scale CCGT plant is more than a third lower than the average carbon intensity of electricity on the ERCOT grid. However, ERCOT's carbon intensity is trending downward as wind, solar, and natural gas are replacing coal generation. Even so, the levelized cost analysis used in this study indicates that an RO plant integrated with a small-scale CCGT benefits enough from reduced energy costs and revenues from electricity sales to justify the capital and fixed costs associated with the CCGT plant.

This analysis assumed that the specific energy consumption of desalination was 13.75 kWh/kgal. This number is based on the most recently built large-scale desalination plants. As the specific energy consumption for seawater reverse osmosis decreases, the energy savings from integrating an RO plant with a small-scale CCGT plant decreases. For example, the Affordable Desalination Coalition has reported specific energy consumption as low as 6.6 kWh/kgal for a demonstration project (ADC [no date]). With such a low specific energy consumption, the energy savings from integrating an RO plant with a small-scale CCGT plant would be only 0.19–0.23 $/kgal instead of the 0.22-0.29 $/kgal energy savings reported in the results. Similarly, the energy savings would be higher than 0.22-0.29 $/kgal if the specific energy consumption was greater than 13.75 kWh/kgal.

The optimization analysis used to estimate the optimal hourly operation for an integrated CCGT-RO plant included an annual capacity factor constraint for the RO plant. A consequence of such a constraint is that the capacity factor of the RO can vary on a monthly basis, with the RO plant running less often in months with high wholesale electricity prices to maximize the revenues that can be earned from electricity sales. Averaging the optimal operating schedule of a CCGT-RO for the years 2011–2015 that were considered in this analysis, the capacity for the RO plant varies from as low as 86% in August to over 98% in months like November, December, and January as shown in Figure 7. These variations correspond to the monthly average wholesale electricity prices also shown in Figure 7. Note that the August prices are skewed by the extremely high prices from 2011 when the hourly average price was over 150 $/MWh. These results indicate that the owner of an integrated CCGT-RO plant would benefit from flexible purchase agreements that allow for some variation in monthly operation. Conversely, hot, dry months with high electricity prices may be coincident with high water demand or water scarcity. Thus, customers for desalinated water might choose to have water purchase agreements that require the RO plant to produce a minimum amount of desalinated water on a monthly basis. Future research should consider how stricter constraints on the monthly or daily capacity factor for the RO plant would impact estimates for the revenues that can be earned from electricity sales.

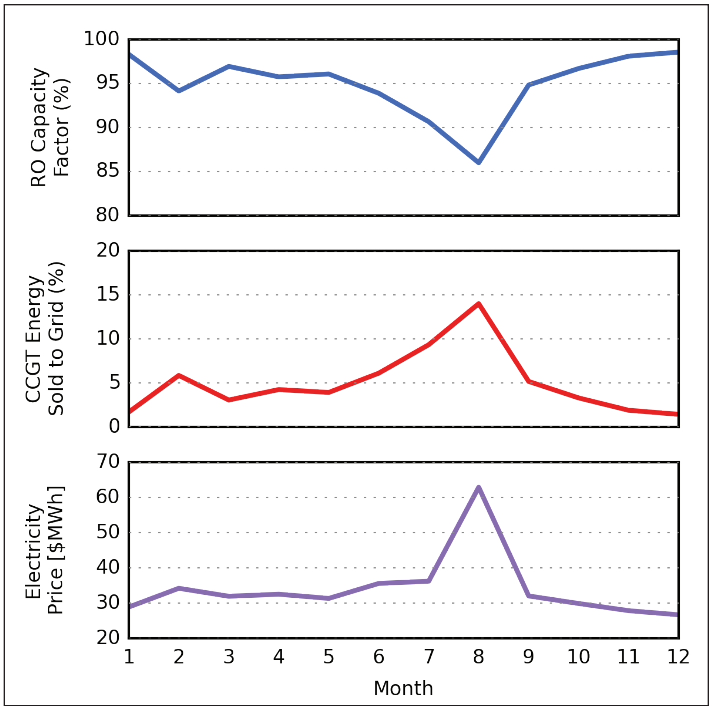

Figure 7. With an annual capacity factor constraint for the RO plant, operation of a CCGT- RO plant varies over the course of the year to maximize revenues earned from electricity sales.

When comparing the cost of an integrated CCGT-RO with that of a stand-alone RO plant, it is assumed that a stand-alone RO plant would have to purchase electricity from the grid at a monthly retail rate. If a stand-alone RO plant were instead allowed to purchase electricity at rates based on the time of use, it is conceivable that the average price of electricity could be cheaper if the RO plant is able to schedule its operation around peak electricity prices. It is also conceivable that time-of-use rates could be designed in such a way that there could be times of day or short-term market conditions when it would be cheaper to power an integrated CCGT-RO plant with electricity purchased from the grid rather than generating electricity on site. Future research should investigate how incorporating different time-of-use rates into this analysis would affect the results.

CONCLUSIONS

There are several benefits from integrating and powering an RO plant with a small-scale CCGT plant rather than purchasing electricity from the grid. With a small-scale CCGT plant, no additional intake capacity is needed for the power plant cooling system. In Texas, the carbon emission intensity for a small-scale CCGT plant is more than 33% lower than the average carbon intensity of electricity on the ERCOT power grid. From an economic standpoint, the cost of powering an integrated CCGT-RO is, on average, less than half the cost of powering a stand-alone RO plant with retail electricity. This reduction plus revenues earned from electricity sales are sufficient to justify the additional capital and fixed costs associated with the CCGT plant.

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APPENDIX

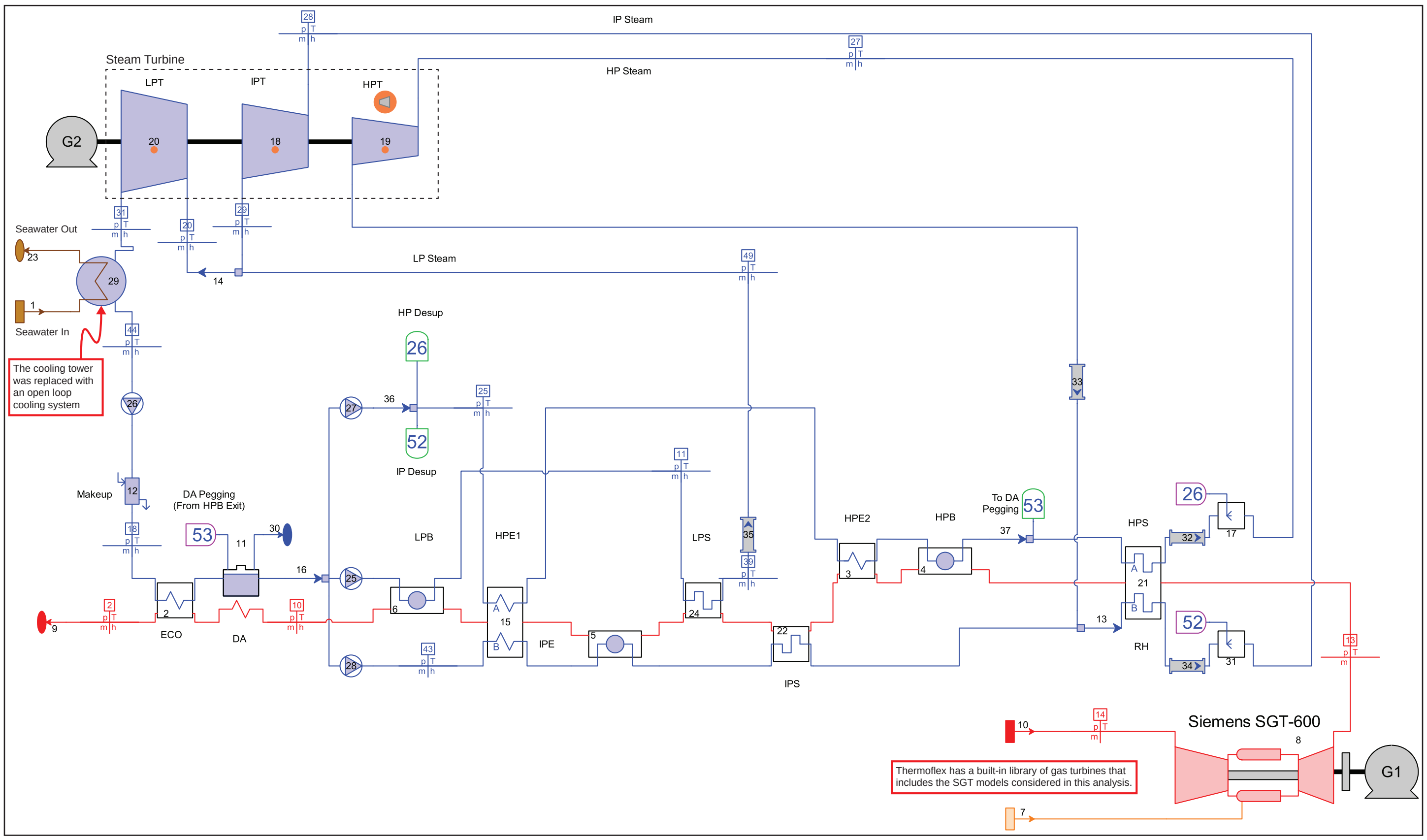

Figure 8. A sample CCGT model included with Thermoflex was used to estimate the coolant flow rate for a CCGT plant. This model was modified to have an open loop cooling system and the SGT models (600, 700, 800) described in the paper.

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Integration of the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) observations into the West Gulf River Forecast Center operations

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Abstract: This article will introduce the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network and illustrate its integration into the daily operations at the National Weather Service West Gulf River Forecast Center (WGRFC). An example will be shown on how the data were used during a specific flood event and will illustrate our extensive use of this data during Hurricane Harvey. The benefits of this network will be discussed. The network provides the WGRFC a source of rain gauge data where other sources of rainfall data are sparse and allows for verification of radar-based precipitation estimates. Members of CoCoRaHS provide observations that are vital in assisting the WGRFC with flood forecasting operations. Information on joining this important network is presented in this article.

Keywords: rainfall, observers, floods

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Terms used in paper

Acronyms	Descriptive name
CoCoRaHS	Community Collaborative Rain, Hail and Snow
HRAP	Hydrologic Rainfall Analysis Project
MPE	Multisensor Precipitation Estimate
NSF	National Science Foundation
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RFC	River Forecast Center
UTC	Coordinated Universal Time
USGS	U.S. Geological Survey
WSR	Weather Service Radar
WGRFC	West Gulf River Forecast Center

INTRODUCTION

In Story (2016), Texas Water Journal readers were introduced to the mission of the hydrologic program of the National Weather Service (NWS). The 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 for most of the river drainages in Texas in an effort to protect life and property. River response and flood potential often depend on the magnitude of each rainfall event. Prior to real-time weather tracking systems, the river forecast centers (RFCs) were faced with using daily rainfall totals from sparse sources, such as airport rain gauges, automated river rain gauges, and NWS co-operative observers. Due to the limited spatial distribution of the gauges, often the most intense rainfall amounts would be missed. This lack of information limited the RFCs' ability to provide real-time or near-real-time flood forecasts, often resulting in the river forecast crests being too low and the timing of those crests being late.

Since the advent of the Weather Service Radar-1988 Doppler (WSR-88D) radars in the mid-1990s, forecasters have been able to receive precipitation estimates each hour. While these estimates give much improved spatial and temporal resolution, the actual amounts of rainfall can be in considerable error. Therefore, dependable rainfall observations from gauges are still necessary. A rainfall network began 20 years ago that helps determine the accuracy of radar-based precipitation estimates. This is the Community Collaborative Rain, Hail and Snow (CoCoRaHS) network.

WHAT IS COCORAHS?

CoCoRaHS is a non-profit, community-based network of volunteers of all ages and backgrounds who work together to measure and map precipitation (rain, hail and snow). CoCoRaHS is now in all 50 states, Puerto Rico and the U.S. Virgin Islands, the Bahamas, and Canada. The network originated with the Colorado Climate Center at Colorado State University in 1998, inspired in part by the Fort Collins flood the prior year (Reges et al. 2016). Since the beginning of this network, the WGRFC has seen the benefits of this precipitation data (as the WGRFC has river forecast responsibility in southern Colorado). In the years since, more than 6,100 Texans have joined CoCoRaHS, and more than 62,000 volunteers have joined nationwide (CoCoRaHS website 2018). While many of these observers have moved, passed on, or lost interest over time, the WGRFC receives around 1,000 CoCoRaHS observervations per day. Volunteers agree to take precipitation measurements and are asked to report even on days when no precipitation has occurred. We hope to receive rain reports from as many locations as possible. These precipitation reports are entered either through the CoCoRaHS website (www.cocorahs.org) or through an application on a mobile smart phone. The data are then recorded in a central archive at CoCoRaHS headquarters and made available to the public in near-real time on the CoCoRaHS website. The data are displayed and organized for many end users to analyze daily, with purposes ranging from water resource analysis and severe storm warnings to neighbors comparing how much rain fell in their backyards. CoCoRaHS is used by a wide variety of organizations and individuals. Aside from the NWS, meteorologists, hydrologists, and emergency managers routinely use this resource. Additionally, CoCoRaHS data benefit city utilities (for water supply, water conservation, or stormwater), insurance adjusters, agriculture, engineers, mosquito control personnel, ranchers and farmers, outdoor and recreation interests, teachers, students, and neighbors in the community.

CoCoRaHS has several goals: 1) to provide accurate high-quality precipitation data on a timely basis; 2) to increase the density of precipitation data available by encouraging volunteer weather observing; 3) to encourage citizens to have fun participating in meteorological science and heightening their awareness about weather; and 4) to provide enrichment activities in water and weather resources for teachers, educators and the community at-large. For its detailed mission statement, visit the link in the reference section (CoCoRaHS website 2018). Most importantly, this is a community project. The only requirements are that one have an enthusiasm for watching and reporting weather conditions, a desire to learn more about how weather can affect and impact our lives, and a good place to measure rainfall. By providing daily observations, one can help to fill in a piece of the weather puzzle that affects many across Texas. By using low-cost measurement tools, stressing training and education, and using an interactive website, the network's aim is to provide the highest quality data for natural resource, education and research applications, which can greatly aid flood forecasts and radar corrections. Both the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF) are primary sponsors of CoCoRaHS. Other organizations have contributed financially and/or with supplies and equipment. The list of sponsors continues to grow. Many other organizations and individuals have contributed time and resources to help keep the network running.

COCORAHS OBSERVATIONS AT WGRFC

Hydrometeorologists at WGRFC continuously monitor rainfall over their area of responsibility. As stated in Story (2016), the NWS uses rainfall estimates from multiple sources, but primarily from radars, in generating river forecasts. Precipitation estimates from the more than 24 WSR-88D radars with observations within the WGRFC area have allowed for better analysis of timing and areal distribution of precipitation. These rainfall estimates are adjusted based on comparisons to rain gauge data from all sources. These "best estimates" are used in NWS river forecasts models. Now, hundreds of 24-hour CoCoRaHS rainfall reports are available for post-analysis of this best estimate. Direct comparisons of the estimates and observer rainfall totals are made shortly after 1200 Coordinated Universal Time (UTC) (7 AM Central Daylight Time) each morning. These reports allow WGRFC's hydrometeorologists to determine areas where the radar-based estimates may be too low or too high. Forecasters can adjust estimates in specific hours to reproduce a 24-hour estimate that is more consistent with 24-hour gauge reports. The goal is to achieve a "general" level of acceptable error in the estimates. Computations are performed that show the correlation coefficient and percent bias of radar estimates, which vary by time and location. The goal is to modify the estimates to achieve minimum correlation coefficients (r) of 0.85 (an arbitrary in-house goal). Originally, most initial estimates are biased low (e.g. the 24-hour gauge reports are higher) and frequently have poor correlation. When initial radar-based estimates are linearly adjusted, which are spatially variable, the inherent error of most estimates is improved to the desired correlation ($r > 0.85$). Removal of this bias is crucial to improve flood forecasts. If these biases are not mitigated, a false identification of a flood wave that is too low might occur over time. An example of the WGRFC Gauge Check program is shown in Figure 1.

There are two types of CoCoRaHS reports used at the WGRFC. First, CoCoRaHS spotters can submit intense rainfall reports whenever the situation warrants. These reports are invaluable to forecasters, so much so that we have these reports trigger an "alarm" on our NWS workstations. Any observer can make a significant weather report. An example of the form an observer fills out on the CoCoRaHS website is shown in Figure 2.

An example of an intense rainfall report from Hurricane Harvey is shown in Figure 3.

Such reports are often a preemptive warning that rainfall may be occurring or even exceeding remotely sensed data from radar. It also allows WGRFC forecasters to adjust hourly estimates in near real time, improving flood forecasts.

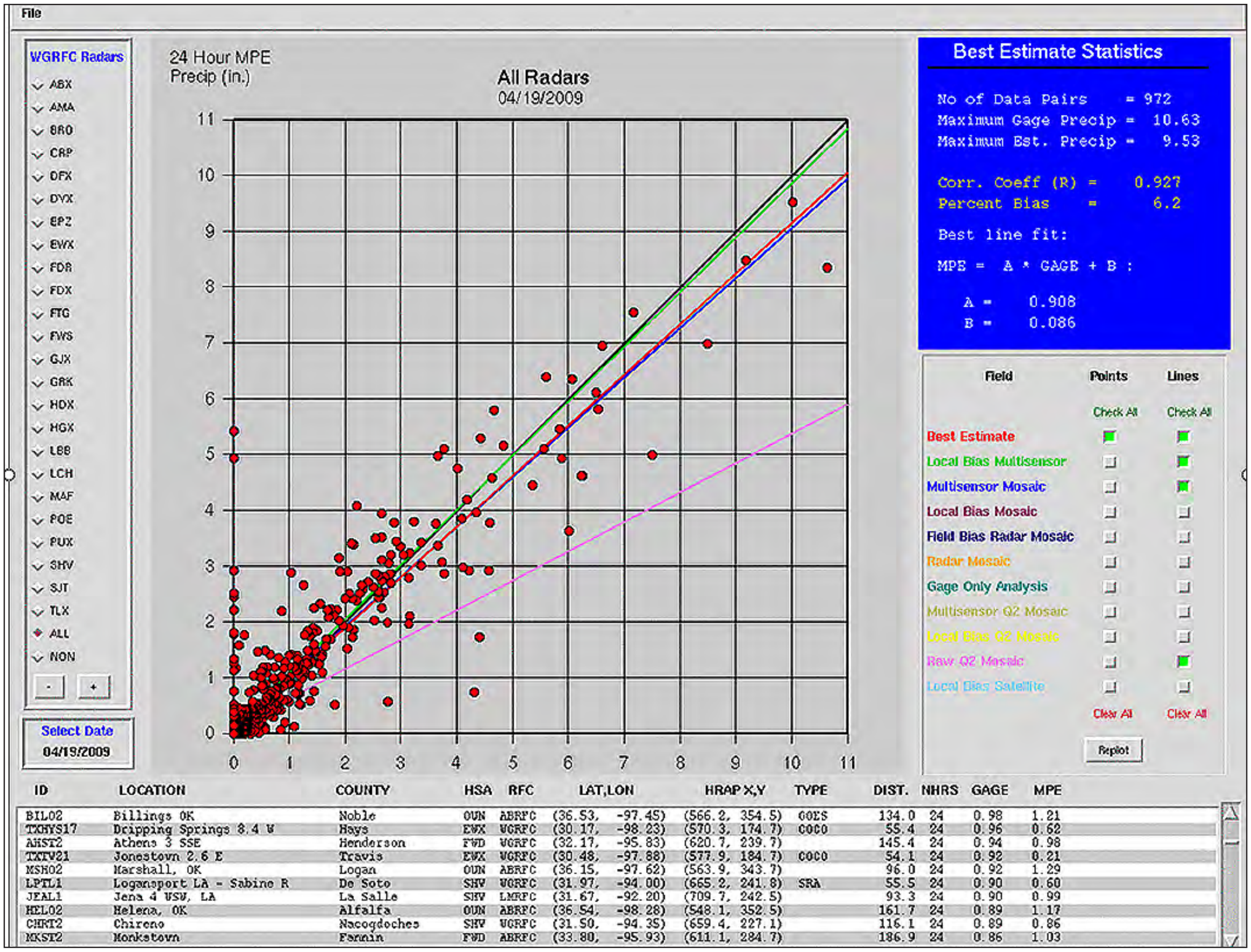

Figure 1. The Gauge Check Program used at WGRFC. Rain gauge values for the 24-hour period ending as 12 UTC (x-axis) are plotted against the associated Multisensor Precipitation Estimate (MPE) best estimate of precipitation (y-axis) at the location of that gauge. Values above the diagonal black line show an MPE overestimate, while values below indicate an underestimate. Colored lines show the calculation of MPE versus gauges for each radar-based field within MPE, with the red line being the final best estimate. The observations show a good correlation (R = 0.927) to radar estimates but is biased low by 6.2%. The MPE radar data are linearly adjusted to best match gauge data.

Second, the 24-hour CoCoRaHS rainfall measurements are ingested at the WGRFC through the morning, which are then compared to radar-based estimates (along with rain gauge observations from other sources). The CoCoRaHS rain gauge data are considered to be ground truth and one of the most readily available best data sources for radar corrections. Figure 4 shows an example from 2012 when CoCoRaHS reports from Ellis County helped improve a flood forecast:

In this example, the CoCoRaHS observer, who was located 0.6 of a mile west-southwest of Maypearl, gave us a rainfall reading of 4.51 inches. Our initial "best estimate" for that location was 2.60 inches, or about ½ the amount that fell. We went back to the hours it rained in this location and increased the radar-based estimates. This allowed us to match the CoCoRaHS amount in real time. This led to more runoff being calculated within our hydrologic model and produced a forecast hydrograph with higher runoff volumes than was originally produced. A small flood wave occurred on Chambers Creek that may have gone unforecasted had the CoCoRaHS gauge not shown the larger rainfall totals.

All 24-hour rainfall observations received from all sources, including the CoCoRaHS observations, are available each morning around 10 AM at: https://forecast.weather.gov/product.php?site=NWS&product=HYD&issuedby=FWR

This list can be used to compare all the rainfall readings in the WGRFC region.

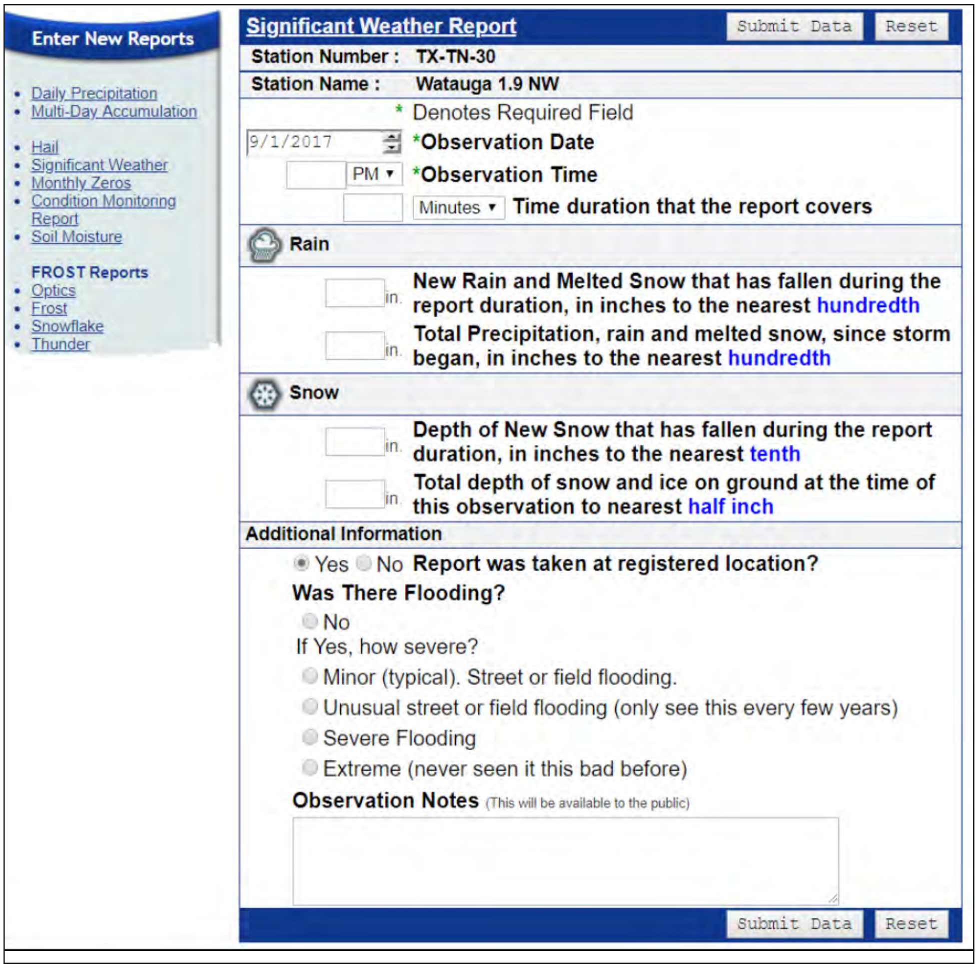

Figure 2. The significant weather report form for CoCoRaHS observers. This form can be used to report rainfall or snowfall of a short duration.

```
intense rain report from CoCoRAHS spotter:

08/28/2017 12:00 AM local time
County: Brazos TX
College Station 1.6 S (number TX-BZS-92)
Latitude: 30.577365
Longitude: -96.31456
15.33 inches so far, with 0.28 inches in the past 60 mins
Flooding: Unusual
Comments: Hurricane Harvey rainfall from 2300-2359 on 8/27

Received NWS Boulder Sun Aug 27 23:09:31 2017 MDT
Sent to WFOs: HGX,FWD,FWR

All of today's CoCoRAHS observations are in WRKCCR (Boulder and Pueblo only)
Or at http://www.cocorahs.org (click on reports)
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Figure 3. An intense weather report from a CoCoRaHS observer during Hurricane Harvey reporting over 15 inches of precipitation and 0.28 inches in the last hour as received on a WGRFC text workstation.

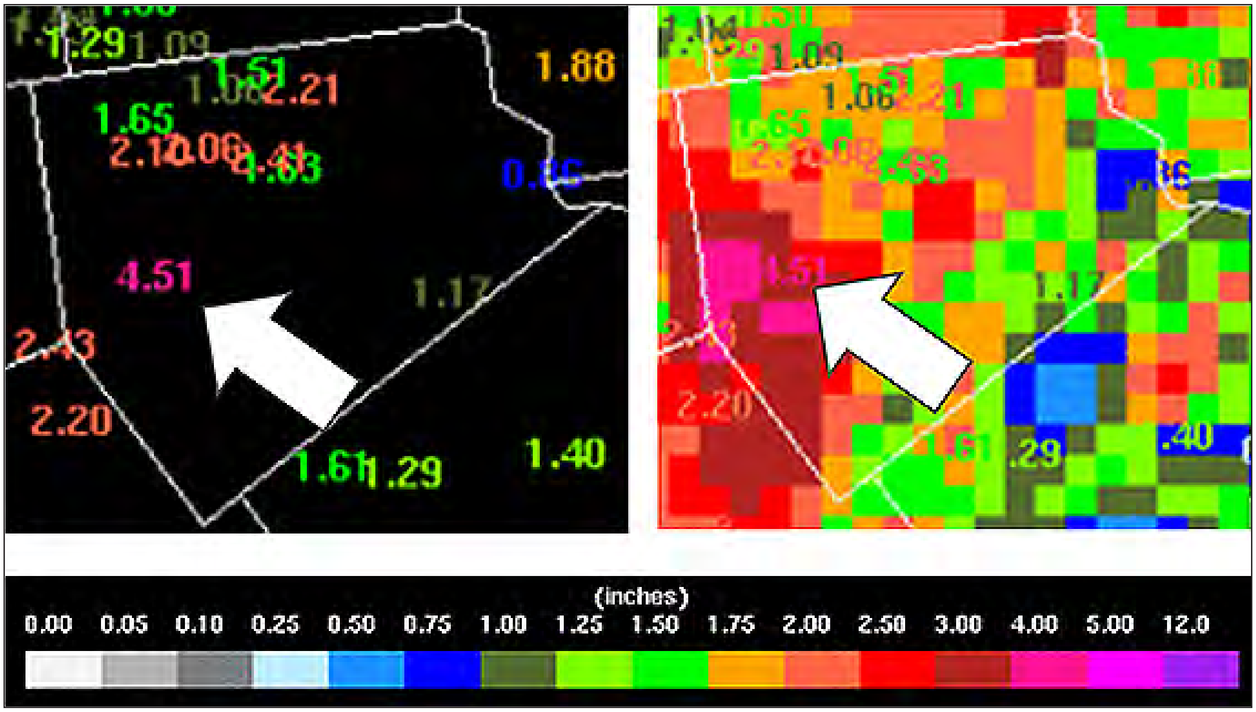

Figure 4. (Left) Location of CoCoRaHS gauge where initial underestimation was determined. Gauge values match the color scale. (Right) MPE final precipitation analysis with CoCoRaHS data overlaid after an adjustment was made to the 24-hour field. The arrow indicates where estimates were increased near Maypearl, Texas. The goal is to have the color of the MPE precipitation field match the color of the gauge reading.

EXAMPLES FROM HURRICANE HARVEY

Hurricane Harvey was the first major hurricane to make landfall in the United States since Wilma in 2005. The storm produced catastrophic impacts over southeast Texas and southwest Louisiana. Harvey made landfall near Rockport, Texas as a Category 4 hurricane. In a four-day period, many areas received more than 40 inches of rain as the cyclone meandered over southeast Texas and adjacent waters, with peak accumulations of over 60 inches (Blake and Zelinsky 2018). Hurricane Harvey produced the most rain on record for a tropical storm or other weather event in the contiguous United States. For more information, see the NWS Service Assessment on Harvey (NWS 2018), and see a scientific investigation report from the U.S. Geological Survey (USGS 2018).

Rainfall estimation from tropical systems is quite challenging. All sources of remote sensing have limitations during excessive rains and high winds. For an explanation of the reasons for these challenges, see Story (2012). Figure 5 shows Hurricane Harvey on the evening of August 25, 2017.

In the 24-hour period ending at 12 UTC on August 26, heavy rain from Harvey fell as it moved over parts of south central and southeast Texas. Figure 6 shows the CoCoRaHS reports, which were received just after 12 UTC.

The initial radar estimates ranged from 4 to 8 inches. However, the CoCoRaHS 24-hour readings had several contributors reporting 8.00 to 9.60 inches. The WGRFC initial estimates were too low, and these observations led us to increase final estimates. The final rainfall estimate from WGRFC software is shown in Figure 7:

The next day, for the 24-hour period ending at 12 UTC on August 27, we saw even larger underestimations. We initially estimated 8 to 13 inches of rain over southeast Texas, but the CoCoRaHS reports were much higher. The CoCoRaHS reports are shown in Figure 8 from day 2 of Hurricane Harvey and Figure 9 shows this graphically.

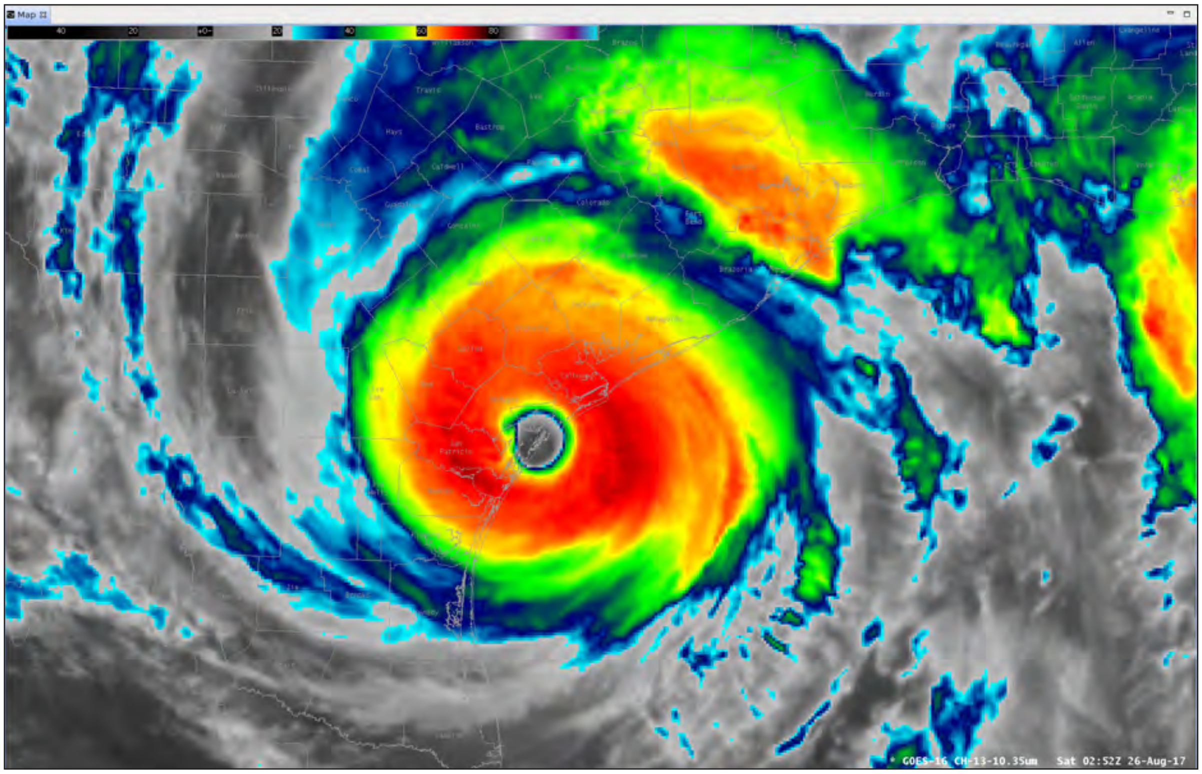

Figure 5. Hurricane Harvey at landfall as seen from GOES 16 satellite. The eye of Harvey is making landfall. The bright red colors around the eye indicate the eye wall and can be indicative of high rainfall rates.

LID		GAGE	MPE	LOCATION
TXFB17	:	9.60	8.63	Richmond 3.4 NE
TXGD15	:	8.92	5.35	Weser 1.9 NW
TXFB18	:	8.69	8.63	Richmond 2.9 NE
TXFB05	:	8.22	6.80	Sugar Land 3 SSE
TXFB12	:	7.61	6.74	Sugar Land 1 W
TXWH18	:	7.60	9.67	East Bernard 7.6 S
TXCLR10	:	7.50	4.99	New Ulm 5.1 S
TXCLR06	:	7.45	5.90	New Ulm 7.2 S
TXFB51	:	7.45	8.20	Richmond 4.4 NNE
TXDW19	:	7.41	5.31	Cuero 8.4 S

Figure 6. This table shows the ten highest August 26 CoCoRaHS reports. Alongside the gauge ID is the observed amount and our initial MPE estimate for that location.

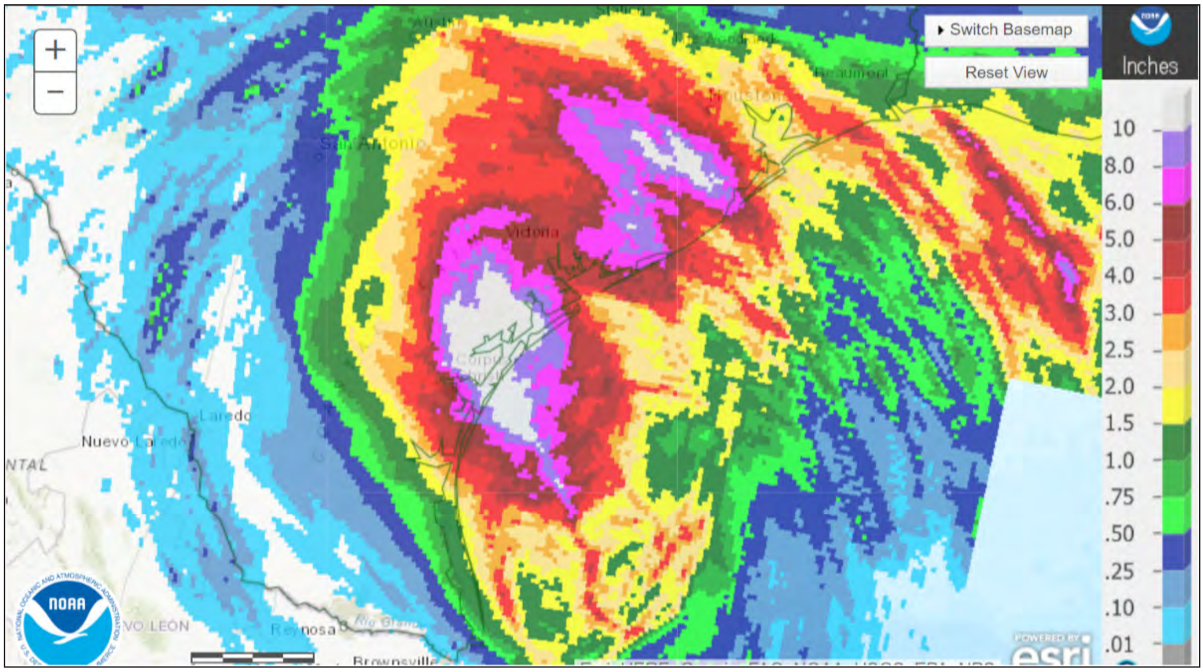

Figure 7. WGRFC best estimate of rainfall from the first day of Hurricane Harvey, 26 August 2017.

Again, since we were too low in our initial estimates, we increased them. This meant that increased flood volumes were forecasted. That resulted in many crest projections exceeding the major category (where extensive inundation of structures and roads occurs, with significant evacuations of people and property) or record category (where a river at a set forecast point had never been higher historically). Figure 10 shows our final estimate field from MPE after this increase.

LID		GAGE	MPE	LOCATION
TXGV44	:	21.62	12.90	Bacliff 0.5 SSE
TXHRR32	:	20.84	12.90	South Houston 4 SSW
TXHRR93	:	20.54	12.90	Pasadena 4.4 WNW
TXHRR31	:	19.41	12.90	Friendswood 2.5 NNE
TXGV60	:	19.38	12.90	Santa Fe 0.7 S
TXGV64	:	18.20	12.90	Hitchcock 1.6 NNW
TXHRR139	:	17.98	12.90	Cloverleaf 1.7 W
TXGV51	:	17.57	8.74	La Marque 1.8 E
TXHRR28	:	17.00	12.90	Webster 0.4 NW
TXGV63	:	16.59	12.90	Friendswood 1 SE

Figure 8. This table shows the 10 highest CoCoRaHS reports ending 12 UTC 27 August 2017. The data indicate five readings in excess of 19.25 inches that correspond to initial MPE estimates of just under 13 inches over parts of Harris and Galveston counties in southeast Texas.[1]

[1]The reason for the 12.90" matching so many gauges is two-fold. All have to do with the multisensor approach in MPE itself. MPE uses the Hydrologic Rainfall Analysis Project (HRAP) grid array. One HRAP grid is roughly 4 square kilometers. MPE arrives at just one value for an entire grid. You can have multiple CoCoRaHS gauge readings located in the same HRAP grid. That happens to be the case with a few of the gauges in Figure 8. Also, the HRAP grid value is derived from an hourly rain gauge if there is an hourly gauge located in that grid. Gauge values in the multisensor analyses actually have a sphere of influence, which is larger than one grid size, thus gauge readings can bleed over into other surrounding grids. Therefore, multiple grids can have the same value in a general location.

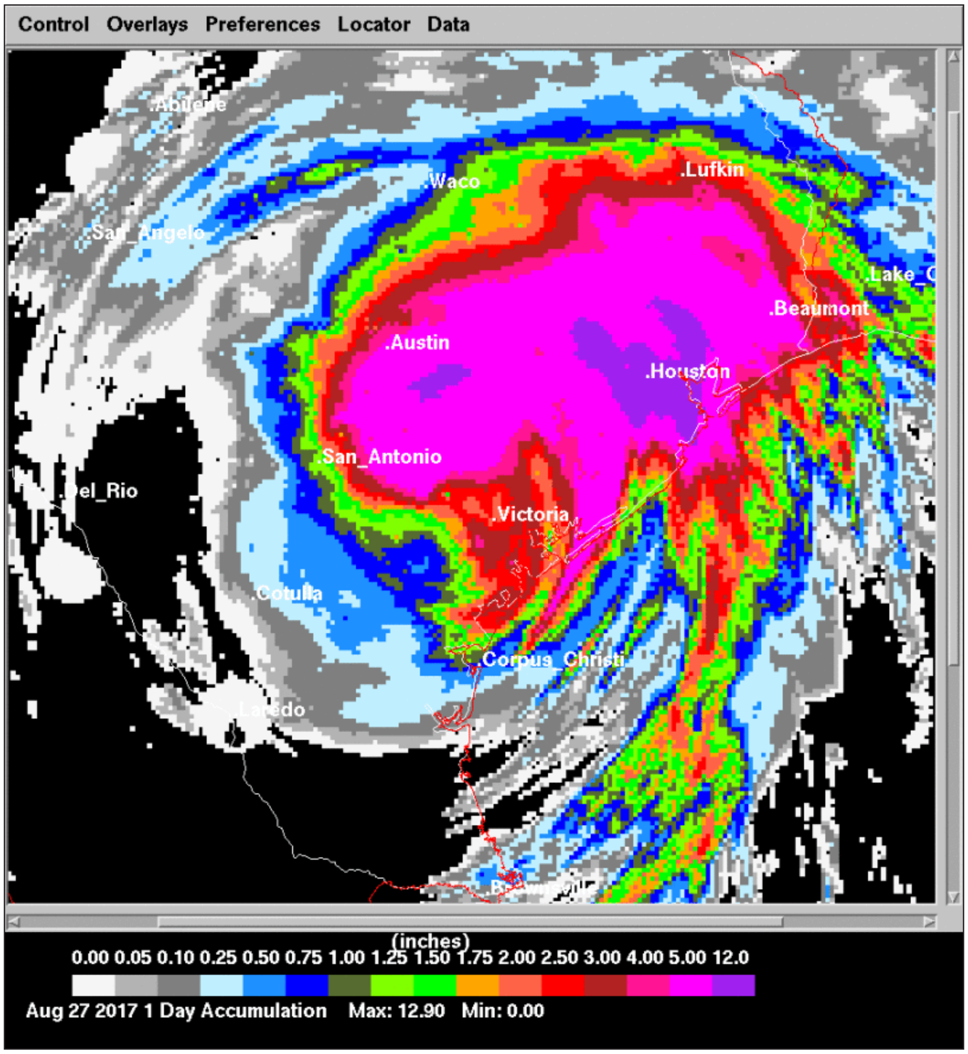

Figure 9. This was the initial estimate of rainfall from day two of Hurricane Harvey from WGRFC multisensor software.

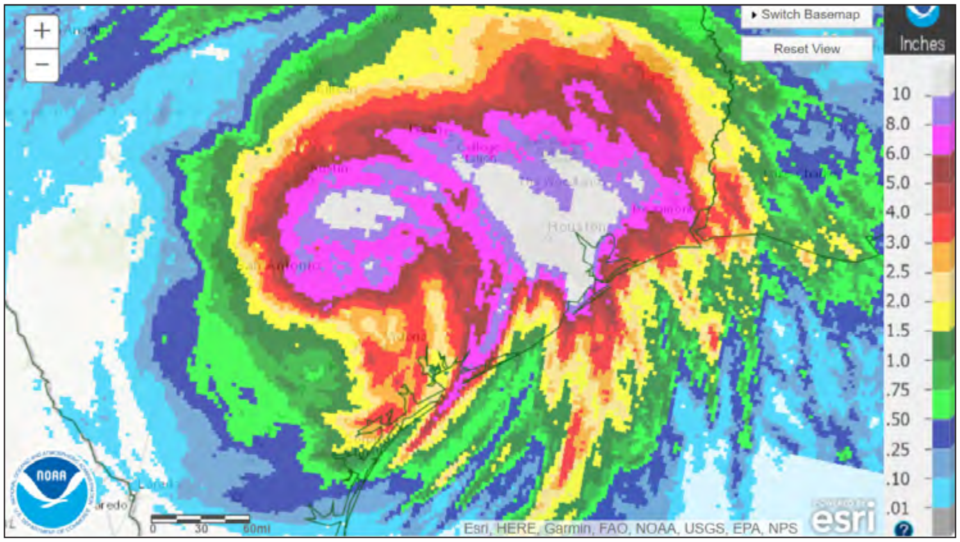

Figure 10. The final best estimate field from 12 UTC 27 August 2017. Note the sizable increase in the areal coverage of the heaviest rainfall over the initial estimates in Figure 9.

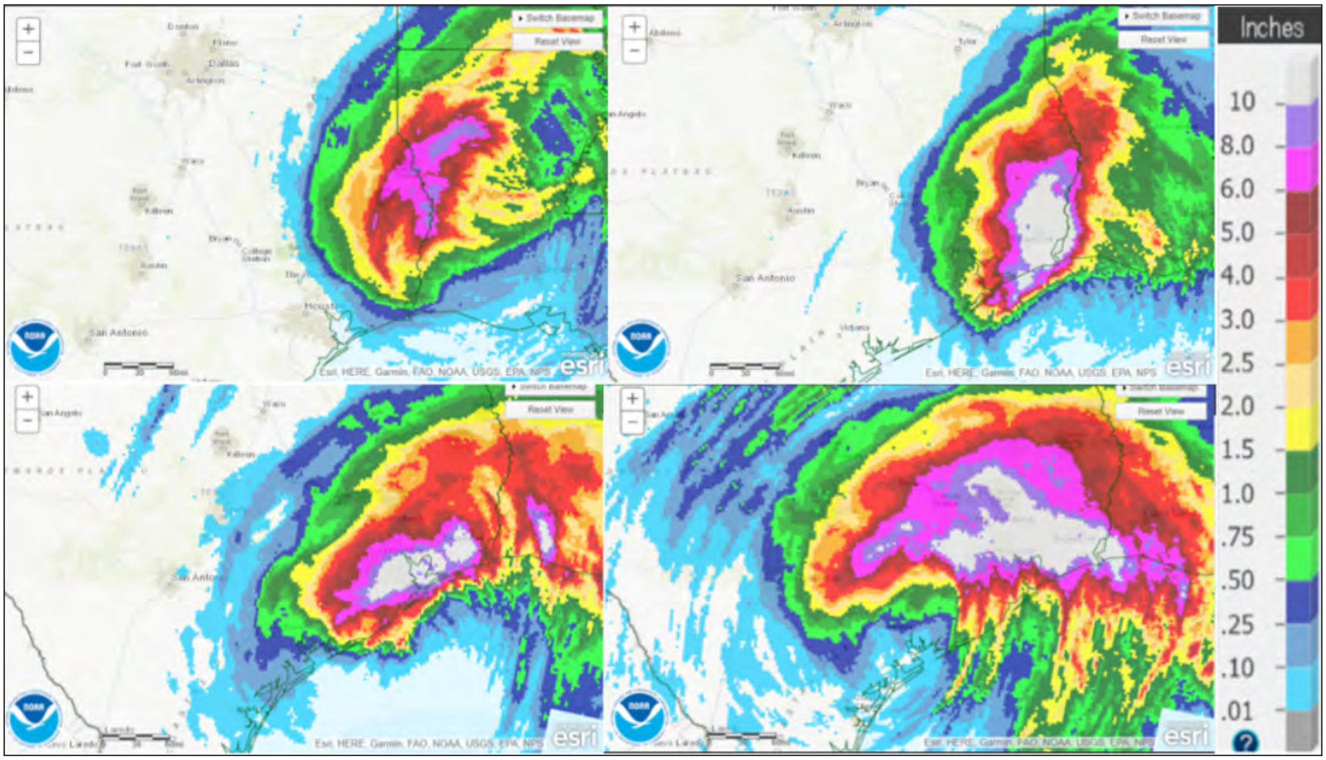

Figure 11. Final rainfall estimates. (Lower Right) August 28. The CoCoRaHS rain gauge data showed a maximum of 18.35 inches near Katy and a dozen observations in excess of 13.25 inches. The initial maximum MPE estimate was 12.90 inches, thus MPE showed severe underestimation and was adjusted higher. (Lower Left) August 29. CoCoRaHS rainfall readings showed a maximum rainfall of nearly 15 inches northeast of Friendswood, with ten observations in excess of 13 inches. Initial MPE rainfall estimates were in excess of 12 inches from south of Houston to near Beaumont/Port Arthur, showing the underestimation from radar-based MPE was not quite as severe. (Upper Right) August 30. CoCoRaHS rainfall readings indicated a maximum rainfall of over 15 inches about 5 miles south of Beaumont, with six observations in excess of 10.50 inches. The initial MPE estimates around 12 inches over extreme southeast Texas centered on Beaumont were too low and were adjusted upward for the final analysis. (Upper Left) August 31. CoCoRaHS rainfall readings confirmed the heaviest rainfall in excess of 7 inches had shifted into Sabine Parish, Louisiana. The initial MPE estimates were much closer as the rain rates decreased and shifted into western Louisiana, thus only limited adjustment upward was necessary for the final analysis.

Based on the CoCoRaHS observations, the initial MPE estimates were too low for the remainder of the Harvey rain event. The final daily rainfall for Harvey from August 28–31 are shown in Figure 11.

In the end, approximately 90% (60 out of the 67) of NWS river forecast locations in southeast Texas reached flood stage. Approximately 69% (46 out of the 67) reached major flood stage and approximately 46% (31 out of the 67) set flood records. The NWS issued more than 300 flood-related warnings at official river forecast points where USGS stream gauges measure flow volumes, out of 330 in the WGRFC area of responsibility (NWS 2018). The CoCoRaHS observations helped improve the NWS lead time on the magnitude of flooding. With initial estimates biased low, adjustments were made in real time to radar precipitation totals. These CoCoRaHS readings contribute greatly to the NWS WGRFC's mission of saving lives and property from floods here in Texas. Quite often the majority of the highest ten rainfall readings in the state on any given day come from CoCoRaHS observers. Figure 12 shows the gauge-corrected totals using CoCoRaHS and other data sources that gave the WGRFC its best estimate of rainfall from Hurricane Harvey.

CONCLUSION

CoCoRaHS is a volunteer, community-based organization that always needs more observers. The more reporting observers, the better the chances that the WGRFC can match the magnitude of rainfall. Even a daily report of no rainfall is useful information, as the final precipitation estimates that are computed also go into the state and national Drought Monitor maps each week (see http://droughtmonitor.unl.edu/CurrentMap.aspx).

To become a volunteer, you may follow these simple steps:

1. Read through the website and see what the project is about (https://www.cocorahs.org/).The website has information on "How To Measure Precipitation," "How To Measure Snow,"

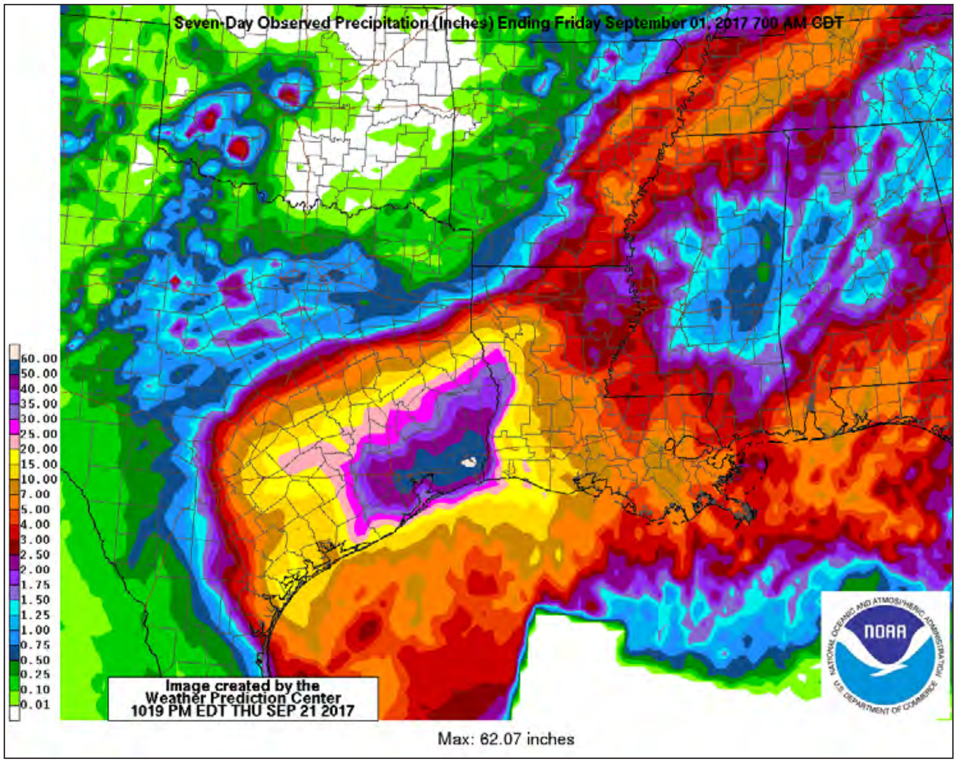

Figure 12. Total accumulated rainfall from Tropical System Harvey. Note the 62-inch final maximum total near Beaumont/Port Arthur.

and "How To Measure Hail" as well as information on the equipment used.

2. Make sure you have a rain gauge. You may purchase an official rain gauge from the link on the CoCoRaHS website for approximately $31.50 (see www.weatheryourway.com/cocorahs). They are excellent gauges that measure in hundredths of an inch. It is asked that your rain gauge be a 4" diameter all-weather gauge or better.

3. Go to our "Join CoCoRaHS" web page and sign up (https://www.cocorahs.org/application.aspx).

4. Either attend a training session for volunteers in person, or view the "Training Slide Show" found on the CoCoRaHS home page. It is very beneficial to read through the website on-line training materials completely. It is important to know how CoCoRaHS observers make and report their measurements. Good training along with careful observing and reporting are very important to the network and the users of the data.

5. Contact CoCoRaHS with any questions that you may have. Coordinators are available at the state and regional levels as a resource to assist you in getting started. Texas coordinator contact information can be found at: https://www.cocorahs.org/Content.aspx?page=coord_tx

6. Report your data daily on the website (www.cocorahs.org/Login.aspx) or use the CoCoRaHS smart phone application (Apple or Android). If you are unable to report on the internet, you may obtain CoCoRaHS Precipitation measurement forms from CoCoRaHS headquarters (or you may print your own from the website) and mail them.

We look forward to receiving many new observers in the future.

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Texas' water quality challenge and the need for better communication in an era of increasing water quality contamination events

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Abstract: As Texas cities experience an increase in incidents associated with water quality contamination, the need for public education and engagement increases. The discussion in this paper identifies, based on publicly available data, three of the most common incidents in Texas related to drinking water and environmental contamination: boil water notices (BWNs), sanitary sewer overflows (SSOs), and lead in drinking water. Trends observed from 2011 to 2016 indicate a sharp upward increase in the incidents of such events. Increased frequency of incidents that threaten water quality often erodes public trust in the city and utility, thus making it more difficult in the long term to get public support for increased investment in water and wastewater infrastructure. The recommendations in this study focus on how to manage communications when events associated with water quality create a public relations challenge for city and utility leaders.

Keywords: Safe Drinking Water Act, Environmental Protection Agency, MCLs, Maximum Contaminant Levels, Texas Commission on Environmental Quality, Texas Water Development Board

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Terms used in paper

Acronyms	Descriptive name
TWDB	Texas Water Development Board
TCEQ	Texas Commission on Environmental Quality
MCLs	Maximum Contaminant Levels
SDWA	Safe Drinking Water Act
EPA	U.S. Environmental Protection Agency
BWNs	boil water notices
SSOs	sanitary sewage overflows
LCPE(s)	Lead Contamination Public Education

INTRODUCTION

When Texans experience a threat to their water quality, it erodes public trust in city and utility leaders. That trust can take years to rebuild. The frequency of incidents threatening drinking water quality in Texas has increased over the past six years. In particular, incidents of boil water notices (BWNs), sanitary sewer overflows (SSOs), and Lead Contamination Public Education (LCPE) increased by 73%, 983%, and 1,300%, respectively, from January 2011 to December 2016.

The above-mentioned trend forewarns of how relationships between utilities and customers will deteriorate if these events persist and city and utility leaders cannot effectively communicate and reassure their users. To be sure, cities and utilities are actively implementing corrective measures to address these types of incidents; how these measures are communicated also impacts customers' views. Trust and dependability are values city and utility leaders need to engender in their customers, especially since infrastructure financing is heavily dependent on taxpayers' contributions, and thus their perceptions.

Public relations will increasingly become a critical part of the city and utility leaders' jobs because Texas' water and wastewater infrastructures are aging and in desperate need of repair and replacement. According to the Texas Section of the American Society of Civil Engineers (2012), Texas requires $33.9 billion to address water infrastructure issues over the next 20 years.

The need for increased investment will ultimately lead to higher water rates. Rates are the only low-cost means cities and utilities have at their disposal to raise the needed funds within a short amount of time. Therefore, it is necessary that customers understand the true cost of delivering water. Water quality crises and the mismanagement of rate increases, along with other situations, will only create obstacles to changing customer's minds on the ability of utilities to perform their job adequately.

To demonstrate the extent of the water quality issues in Texas, the authors analyzed the data on three types of incidents between 2011 and 2016 most commonly associated with threats to drinking water quality: BWNs, SSOs, and LCPE. The frequency of the incidents is correlated with other variables: duration, population density, and water regions as defined by the Texas Water Development Board (TWDB) regional water planning groups (See Figure 1).

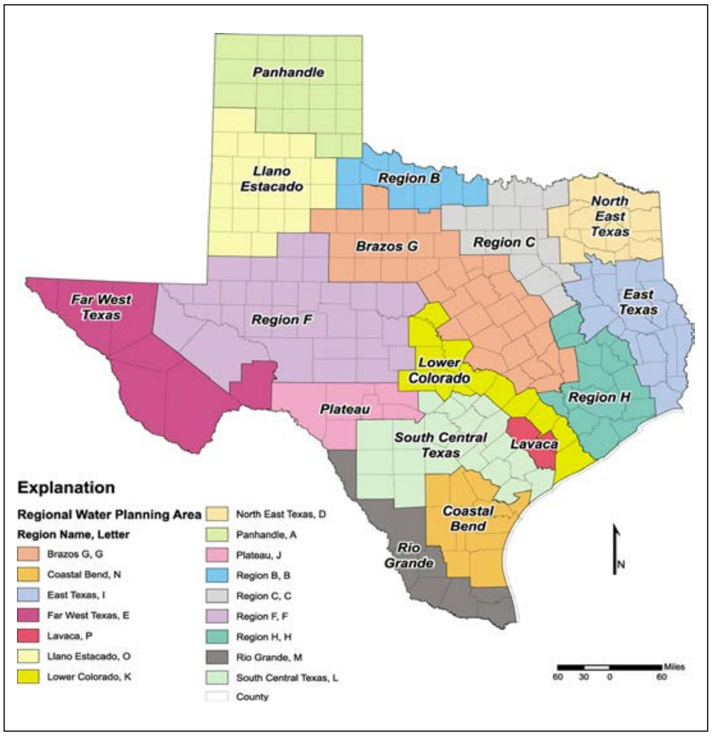

Figure 1: Regional water planning areas. Source: Texas Water Development Board.

BWNs are issued when a utility suspects harmful levels of bacteria and other pathogens are in the drinking water supply. During such incidents, consumers are advised to boil and then cool the water prior to consumption. "Common reasons for a boil water notice include loss of pressure in the distribution system and loss of disinfection. BWNs often result from other events such as waterline breaks, treatment disruptions, power outages, and floods (NY.GOV 2016)."

SSOs occur when raw sewage spills out of a collection system and into the environment—whether into a basement, out of manholes, onto a street, or into a waterway—before reaching a treatment plant. In a report to Congress, the U.S. Environmental Protection Agency (EPA) estimated up to 75,000 SSO events occur per year (EPA 2004), often during extreme wet weather patterns, such as floods, blocking sewage systems. Coastal cities are especially vulnerable due to extreme weather flooding, such as hurricanes. This is true particularly for Texas cities along the Gulf Coast.

Frequent SSO occurrences are indicative of failing infrastructure, lack of maintenance, ineffective operational procedures, and inadequate flow capacity (US EPA 2016a). The Texas Commission on Environmental Quality (TCEQ) recognizes the increase in SSO incidents and in 2004 established a compliance agreement coupled with a discretion-driven enforcement program called the SSO Initiative. This find-it-and-fix-it approach incentivizes corrective action by cities and utilities. The initiative addresses "an increase in SSOs due to aging collection systems throughout the state and encourage(s) corrective action before there is harm to human health and safety or the environment (TCEQ c2002-2018)."

Lead contamination in drinking water is considered detrimental to humans if sample results indicate a value of 15 parts per billion, according to TCEQ (following EPA guidance). Under Title 30 of the Texas Administrative Code and per the federal Lead and Copper Rule, public water systems are required to issue LCPE notices if they exceed this lead action level.

Lead in drinking water generally occurs because of corrosion of water pipes installed over 30 years ago or due to chemical reactions. Lead contamination is a silent threat as it does not give a unique taste or color to water; lead in pipes can only be detected through the testing of drinking water or by blood tests of those who drink the water. Lead also has long-lasting health impacts, including lifelong learning disabilities in children.

METHODOLOGY

In fall 2016, data sets on the total number of BWNs, SSOs, and LCPEs reported in Texas between January 2011 and December 2016 were acquired from TCEQ via a public information request. Data on BWNs were organized by entity (i.e., public and private utilities), date the event began, and a tracking number. In the case of SSOs, the data sets included the date of the SSO, water region, city, total units spilled, source of incident when available, and the water bodies impacted when applicable. Finally, LCPEs were organized by public water systems that delivered such notices and the date that notices were issued to the public.

To create uniformity among the data sets, each of the spreadsheets was reorganized by the total number of incidents by year and by water region. The regions are identified alphabetically starting from Region A all the way to P. Based on the tabulated data, line charts (See Figures 2, 3, 4, and 5 and Tables 1, 2, and 3) were generated to display the trends in the total number of incidents in each region over a six-year period. The data were also organized by population in each region to determine the correlation between population and the frequency of incidents associated with SSOs, BWNs, and LCPEs.

RESULTS

Between 2011 and 2016, the number of reported incidents associated with SSOs, BWNs and LCPEs increased significantly. Regions observed to have higher rates of incidents also have a high population density and are located close to or by the Gulf Coast. Increased awareness, visibility, and concern of water quality impacts from such incidents in densely populated

Table 1. Total number of boil water notices by region from January 2011 to December 2016.

	2011	2012	2013	2014	2015	2016	Total
Region A	2	5	5	6	11	9	**38**
Region B	7	16	12	5	11	5	**56**
Region C	29	71	73	77	126	86	**462**
Region D	29	38	55	57	68	47	**294**
Region E	2	3	9	4	3	3	**24**
Region F	21	32	22	26	30	20	**151**
Region G	66	148	159	181	247	191	**992**
Region H	109	181	186	253	249	145	**1,123**
Region I	193	332	308	282	311	214	**1,640**
Region J	2	5	9	5	11	2	**34**
Region K	57	66	96	118	144	85	**566**
Region L	12	27	24	52	101	84	**300**
Region M	3	14	7	5	7	9	**45**
Region N	6	24	29	15	7	4	**85**
Region O	6	27	27	25	20	34	**139**
Region P	0	1	1	3	2	1	**8**
Total	**544**	**990**	**1,022**	**1,114**	**1,348**	**939**	**5,957**

urbanized areas may drive increased reporting. Detailed results and trends for each type of incident are discussed below.

Boil Water Notices (BWNs)

The total number of BWNs recorded in the six-year period observed was 5,957 incidents. The annual number of incidents increased generally during the six-year period in all 16 regions. The overall increase—from 544 incidents reported in 2011 to 939 by the end of 2016—represents a 73% increase in the number of BWNs reported in Texas (See Table 1 and Figure 2).

Four regions—G, H, I, and K—recorded a higher than average number of incidents. Although the number of BWNs reported decreased in 2016, this is not an anomaly and could be attributed, in part, to reporting and recording inconsistencies, as well as a decrease in extreme weather events.

Regions G, H, I, and K are also high population centers, representing approximately 42% of the total Texas population. In addition to Houston-based Region H, Region G includes Abilene, Bryan, College Station, Killeen, Round Rock, Temple, and Waco; Region I includes Beaumont, Tyler, Port Arthur, Nacogdoches, and Lufkin; and Region K includes Austin, Bay City, Pflugerville, and Fredericksburg.

A notable spike can be seen between 2011 and 2012 where incidents increased by 82% from 544 to 990, respectively. The spike is most likely attributed to the regional impacts noted from the severe drought that began in 2009 and peaked in 2011. Severe droughts and resulting soil moisture loss can damage infrastructure, resulting in line leaks, water main breaks, and overall system pressure loss.

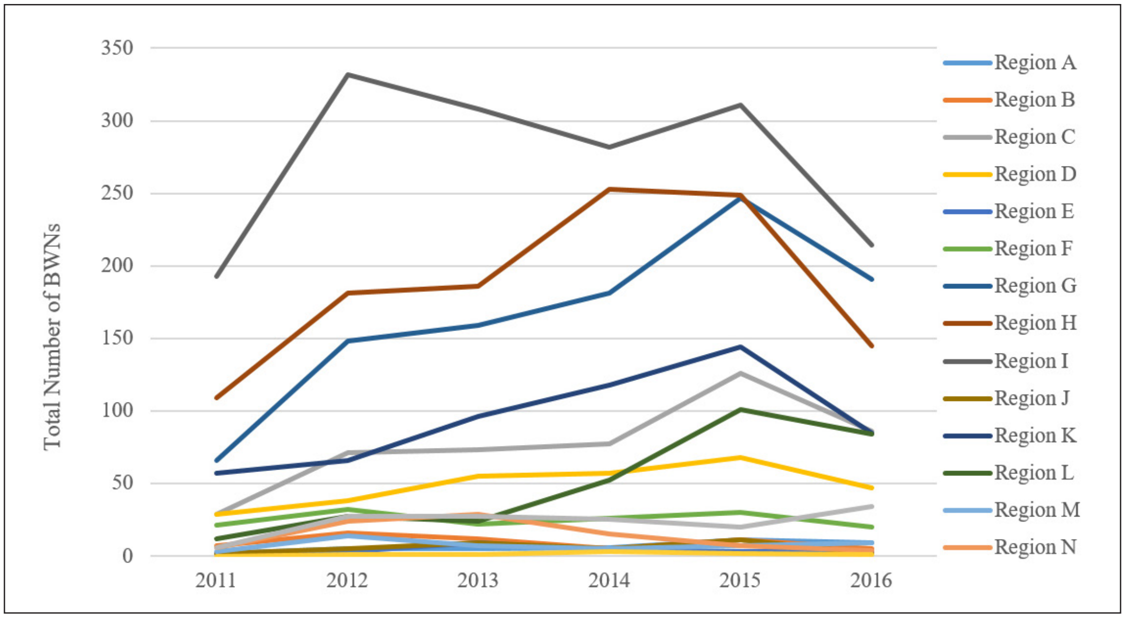

Figure 2. Total number of boil water notices by region from January 2011 to December 2016.

Sanitary Sewer Overflows (SSOs)

In the six-year period examined, there were 7,982 SSO incidents; the total rose by 983% over this period with approximately 424 incidents in 2011 and 4,594 in 2016 across all 16 regions (See Table 2 and Figure 3). Five of the regions—F, G, H, K, and L—recorded a higher-than-average number of SSOs over the six-year period; Regions H and L recorded the highest total number of SSOs at 2,468 and 1,916, respectively. These regions are also high population centers, representing approximately 50% of the total Texas population.

The largest cities in Region H are Houston and Galveston, while the largest cities in Region L are San Antonio, Victoria, San Marcos, and New Braunfels. Both Region H and L include segments of the Gulf Coast, making them more susceptible to extreme wet weather conditions, often causing flooding. Floods can overwhelm aging wastewater systems and result in SSOs.

There were two notable spikes observed in the SSO data. The first spike occurred between 2014 and 2015, during which the number of reported statewide SSO incidents increased by 79%, which was likely caused by the heavy rainfall and resulting flooding at the end of the 2010–2014 Texas drought. The second spike was specific to Region H, where the number of SSOs rose from 75 in 2015 to 2,364 in 2016. This spike was driven mainly by Region H and the history of SSO incidents and response to the same by the Greater Houston area in particular.

The Houston region is known for subsidence issues. Periods of drought followed by flooding can cause significant soil movement, particularly in clay soil areas. This movement can wreak havoc on infrastructure and cause flooding events that increase infiltration to sewer systems, which can then quickly overtake their design capacity, resulting in SSOs.

The city of Houston, recognizing the need to remedy these SSO trends, has undertaken a multiyear infrastructure replacement program. A report from the Houston Chronicle claims that "ramping up maintenance and educating the public on how to avoid clogging Houston's 6,700 miles will cost up to $5 billion (Morris 2016)."

Table 2. Total number of sanitary sewer overflows by region from January 2011 to December 2016.

	2011	2012	2013	2014	2015	2016	Total
Region A	0	0	0	59	27	33	**119**
Region B	0	0	0	0	9	38	**47**
Region C	2	30	5	4	46	399	**486**
Region D	0	1	7	3	26	33	**70**
Region E	16	7	3	6	0	19	**51**
Region F	95	74	60	91	97	91	**508**
Region G	106	310	1	4	21	375	**817**
Region H	1	14	9	5	75	2,364	**2,468**
Region I	2	2	0	3	82	415	**504**
Region J	0	0	0	0	4	25	**29**
Region K	0	1	1	153	266	279	**700**
Region L	201	269	436	267	384	359	**1,916**
Region M	0	1	0	0	0	2	**3**
Region N	1	5	7	6	2	113	**134**
Region O	0	0	0	16	65	49	**130**
Region P	0	0	0	0	0	0	**0**
Total	**424**	**714**	**529**	**617**	**1,104**	**4,594**	**7,982**

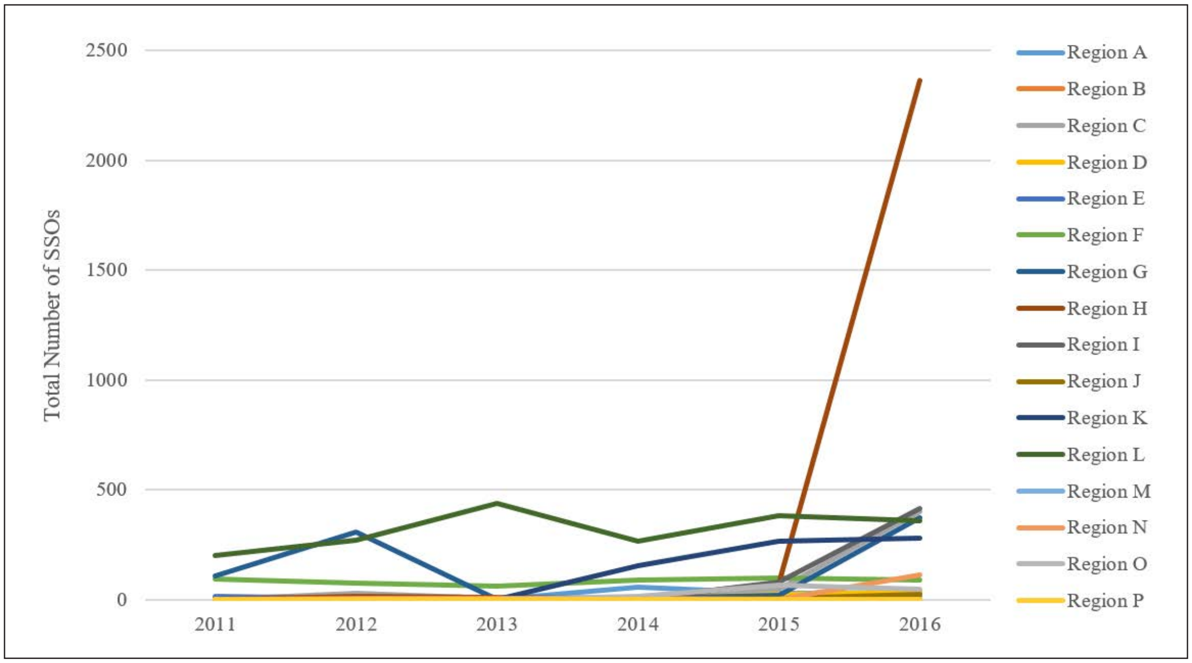

Figure 3. Total number of sanitary sewer overflows by region from January 2011 to December 2016.

Table 3. Total number of lead contamination public education notices by region from January 2011 to December 2016.

	2011	2012	2013	2014	2015	2016	Total
Region A	0	0	0	1	0	0	**1**
Region B	0	0	0	0	0	1	**1**
Region C	0	0	4	1	2	1	**8**
Region D	0	0	1	4	3	0	**8**
Region E	0	0	0	3	0	0	**3**
Region F	0	0	1	3	5	1	**10**
Region G	1	1	3	9	2	8	**24**
Region H	1	2	21	28	35	21	**108**
Region I	0	0	3	2	3	1	**9**
Region J	0	1	3	4	1	0	**9**
Region K	0	0	7	6	5	4	**22**
Region L	1	0	4	4	5	3	**17**
Region M	0	0	0	0	0	0	**0**
Region N	0	0	1	0	1	1	**3**
Region O	0	0	0	0	1	1	**2**
Region P	0	0	0	0	1	0	**1**
Total	**3**	**4**	**48**	**65**	**64**	**42**	**226**

Lead Contamination Public Education (LCPE)

In comparison to SSOs and BWNs, public education notices related to lead contamination decreased during the six-year period. However, there was an overall increase in the number of LCPEs recorded, totaling 226 incidents. The number of incidents increased consistently during the same period in all 16 regions (See Table 3 and Figure 4). Overall, a sharp increase of almost 1,300% is observed in the same six-year period.

There was a notable spike between 2012 and 2013 where reported incidents increased by 1,100% from 4 to 48, respectively. This was most likely attributed to better reporting from the jurisdictions to TCEQ. In Region H, where the highest number of incidents was recorded, this trend was most likely due to the influence from the petrochemical industry. Aging or poorly maintained infrastructure also contributed to the trend.

Four regions—G, H, K, and L—recorded a higher-than-average number of LCPEs. Most of the sources of LCPE notices were from industry followed by municipalities. In Region H, LCPE notices were largely attributed to the petrochemical industry, which is the region's largest economic sector and also "accounts for two-thirds of the petrochemical production in the United States (TWDB 2016a)."

The most pertinent trends in lead notices relate to the population and geographical location of each region. The majority of incidents occurred in Central and East Texas (along the I-35 corridor) and Region C where the population is dense. Region C includes the Dallas-Fort Worth metropolitan area and the fastest growing regions in the state (TWDB 2016b). As previously mentioned, part of this observed increase may be due to the large and dense population and to increased awareness and monitoring of discrete sites (specific schools, churches, industrial facilities, etc.), which may explain part of this observed increase.

Reports of lead in water samples do not necessarily indicate system-wide problems, although areas with significant population growth over the last decade can benefit from newer infrastructure and plumbing codes, thus reducing the incidents of reported lead in drinking water. Within older developed areas, many instances of reported lead in water can be attributed to post-meter in-property plumbing, which may be of significant age.

Overall Results

Despite the few mentioned limitations, the authors believe TCEQ data provides enough detailed information to make the study conclusive. There are various factors possibly causing the fluctuations in total incidents recorded, such as dilapidating infrastructure, extreme weather events, and inconsistent reporting/recording. For this reason, the data analysis focused on overall trends in the six-year period and made note of

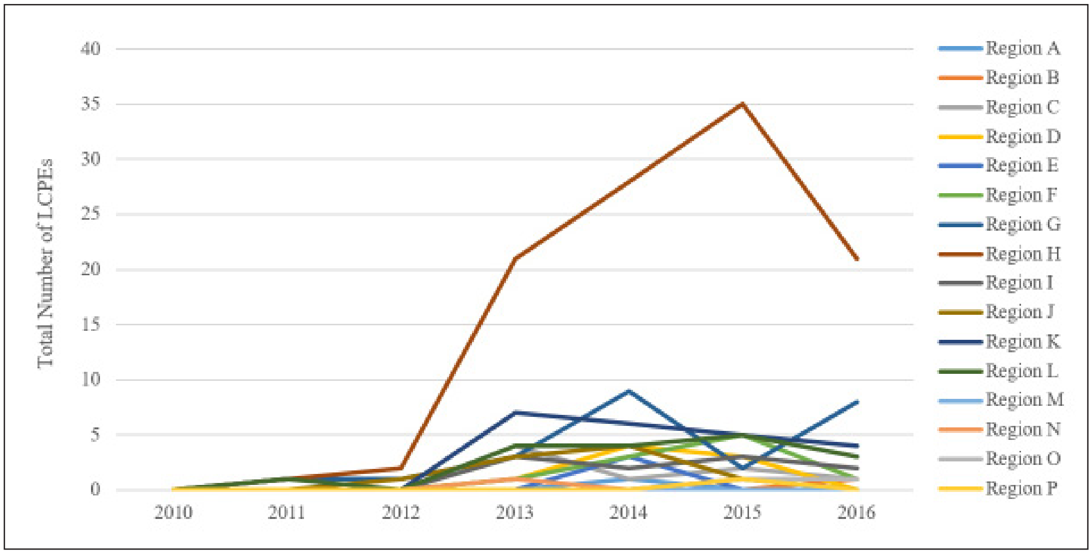

Figure 4. Total number of lead contamination public education notices by region from January 2011 to December 2016.

unique factors as it relates to population density, location, and unique weather patterns.

The study shows that regions with a population of one million or more (G, H, I, K, L, and M) are more likely to have a higher number of incidents associated with BWNs, SSOs, and LCPEs. These regions also happen to be close to or on the Gulf Coast, which makes their water and wastewater systems even more susceptible to extreme weather events, coupled with their aging infrastructure, which impacts capacity management and efficiency.

The data reveals an overall increase in BWNs, SSOs, and LCPEs issued in Texas from 2011 to 2016 (See Table 4). During the study time frame, BWNs increased about 73%, while SSO incidents increased 983%, and LCPE reports increased 1,300%. The formula to calculate the percentage difference is as follows:

(Total number of BWNs or SSOs or LCPEs in 2016 - Total number of BWNs or SSOs or LCPEs in 2011 x 100)/ Total number of BWNs or SSOs or LCPEs in 2011.

The overall trends suggest that there is an increasing frequency of threats to the water quality in Texas. The reasons for the trends are most likely due to pressure on aging water infrastructure from rapid population increases and increased frequency of extreme weather events e.g. flooding and hurricanes. As seen from the results discussion, some areas are driving these trends more than others are, such as Regions H and I. While other regions are low in comparison to the number of incidents between 2011 and 2016, it is important to note that the trend is still upward for most part.

It is important to note that west and northwest regions of the state observed fewer incidents than regions in Central or East Texas or by the Gulf Coast. The reason for such a trend is most likely due to the sparser populations in West Texas regions, along with the lower threat of extreme weather events such as hurricanes and flash flooding.

Unsurprisingly, the number of LCPE notices is relatively low. Lead contamination in drinking water supply is not common in the United States. However, the water crisis in Flint, Michigan, heightened public fears on the issue, especially because of the amplified risks to infants and children. With the EPA declaring that no level of lead is safe for children, the authors believe city and utility leaders have to make a greater investment in identifying the lead lines in their jurisdictions and replacing them in order to avoid another crisis similar to Flint (EPA 2016b).

The data analysis informed the authors' consideration of the regulatory and reporting standards informing the public on drinking water contamination. The significant overall increase in incidents related to BWNs, SSOs, and LCPEs highlights the need for utility officials to consider embedding crisis communications into their outreach strategies, if they have not done so already. Overall trends also strongly suggest an increase in incidents, especially in densely populated regions of the state, which makes the need for a dedicated crisis communication strategy even more compelling.

Table 4. Total number of incidents in Texas from January 2011 to December 2016.

	BWNs	SSOs	LCPEs	Total
2011	544	424	3	971
2012	990	714	4	1,708
2013	1,022	529	48	1,599
2014	1,114	617	65	1,796
2015	1,348	1,104	64	2,516
2016	939	4,594	42	5,575
Total	5,957	7,982	226	14,165
Percentage Change	**73%**	**983%**	**1,300%**	-

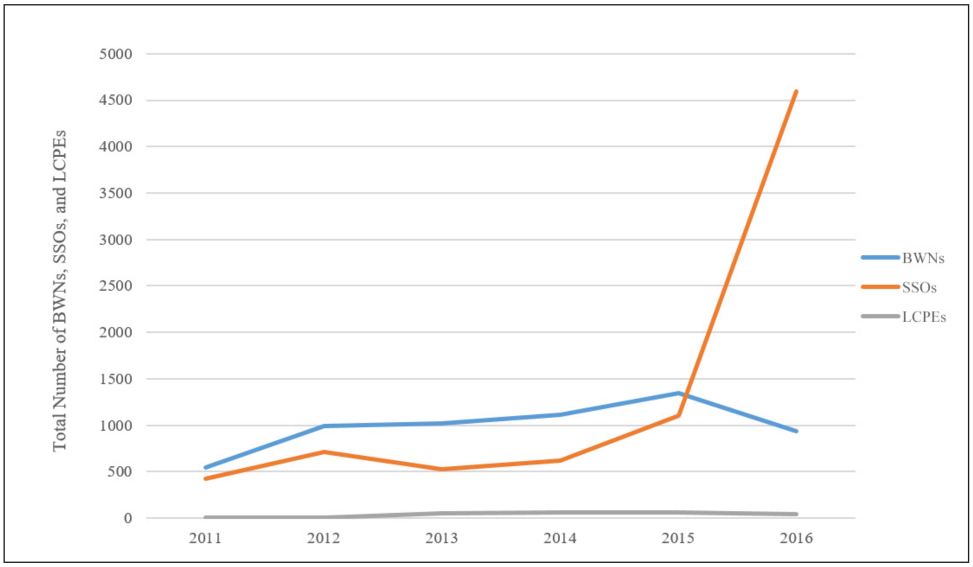

Figure 5. Total number of SSOs, BWNs and LCPEs in Texas from January 2011 to December 2016.

Limitations

The data provided by TCEQ have allowed for strong and conclusive results, the observation of specific trends, and the identification of correlations. However, data analysis was limited by a few ambiguities in the data sets. For example, there was a lack of data reported on the number of incidents, mainly SSOs and LCPEs, recorded between 2011 and 2013. Gaps in the data are most likely due to inconsistencies in data collection, monitoring, and reporting to TCEQ by the respective entities.

Another anomaly observed was in the data obtained on SSOs. Region K reported zero SSO incidents in 2011, and yet listed 919,984 gallons of sewage released. We were unable to ascertain the total number of incidents in 2011 or the rationale for such information management.

DISCUSSION – THE NEED FOR BETTER AND MORE COMMUNICATIONS

To reduce these threats to drinking water safety, utilities will have to continue to invest in improving and maintaining their water and wastewater infrastructure, which is no easy feat. In the meantime, cities will most likely continue to experience water crises of varying proportions.

Water crises often feed peoples' tendencies to exaggerate, incite chaos, and place blame. To prevent a water crisis from doing long-term damage to a company or municipality's reputation, they must invest in thorough communication strategies to engage and educate. A well-managed water crisis helps to manage costs, alleviate community unrest, prevent erosion of public trust, and maintain political credibility.

An example of customer-expressed loss of trust in a utility occurred southwest of Fort Worth, where residents experienced a six-week long BWN in 2016 (Walker 2016). Even after the notice was lifted, residents did not trust their water. One resident said of the impacted water provider, "They seem like they don't care, which makes us not trust them even more and it just seems unethical. It's just not right (Walker 2016)."

Most political and utility leaders and staff who have had the misfortune of being caught in a crisis can attest to how quickly it can become divisive. False and inaccurate stories will often appear in the media, and interest groups will distract from the real issue at hand. Social media adds to the challenge by quickly fueling rumors, which only prolong and inflame the crisis.

During a crisis, there are certain fundamental values that must be integrated into every decision-making process within the utility before it publicly communicates to customers and the broader community. These basic principles of crisis communication include transparency and honesty, clarity and commitment, compassion and reassurance, and listening and engaging.

Transparency and honesty

Transparency and honesty form the backbone of efforts to maintain or rebuild trust and credibility. When a spokesperson is upfront about the cause of a crisis it demonstrates the utility is taking ownership of the situation and showing commitment to the public's welfare. Providing accurate and clear information is the first and most critical step to preventing a crisis from getting out of control. If there is no answer to a particular question, spokespeople can follow up with accurate answers at a later specified time.

Transparency can be demonstrated by divulging details regarding the steps being taken to address the crisis, through regular updates to the public. The consequences of a lack of such transparency, along with broken promises to the public and ambiguous communication techniques, can be damaging to the reputation of a utility or city. Reoccurring water quality crises can and have resulted in resignations of high-level pubic officials. This level of dissatisfaction can also drive voting trends toward change, particularly for local elected officials.

A classic example of where denial or lack of transparency exacerbated a water crisis was in Flint, Michigan. When confronted about his level of knowledge of the situation in Flint before it became public, Governor Rick Snyder of Michigan denied knowledge of the lead contamination, adding, "I wish I would have asked more questions (Oosting and Carah 2016)." He did not provide enough evidence to the public to prove his lack of knowledge on the situation, which quickly made him a target for blame. "...The idea that every one of his top staff were actively debating the Flint Water Crisis and that he was unaware is no longer credible," State Representative Jeff Irwin said (Oosting and Carah 2016).

To this day Governor Snyder's role in the crisis is being questioned. According to a new report from the University of Michigan School of Public Health, Governor Snyder "bears significant legal responsibility for the (Flint water) crisis based on his supervisory role over state agencies (Fonger 2018)."

Clarity and commitment

Clarity and commitment in providing the facts about a water safety crisis will help ensure that the situation is neither exaggerated nor underemphasized. Facts need to be presented simply and without jargon. Sometimes information spread via mainstream or social media is inaccurate or untrue. Online rumors and "fake news" spread quickly and can turn people against an agency overnight.

Inaccuracies about the cause of a crisis only fuel doubt and mistrust in the utility as credible, ethical, and responsible leaders in the community. The facts about a crisis need to be communicated repeatedly, like a mantra, in order to ensure continuous visibility and factual coverage of the situation in local media.

Commitment can be demonstrated by taking responsibility for a situation and its solution, and by ensuring that the facts are disseminated. However, *saying* civic or utility leaders are committed to resolving a crisis without being transparent about the actions being taken serves no purpose.

An example of leaders missing a chance to express commitment has been seen in situations where heavy rains have resulted in several SSOs. In one such incident, local officials did not communicate any actions being taken to solve the problem, instead saying, "There is no way to prevent raw sewage from spewing into the streets when we receive as much rain as we did (Quinn 2015)."

Instead of implying that the problem could not be solved, the city officials should have communicated its focus and commitment to fixing the issue and concrete steps to prevent a reoccurrence. City officials could have also taken the incident as an opportunity to explain why SSOs occur and what the City is doing to reduce incidents.

A good example of a water utility that took responsibility for its actions and went above and beyond to demonstrate its commitment is the San Antonio Water System (SAWS) when it was hit with an EPA consent decree to curb sewer spills by investing an additional $492 million in infrastructure and maintenance.

SAWS' acceptance of the situation and promise to fix the situation was nicely captured in President and CEO Robert Puente's comments, "This agreement is designed for the most cost-effective use of ratepayer dollars and avoids costly federal litigation (SAWS 2013)." Focusing on the customer and emphasizing the legal and fiscal responsibility of the utility is a positive message that helps build public support for the utility.

Compassion and reassurance

Utilities should be relatable to customers and express understanding of a water crisis' impact on their well-being. They should share sincere sympathies with the public while at the same time reassuring customers that experts are managing the crisis with speed, thoroughness, and integrity.

Note that customers and the public do not want nor need to hear about how hard a situation is on the city, utility, or responsible entity. When BP CEO Tony Hayward said in response to the Deepwater Horizon disaster, "There's no one who wants this over more than I do. I'd like my life back," it only angered the public.

A good example of a city official showing compassion comes from former Corpus Christi Mayor Dan McQueen. Following the announcement of a tap water advisory (Hersher 2016), he said, "I hope you guys understand and feel the emotion I have right now. This certainly isn't something the city wanted to do. It's the 18th of December. We have Christmas right around the corner. My heart goes out to everybody in our city right now. I apologize. I apologize personally."

Listening and engagement

Traditional and social media should be used both to assess the public's concern and to disseminate information to the public. For example, Twitter can be used for brief alerts and updates, with Facebook allowing for more elaboration using various media assets such as videos, infographics, links, etc.

While social media reaches a broad spectrum of customers quickly, a crisis response requires direct engagement—usually face-to-face—by utilities and government entities connecting directly with the community. Allow opportunities for people to have conversations and ask officials and experts questions at open houses. This engagement should be conducted from the earliest stages of a crisis to clear up misinformation, help customers understand, and, most importantly, empower them to be heard.

A utility leader who is known for listening and relating to his customers is the former general manager of DC Water, George Hawkins. In 2004, a Washington Post article reported that DC Water attempted to 'cover up' its survey findings of 4,000 homes having lead levels exceeding the federally acceptable level set by EPA. Over 200 stories on the lead issue followed. At that moment, Hawkins being upfront and engaged in addressing the public's concerns helped to qualm the rightfully upset families that were impacted. "We've never denied what happened in the early 2000s…No question, it was a very significant problem in the District…We certainly learned from it, and now we have a very advanced [lead] control system in place (Shaver and Hedgpeth 2016)."

CONCLUSION

The number of SSOs, BWNs, and LCPEs in Texas has significantly increased over the past six years, and the lack of an investment boost for infrastructure development suggest that the trend will continue. Crisis communication on water issues serves as a solution to the larger problem of our water infrastructure needing desperate and urgent attention. But improving water infrastructure is a massive feat and will take years to accomplish. To Texas' credit, several highly attractive public funding mechanisms are in place to assist and incentivize these needed improvements. Yet public funding and local ratepayer capacity alone may not be enough to meet all needs. Private capital investment should also be encouraged and relied upon. Effective communication can promote constituent support for infrastructure improvements. Absent of these efforts, communities may continue to be heavily impacted by water crises.

In order to prevent increased public dissonance, particularly on a highly sensitive issue such as clean drinking water, our recommendation is to increase investment in strategic communication and outreach on water crisis matters. Implementing the principles of effective crisis communication require discipline and experience to act fast while considering all factors of influence. It is important to get the right messages across at the right time. Furthermore, a good crisis communication plan prevents further deterioration of a utility- or city-customer relationship.

If water crises are not managed with the sensitivity needed, public trust can be eroded, and that is very hard to rebuild. This lack of trust in a utility or city officials makes it very difficult to get approval for other initiatives (e.g. rate increases) when needed the most. The water crisis in Flint may have changed public perception toward water utilities indefinitely. Americans doubt their water quality more than ever, and if water utilities do not do a good job of reassuring their customers, especially during a crisis, then water professionals have failed.

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Water security for Texas: a post-secondary education pathway for water workforce readiness

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Abstract: Water and wastewater industry leaders in Texas and throughout the United States have expressed concern over high rates of retirement eligibility and difficulties finding and attracting workers ready to fill job openings, especially for work in smaller systems. In late January 2018, the U.S. Government Accountability Office released a report on water workforce readiness and a bill was introduced in the U.S. Senate to establish a water infrastructure workforce development program. Concern over existing education of workers in water and demographic information projecting future workforce readiness are commonly cited as signaling a coming crisis for the water industry. An alignment of post-secondary training and industry needs is recommended to meet coming workforce employment requirements for Texas and the nation. A model post-secondary education pathway for water science and technology is described to support water workforce readiness.
Keywords: water education, water industry, water workforce, water and wastewater degree, water security

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Terms used in paper

Acronyms	Descriptive name
AWWA	American Water Works Association
B.A.A.S.	Bachelor of Applied Arts and Sciences
B.S.	Bachelor of Science
GAO	U.S. Government Accountability Office
TAMU–SA	Texas A&M University–San Antonio
TCEQ	Texas Commission on Environmental Quality
TEEX	Texas A&M Engineering Extension Service

INTRODUCTION

In late January 2018, two events took place over the course of two days that may shape future education and training opportunities for work in water and wastewater (hereinafter termed "water" with equal weight to water and wastewater sectors) systems and treatment industries in the United States. The U.S. Government Accountability Office (GAO) released a report on water workforce readiness (USGAO 2018), and a bill was introduced in the U.S. Senate to establish a water infrastructure workforce development program (USS 2018). Both actions stem from long-standing alarms raised by the water industries about high rates of retirement eligibility and difficulties finding and attracting job-ready workers to fill job openings, especially for work in smaller water systems (Kemp-Rye 2005; Mann and Runge 2008; Grigg and Zenzen 2009; Brueck et al. 2010; SFPUC 2012; PCAST 2016; AWWA 2017).

The GAO report and Senate Bill 2346 (S. 2346) describe workforce demographic information commonly cited as evidence of a coming crisis for the water industry. Findings in S. 2346 state that the median age of water sector workers is 48 years old, which is six years older than the national median age of workers. In turn, there will be unprecedented workforce replacement needs over the next 10 years because 37% of water and 31% of wastewater workers will retire during that period. The GAO report also describes industrywide concern about filling future job openings. The report and proposed legislation demonstrate the need for a well-trained and knowledgeable workforce for proper management of water utilities to prevent water pollution and to ensure safe drinking water and long-term sustainability of public water systems. In particular, both described the vital role of the water workforce in ensuring compliance with the Safe Drinking Water Act (42 U.S.C. §§ 300f et seq.) and Clean Water Act (33 U.S.C §§ 1251-1387 et seq.).

WATER INDUSTRY EXPERTS IN TEXAS AND THROUGHOUT THE UNITED STATES EXPRESS ALARM ABOUT WORKFORCE READINESS

While assessments of the status of the water workforce have varied, multiple industry studies support the findings of the GAO and S. 2346 sponsors. For more than a decade the American Water Works Association's (AWWA) annual *State of the Water Industry* report, which surveys member opinion nationally, has been drawing attention to water workforce shortages (Mann and Runge 2008; Brueck et al. 2010; AWWA 2017). In 2017 the AWWA reported that only 1% of water industry survey respondents indicated that the industry was fully prepared to address workforce attraction and retention in the next five years (AWWA 2017), the same percentage reported each year since 2014 (AWWA 2014, 2015, 2016). The AWWA also ranked major issues facing the industry during these years, with the aging workforce and talent attraction and retention ranked as the fifth overall most important issue facing the industry in 2013 (AWWA 2013). One comprehensive study supported by the AWWA indicated retirement eligibility may be as high as 50% of the entire workforce within 10 years, with an additional potential 45% increase in recruitment of water workers needed due to new regulations, infrastructure growth, security challenges, and customer demand (Brueck et al. 2010). There are about 478,700 workers in the combined water and wastewater utilities sector, with about 55% estimated to be facility operators, according to references used by the GAO. The AWWA concluded in its 2015 report that the water industry is continuously facing difficulty recruiting, training, and retaining these skilled employees, especially for small systems (AWWA 2015).

Texas water experts similarly identified a coming crisis in the Texas water workforce at a series of industrywide planning forums exploring key future water security issues in 2015 and 2016 (Mohtar and Rosen 2015; Rosen 2017; Rosen et al. 2017). Participants expressed expert opinions and recalled past conversations and discussions from earlier industry meetings. They reiterated concerns about a coming wave of retirements and attrition, accompanied by inadequate recruitment to the water workforce and identified another major issue: the general failure of post-secondary educational institutions to supply workforce-ready graduates for Texas' evolving urban and rural water sectors. Participants at the forums submitted a series of proposals as solutions, focusing largely on reversing the failure of existing post-secondary educational institutions to meet water industry demand for graduates with job-ready training.

WATER WORKFORCE EDUCATION

Industry reports, planning documents, and conference discussions confirm that there is concern about education and recruitment of the future water workforce in many states (SFPUC 2012; PCAST 2016) and even in Canada (Yessie 2012). Impacts on water security due to failure of our educational institutions to respond to industry workforce needs will be felt nationwide and beyond, not just in Texas.

In general, the most prominent recommendations in industry publications for enhancing recruitment of water workers include mentoring, internships, and increased access to industry training programs. It has been industry-driven training, focused on regulatory licensing and certification requirements, which has been the traditional mainstay for educating the water workforce. Occupational licensing and education requirements for workers in the water industries in Texas are the responsibility of the Texas Commission on Environmental Quality (TCEQ). Current requirements for licensing include various combinations of high school and secondary education credits, work experience, completion of licensing-related training, and passing a licensing exam. Licensing is required for water operators at public utilities. Licensing for wastewater treatment plant and collection system operators varies according to workers' levels of knowledge, experience, and education (Table 1). Options for licensing water system operators start with a minimum base of education, work experience, and training requirements for a Class D license, increasing levels of competency in water distribution, groundwater, and surface water for Classes B and C operators, and a combination of all for Class A water operators (Table 2).

Few efforts described by the water industry focus on creating pathways to training by higher education institutions that are equipped to prepare the future workforce with job-relevant workforce-ready training, plus a degree that will enable long-term professional growth into managerial positions. Industry-level training delivers licenses required for employment in many water jobs and provides an excellent and highly applied complement to degree granting programs, but it does not equip the future workforce for today's emerging requirements for a bachelor's degree for basic employment as a manager. Nor does industry training alone provide a means for employment in a company where a university degree is basic entry-level criteria for any significant position or help attract people to a water career who are interested in obtaining a future competitive edge by having broader training, including in subject areas such as computer science, policy, engineering, business, or other studies that may help expand future job opportunities.

Public faith in water management institutions fell in the aftermath of publicity surrounding impacts to public health from harmful drinking water supplied to residents of Flint, Michigan (Heard-Garris et al. 2017). Among results has been a heightened recognition of a need for education and workforce development in water treatment (FWATF 2016). Post-secondary education degrees for water workers may become essential for utilities and water providers worried about liability for proper water and wastewater treatment and where there are significant water security concerns.

The GAO report and S. 2346 suggest possible pathways. For example, to fund the need for enhanced water workforce planning and training, S. 2346 would authorize a competitive grants program for infrastructure workforce development. The grants program would be managed by the Administrator of the U.S. Environmental Protection Agency and the Secretary of the Army. Should S. 2346 pass and appropriations be provided by the U.S. Congress, many education initiatives would be started or enhanced. Fortunately, nearly all of the recommendations in the proposed bill are being used to some degree in various locations already. Such initiatives include internships, apprenticeships, post-secondary bridge programs, and collabo-

Table 1. Occupational licensing education, work experience, and training requirements for wastewater treatment plant and collection system operators. From Texas Commission on Environmental Quality occupational licensing requirements webpage accessed October 16, 2018: https://www.tceq.texas.gov/licensing/licenses/wwlic/#require1

Education and Work Experience – Wastewater Treatment Licensing			
Class A	**Class B**	**Class C**	**Class D**
Master's Degree: • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: four years of "hands-on" experience. At least one half of the work experience must be obtained in the specific field for the license that is requested. **Bachelor's Degree:** • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: five years of "hands-on" experience. At least one half of the work experience must be obtained in the specific field for the license that is requested. **High School diploma or General Equivalence Diploma (GED):** • Education: High School diploma or GED. • Work Experience: eight years of work experience, six of which must be "hands-on". At least one half of the work experience must be obtained in the specific field for the license that is requested. **Acceptable Work Experience Substitute:** Applicants with a High School diploma or GED may substitute up to two years of experience with college hours or additional TCEQ approved wastewater operator training. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience • 16 semester hours of college or 20 additional hours of approved training for six months of work experience.	**Bachelor's Degree:** • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: 2.5 years of "hands-on" experience. At least one half of the work experience must be obtained in the specific field for the license that is requested. **High School diploma or General Equivalence Diploma (GED):** • Education: High School diploma or GED. • Work Experience: five years of work experience, three of which must be "hands-on". At least one half of the work experience must be obtained in the specific field for the license that is requested. **Acceptable Work Experience Substitute:** Applicants with a High School diploma or GED may substitute up to two years of experience with college hours or additional TCEQ approved wastewater operator training. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience. • 16 semester hours of college or 20 additional hours of approved training for six months of work experience.	**High School or General Equivalency Diploma:** • Education: High School diploma or General Equivalency Diploma. • Work Experience: two years of work experience. At least one half of the work experience must be obtained in the specific field for the license that is requested. **Acceptable Work Experience Substitute:** Applicants with a High School diploma or GED may substitute up to one year of experience with college hours or additional TCEQ approved wastewater operator training. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience. • 16 semester hours of college or 20 additional hours of approved training for six months of work experience.	**High School or General Equivalency Diploma:** • Education: High School diploma or General Equivalency Diploma. • Work Experience: none.
Training Courses – Wastewater Treatment Licensing			
Class A	**Class B**	**Class C**	**Class D**
Core Courses: Activated Sludge or Wastewater Treatment, Wastewater Collection, Wastewater Laboratory, Water Utility Management, Water Utility Safety, plus one elective course. **Elective Courses:** Intermediate Wastewater Laboratory, Water Utility Calculations, Wastewater Technology, or Advanced Management.	**Core Courses:** Activated Sludge or Wastewater Treatment, Wastewater Collection, Wastewater Laboratory, Water Utility Safety, plus one elective course. **Elective Courses:** Intermediate Wastewater Laboratory, Water Utility Calculations, or Wastewater Utility Management.	**Core Courses:** Basic Wastewater Operation, Activated Sludge or Wastewater Treatment, plus one elective course. **Elective Courses:** Wastewater Collection, Wastewater Laboratory, Water Utility Calculations, or Water Utility Safety.	**Core Courses:** Basic Wastewater Operation

Table 2. Occupational licensing education, work experience, and training requirements for water system operators. From Texas Commission on Environmental Quality occupational licensing requirements webpage accessed October 16, 2018: https://www.tceq.texas.gov/licensing/licenses/waterlic

Education and Work Experience – Water System Operator Licensing			
Class A	**Class B**	**Class C**	**Class D**
Master's Degree: • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: four years of "hands-on" experience in public water system operations. **Bachelor's Degree:** • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: five years of "hands-on" experience in public water system operations. **High School or General Equivalency Diploma:** • Education: High School diploma or GED. • Work Experience: eight years' experience in public water system operations, six of which must be "hands-on". **Acceptable Work Experience Substitute:** Applicants with a High School diploma or GED may substitute up to two years of experience with college hours or additional TCEQ approved water operator training. • 64 semester hours of college or 80 additional hours of approved training for two years of work experience. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience.	**Bachelor's Degree:** • Education: degree major must be in chemistry, biology, engineering, microbiology, bacteriology, or another similar discipline as approved by the TCEQ Executive Director. • Work Experience: 2.5 years of "hands-on" experience. At least one half of the work experience must be obtained in the specific field for the license that is requested. **High School or General Equivalency Diploma:** • Education: High School diploma or GED. • Work Experience: five years of work experience, three of which must be "hands-on". At least one half of the work experience must be obtained in the specific field for the license that is requested. **Acceptable Work Experience Substitute:** Applicants with a High School diploma or GED may substitute up to two years of experience with college hours or additional TCEQ approved water operator training. • 64 semester hours of college or 80 additional hours of approved training for two years of work experience. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience.	**High School or General Equivalency Diploma:** • Education: High School diploma or GED. • Work Experience: two years of experience, one of which must be "hands-on". At least one half of the work experience must be obtained in the specific field for the license that is requested. **Acceptable Work Experience Substitute:** Applicants may substitute up to one year of experience with college hours or additional TCEQ approved water operator training. • 32 semester hours of college or 40 additional hours of approved training for one year of work experience • 16 semester hours of college or 20 additional hours of approved training for six months of work experience	**High School or General Equivalency Diploma:** • Education: High School diploma or GED. • Work Experience: no work experience requirements.

Training Courses – Water System Operator Licensing			
Class A	**Class B**	**Class C**	**Class D**
Core Courses: Basic Waterworks Operation, Surface Water Production I, Surface Water Production II, Groundwater Production, Water Distribution, Water Laboratory, Water Utility Management, and Water Utility Safety . **Elective Courses:** Plus an additional 20 hours of training to meet the 184 hour requirement.	**Class B Surface Water** **Core:** Basic Waterworks Operations, Surface Water Production I, Surface Water Production II, Water Distribution, Water Utility Safety, Water Laboratory, Water Utility Management. **Elective Courses:** None. **Class B Groundwater** **Core:** Basic Waterworks Operations, Groundwater Production, Water Distribution, Water Utility Safety, Water Laboratory, Plus one elective course. **Elective Courses:** Water Utility Management, Water Utility Calculations, Chlorinator Maintenance, Pump and Motor Maintenance, Valve and Hydrant Maintenance. **Class B Distribution** **Core:** Basic Waterworks Operations, Water Distribution, Water Utility Safety, Pump and Motor Maintenance, Valve and Hydrant Maintenance, Plus one elective course. **Elective Courses:** Water Utility Management, Water Utility Calculations, Chlorinator Maintenance, Water Laboratory.	**Class C Surface Water** **Core:** Basic Waterworks Operations, Surface Water Production I, Surface Water Production II. **Elective Courses:** None. **Class C Groundwater** **Core:** Basic Waterworks Operations, Groundwater Production, Plus one elective course. **Elective Courses:** Water Distribution, Water Laboratory, Water Utility Safety, Water Utility Calculations, Chlorinator Maintenance, Pump and Motor Maintenance, Valve and Hydrant Maintenance. **Class C Distribution** **Core:** Basic Waterworks Operations, Water Distribution, Plus one elective course. **Elective Courses:** Water Laboratory, Water Utility Safety, Water Utility Calculations, Chlorinator Maintenance, Pump and Motor Maintenance, Valve and Hydrant Maintenance .	**Core Courses:** Basic Wastewater Operation

rations with trade organizations, community colleges, universities, federal programs, and other training initiatives. Others include kindergarten through 12th grade and young adult education about the role of water and wastewater systems in communities, development of appropriate water curricula, and learning laboratories. Finally, S. 2346 would fund leadership development, education, and mentoring to prepare water utility workers for higher level professional, supervisory, and managerial positions.

It is this last category of recommendation in S. 2346 that creates a means for water workers to obtain a bachelor's degree. This offers the greatest departure from traditional approaches to water worker training and recruitment. It also promotes education that helps prepare the future workforce to use new technologies, meet basic standards of education for professional advancement, and reduce potential adverse public exposure and liability should public health or environmental pollution problems occur.

And finally, as treatment technologies advance, greater levels of education through industry training plus a university degree will become more often a requirement for job applicants, especially at large utilities. The GAO found considerable variation in the results of past efforts at workforce planning and development at large versus small water utilities when implementing past recruitment and retention initiatives. In response, the GAO describes recommendations to enhance security of the U.S. water supplies by providing new oversight on workforce matters, including recommendations for enhanced workforce planning and training, during inspections of water systems for compliance monitoring of drinking water and wastewater facilities. In particular, the GAO was concerned about violations of pollution discharge and drinking water rules, and impacts to the environment and public health.

POST-SECONDARY TRAINING AND INDUSTRY NEED MUST ALIGN

Participants at the Texas water forums stated that future education of students seeking employment in water and wastewater management should be different than that generally available through a typical civil or environmental engineering degree program. They believed that water workforce training and education need to be responsive to industry requirements for workers. Industry need is driven by regulatory requirement changes, advancing technologies, and rapid incorporation of new technologies into facility design, operation, and renovation. However, participants saw little or no rapid alignment of university curricula, TCEQ licensing requirements, industry training opportunities, changing technologies, and regulation changes. They noted this lack of alignment with changing technologies and regulations exists despite there is little likelihood that yesterday's curricula, designed for an earlier time, will provide the best training for the jobs of today and tomorrow. Further, as a person moves forward in their career, while they may start on the operational side of the business, many workers eventually end up on the planning and management side of the business.

Participants at the Texas water forums and industry workforce studies (Kemp-Rye 2005; Brueck et al. 2010) also pointed out a need to recognize that and account for differently sized communities have different kinds and scales of water facilities, different needs for water workers, and different training requirements for the water workforce. There will be greater demand for additional skills in a larger versus smaller community as water workers advance in their careers. Participants at the Texas forums also advised that the water workforce should be reflective of the society being served. Educational models should support educating people for jobs in local water systems (Grigg and Zenzen 2009; USGAO 2018; USS 2018). Water forum participants advised this will help ensure the water workforce meets the technical needs of stakeholders for services, as well as the social, economic, and political realities of the communities served. Regional universities, in collaboration with community colleges and extension programs, can be effective in delivering such education, especially if students are presented an attractive education pathway to obtain a degree and training required to enter the workforce.

CHANGING POST-SECONDARY EDUCATION MODELS

University educational models are not ones that bend easily to disruptive change. The current trend in higher education is for universities to become as much alike as possible. Thus, higher education has created an environment that cannot adapt their models quickly enough to respond to new innovative technologies and resulting changes in workforce needs. At present, few universities strive to develop graduates with practical operational training versus theoretical training. Training for work in water is among the casualties. The challenge of change is magnified by a growing separation between what industry needs as technology advances and what is being taught to students. This is greater in higher education than at technical training institutes.

Current incentives that are forcing universities to focus on theoretical training and become as much alike as possible must be reversed. Incentives should be made available to universities that choose to equip graduates with practical operational training that truly makes them ready for today's jobs. Administrative, leadership, and funding models need to change to enable such disruption of current practice. The very definition of career path through higher education may need to evolve to make it possible to address future workforce needs in a way that will meet new technology and related workforce requirements.

Because university curricula are tied to accreditation agencies, these agencies will also need to adapt to enable universities to meet new technology-driven workforce demands in a timely fashion. It remains questionable, however, if higher education can adapt quickly enough. If not, universities will become even less effective at meeting the educational needs of the real-life water workforce and become still farther removed from practical use of the technology it is in the process of helping create.

We offer a post-secondary education initiative in Texas based on three pillars: first, the advice of experts at the Texas water sector planning forums (Mohtar and Rosen 2015; Rosen 2017; Rosen et al. 2017); second, a post-secondary education pathway for water science and technology students recently approved by Texas A&M University–San Antonio (TAMU–SA); and third, our own experiences seeking or developing improved educational curricula and degree programs relevant to educating students at various levels of education and the public about water and creating the future water workforce in Texas (e.g., Rosen 2014 for middle and high school students).

A MODEL POST-SECONDARY EDUCATION PATHWAY FOR WATER SCIENCE AND TECHNOLOGY

We propose a model for an education pathway leading to a Bachelor of Science (B.S.) or Bachelor of Applied Arts and Sciences (B.A.A.S.) degree for students seeking education and related certifications for entry into employment in Texas water industries. The education pathway must be available through a combination of distance education options, extension education, mobile laboratories, competency-based education credits, community colleges, and regional universities, which will ensure local access to water science and technology degrees for students throughout Texas. This learning model addresses the direction of S. 2346 by providing educational opportunities for a future labor force to help ensure a secure water future for Texas that can adapt to changing and emerging needs in the water industries at the rural (small systems) and urban (large systems) levels. The learning model will also help address industry liability issues and regulatory requirements and meet basic educational degree requirements for licensing and long-term employment of graduates.

Traditionally, entry- to technical-level positions in the water treatment industries was available to job seekers having only a high school degree and specialized technical training leading to attainment of certificates of training and licenses issued by regulatory authorities. Today, integration of new technologies in water treatment processes, evolving regulatory requirements, liability issues, and general hiring standards in utilities are driving educational requirements upward. This nationwide trend is expected to continue and possibly accelerate in the near term. In addition, significant job advancement for existing members of the water industry workforce will require college-level degrees due to increases in minimum requirements to hold positions in the water industry. As this trend matures, universities need to better position degree programs in Texas to support water industry professionals who will increasingly be required to obtain advanced-level training or a university degree if they wish to progress within their organizations.

The new educational model must use existing training programs at all levels and new distance learning options, to create an educational pathway for high school graduates and practicing water industry professionals to obtain a job-relevant B.S. or B.A.A.S. degree.

This model must also be generic for use by any community college and regional university in combination with industry, university extension, and government training programs. This model is based on discussion and recommendations from water experts documented in two Texas water forums (Mohtar and Rosen 2015; Rosen 2017; Rosen et al. 2017) and our specific experience designing an education pathway for students to obtain a B.A.A.S. degree in water resources science and technology at TAMU–SA. Northwest Vista College, a community college in the Alamo Community College District, and the Texas A&M Engineering Extension Service (TEEX) cooperated with TAMU–SA in development of the B.A.A.S. degree program.

Figure 1 displays a flow diagram of a model education pathway providing multiple ways a high school graduate or practicing professional can combine progress to completion of a B.S. or B.A.A.S. degree in water science and technology. This model includes an option for a 2+2 degree, with the first two years of academic work completed at a community college and the last two years at a four-year degree granting regional university. Industry professionals who have completed certifications and training through industry, government, or university extension programs, such as those available through TEEX, will be able to earn competency-based credit toward a degree at a participating community college or university. Internships or work-study arrangements in water-related industries will be compulsory for completion of degree requirements for all students. An advisory board consisting of relevant water industry professionals drawn from local sources should guide the overall thrust of the degree curriculum at each participating community college and university, as well as support student internship opportunities. Features of the education pathway for beginning students and practicing professionals follow:

- Beginning students who have completed a high school degree have several options. They can complete the general Texas state education core curriculum at an insti-

Figure 1. Multiple pathway options to obtain a Bachelor of Science or Bachelor of Applied Arts and Sciences in water resources for high school graduates with no previous training and practicing professionals who have completed water industry or TEEX training, certification courses, and regulatory licensing requirements. (Presentation adapted from Porter's Five Forces Diagram by Michael Porter, licensed under CC BY 2.0.)

tution such as the Virtual College of Texas through online courses, or at any community college in the state, complete an associate's degree in water science and technology at any of the participating community colleges, and then finish with a B.S. or B.A.A.S. degree in water science and technology at participating universities. We envision a community college or group of community colleges collaborating with a specific regional university for any given region in Texas. Beginning students can also start and finish their degree program at any participating university.

- Water industry professionals who have finished high school, have completed industry training courses, and have various certifications can similarly obtain a B.S. or B.A.A.S. degree by a combination of steps: complete the Virtual College of Texas core curriculum online, take distance education water science and technology courses, obtain competency-based credit toward a degree for training and certifications already completed, obtain an associate's degree from a community college, and complete coursework toward a B.S. or B.A.A.S. degree from a participating regional university.

To provide access to this program statewide and to meet the needs of working students and practicing professionals, all courses that are not laboratory-based or experiential learning-based would be available online in a three-year time-frame, jointly administered by the participating community college and regional university. Laboratory experiences would be supported by mobile water laboratories maintained by TEEX or other training providers that would be made available to participating colleges and universities. This will reduce the need for participating schools to buy or build expensive specialized laboratory equipment and facilities that may only receive use once or twice a year. Laboratory experiences would be offered as intensive short courses at participating community colleges or the regional university as needed. Short courses and licensing preparatory courses available through TEEX and industry sources would also be made available to students as needed. While students may or may not receive university credit toward their degree for such courses pending the nature of the course, making these courses available to students will allow them to qualify for necessary certificates and licenses for job readiness.

This model relies on application of rigorous science and practical applied industry readiness training. It should be attractive to students seeking a clear path for a position in the water industry and provide long-term professional growth potential. It should also be attractive to practicing water professionals seeking a relevant university degree to enhance their own professional advancement opportunities.

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Surface water-groundwater interaction issues in Texas

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Abstract: In Texas, surface water is owned and regulated by the State of Texas, whereas groundwater is owned by respective property owners under the rule of capture. Owners of surface water rights, issued by the state, and groundwater may use and sell their water as a private property right. The Texas Commission on Environmental Quality administers surface water rights, while groundwater conservation districts (where they exist) are primarily responsible for permitting groundwater use. This paper focuses on the complexity of both systems that are designed to manage water resources differently with specific emphasis on where surface water and groundwater interact. Surface water-groundwater interactions have contributed to disputes over the actual ownership and right to water. The available science and the limitations of the models currently used to make water availability and permitting determinations are discussed, as are the investments in field data gathering and interpretation and model enhancements that can lead to better assessments of surface water-groundwater interactions and impacts. More complete science and enhanced models may also help reduce the timeline associated with the permitting of future water supply and use strategies.
Keywords: surface water, groundwater, interaction, availability models, permitting decisions

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Terms used in paper

Acronyms	Descriptive name
BBASC	basin and bay area stakeholder committee
BFI	baseflow index
DORM	Daily Operational Routing Model
DFC(s)	desired future condition(s)
EAA	Edwards Aquifer Authority
ES	Environmental Stewardship
ESA	Endangered Species Act
GAM(s)	groundwater availability model(s)
GCD(s)	groundwater conservation district(s)
GMA(s)	groundwater management area(s)
IHA	Indicators of Hydrologic Alteration
LCRA	Lower Colorado River Authority
LCRB	Lower Colorado River Basin
MAG(s)	modeled available groundwater(s)
MBFIT	Modified Base Flow Index with Threshold
SCOTUS	Supreme Court of the United States
SW-GW	surface water-groundwater
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas In-stream Flow Program
TPWD	Texas Parks and Wildlife Department
TWC	Texas Water Code
TWDB	Texas Water Development Board
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WAM(s)	water availability model(s)
WRAP	Water Rights Analysis Package

INTRODUCTION

The growing use of water resources and greater frequency of droughts, with associated impacts to streamflow, are placing a greater focus on groundwater and surface water interactions in Texas by state agencies (NAS 2005; Scanlon et al. 2005; TWDB 2016a; Toll et al. 2017; Young et al. 2017; Smith et al. 2015; Chowdhury et al. 2010). Among the regulatory issues affected by surface water-groundwater (SW-GW) interactions in Texas are managing water rights along a river, complying with the Endangered Species Act (ESA), implementing environmental flow recommendations, and obtaining bed and banks permits. A question central to all these regulatory issues is how to quantify the impacts of groundwater pumping on the availability of surface water. This question is at the center of several recent studies, conflicts and lawsuits in Texas involving the Rio Grande, San Saba, Colorado, and Brazos rivers. The situation on the San Saba River resulted, in part, in an interim charge for Texas House Natural Resources Committee (85th Legislative session) to evaluate "emerging issues in groundwater and surface-water interaction, in particular in areas of increasing competition for scarce resources"(Straus 2017).

As shown by the recent events associated with pumping groundwater near the four aforementioned rivers, an emerging issue associated with SW-GW interactions is that groundwater permitting and availability must recognize a person's ownership and property interest in water. Sound science is critical to ensuring such protection and determinations.

To properly address questions of how groundwater pumping is affecting surface-water availability, there is a need to properly understand SW-GW interactions (NAS 2005). Several factors contribute to this lack of understanding, including an inadequate number of field studies that address SW-GW interactions, the use of baseflow estimation techniques that do not provide consistent estimates or consider bank flow, and model simulations that do not adequately reflect the physical processes occurring in SW-GW interactions (Parsons 1999; Halford and Mayer 2000; HDR 2007; Mace et al. 2007; Asquith et al. 2005; Scanlon et al. 2005; Partington 2012; Young et al. 2017).

The purpose of this paper is to (1) define key terms and identify statutes in the Texas Water Code (TWC) associated with SW-GW interactions, (2) summarize the role of SW-GW interactions in the management of water resources, (3) present key physical processes that occur in SW-GW interactions, (4) discuss the limitations of currently used techniques to estimate and model SW-GW interactions, and (5) present recommendations to improve the science in relation to SW-GW interactions in Texas. Although this paper is specific to Texas law, management issues, and case studies, the issues raised could be of benefit and application outside of the state for anyone considering SW-GW interactions in their management decisions.

DEFINITION OF GROUNDWATER AND SURFACE WATER

The TWC does not define surface water specifically but rather makes the terms "surface water" and "state water" synonymous. TWC §11.021 defines state water as "The water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed in the state…"

In addition to the surface water features identified in §11.021, the TWC also uses the term "watercourse." The courts have described a watercourse as having (1) a defined bed and banks, (2) a current of water, and (3) a permanent source of supply (Domel v. City of Georgetown, Austin 1999). These criteria are crucial in determining if water is classifiable as state water. Generally, until water reaches a watercourse (where it becomes state water), it is classified as diffuse water. Diffuse water includes rainwater, snowmelt, and overland flow and is the property of the landowner until it joins a watercourse.

Another water feature classified as state water is "underflow," which is generally associated with the presence of subsurface water within the bed and banks of a watercourse. Texas Commission on Environmental Quality (TCEQ) rule §297.1 defines a stream's underflow as "[w]ater in sand, soil, and gravel below the bed of the watercourse, together with the water in the lateral extensions of the water-bearing material on each side of the surface channel, such that the surface flows are in contact with the subsurface flows, the latter flows being confined within a space reasonably defined and having a direction corresponding to that of the surface flow" (30 Tex. Admin. Code §297.1(55)).

In some situations, the TCEQ may classify groundwater as "under the direct influence of surface water." Groundwater classified as under the direct influence of surface water in Texas requires a higher level of treatment for a public water supply than does groundwater that is not under the direct influence of surface water. TWC Chapter 290, Subchapter D defines groundwater under the direct influence of surface water as:

"Any water beneath the surface of the ground with:

(A) significant occurrence of insects or other macroorganisms, algae, or large-diameter pathogens such as *Giardia lamblia* or *Cryptosporidium*;

(B) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions; or

(C) site-specific characteristics including measurements of water quality parameters, well construction details, existing geological attributes, and other features that are similar to groundwater sources that have been identified by the executive director as being under the direct influence of surface water."

The TCEQ definition above is based on U.S. Environmental Protection Agency regulation (40 CFR 141.2).

Finally, the TWC defines groundwater as "…water percolating below the surface of the earth" (TWC §35.002(5) and §36.001(5)). However, stream underflow has been expressly excluded from being considered groundwater because it is state water. This distinction is important because it grants the TCEQ the legal authority to restrict non-domestic pumping of groundwater near streams if groundwater is present in an underflow zone.

OWNERSHIP AND REGULATION OF SURFACE WATER AND GROUNDWATER IN TEXAS

Texas surface water law has evolved from the Riparian Doctrine to the Prior Appropriation Doctrine. Surface water is owned by the State of Texas held in trust for the public (TWC §11.021, §11.0235). With passage of the Water Rights Adjudication Act in 1967, Texas adopted a unified surface water permit system. Unless the purpose of use is domestic or livestock (exempt uses that remain riparian), anyone wishing to use surface water must receive permission from the state in the form of a "water right." The TCEQ is primarily responsible for granting surface water rights, which then become private property in and of themselves unless forfeited through nonuse.

Texas groundwater law is rooted in the rule of capture. Texas landowners own the water beneath their property (TWC §36.002) and may use or sell the water as private property. The Texas Legislature, however, has authorized the establish-

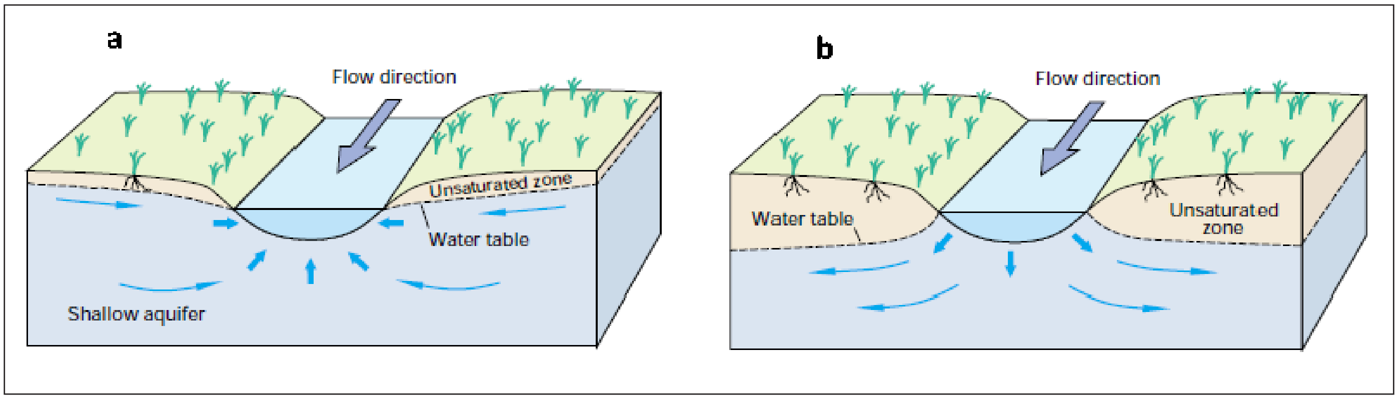

Figure 1. Schematic showing groundwater flow toward a gaining stream (a) and groundwater flow away from a losing stream (b) (modified from Winter et al. 1998).

ment of groundwater conservation districts (GCDs), which generally have the authority to modify the rule of capture by promulgating rules for conserving, protecting, recharging, and preventing waste of underground water. TWC §36.0015 states 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 best available science in the conservation and development of groundwater." There are currently 100 GCDs that cover about 70% of the area of Texas. GCDs operate though a board of directors, whose members are either elected or appointed, generally by elected officials, per the conditions established in the legislative act that created the district or TWC if the district was through petition. GCDs may choose to recognize SW-GW interaction through the adoptions of management goals to maintain springflow and/or stream baseflow.

The TCEQ cannot authorize or regulate groundwater pumping via permit, just as a GCD cannot regulate the permitting and diversion of surface water. Consequently, an inherent statutory conflict is created by having these separate regulatory mechanisms, particularly as it relates to SW-GW interaction. The differences in the regulatory agencies, technical disciplines, and ownership issues associated with surface water and groundwater have led to the development of programs to develop regulatory tools for evaluating groundwater availability and surface water availability but few tools for evaluating SW-GW interactions.

SURFACE WATER-GROUNDWATER INTERACTION

Traditionally, surface water and groundwater have been treated independently when managing these resources in Texas. However, it is well understood that these two resources are often hydrologically connected. In some instances, surface water serves as a source of flow that can change the chemistry and availability of groundwater. Conversely, groundwater can increase the flow volume and affect the chemistry of surface water. In some cases, the same stretch of river may lose flow to the aquifer in one season and gain flow from the aquifer in another season. As the demand for water and the need for new water supplies increase in Texas, understanding the hydrologic connection between surface water and groundwater becomes integral to developing appropriate legislation and strategies to effectively use and manage these two resources.

Gaining and losing streams

A stream that receives water emerging from a submerged spring or other groundwater seepage through its streambed is a gaining stream (Winter et al. 1998). A stream that loses water to groundwater by outflow through the steambed is called a losing stream (Winter et al. 1998). Figure 1 illustrates the dynamics of gaining and losing streams. A stream may always gain water from an aquifer (perennial streams) or always lose water to an aquifer (intermittent or ephemeral streams). The flow conditions in a stream might also vary over time and across space, such that it is characterized as both gaining and losing. The conditions that cause these variances can be natural, such as flood events, or anthropogenic, such as pumping.

An important metric for evaluating SW-GW interactions is the difference in elevation between the water table in an aquifer and the water level in a stream. For a gaining stream, the water-level elevation in the stream is lower than the water level in the immediate aquifer. Under these conditions, the aquifer discharges water to the stream, increasing the stream's flow. For a losing stream, the water-level elevation in the stream is higher than the water-table elevation in the aquifer. Under these conditions, the stream recharges water to the aquifer.

Groundwater contribution to a stream can originate from unconfined aquifers or from confined aquifers. For the case of an unconfined aquifer, groundwater flow typically exits an aquifer and flows to the stream as diffuse flow. In coastal aquifers such as the Gulf Coast Aquifer System, the majority of groundwater contribution to streams occurs as diffuse flow. For the case of a confined aquifer, pressured groundwater flows through preferential flow pathways created by faults, fractures, and karstic features until it exits at a spring location and enters a stream. In the Texas Hill County, the confined section of the Edwards Aquifer produces some of the biggest springs in Texas. These springs include Barton Springs, San Marcos Springs, Comal Springs, Las Moras Springs, and San Felipe Springs.

The Texas Water Development Board (TWDB) (2016a) made several key points regarding SW-GW interactions in Texas:

- An estimated 9.3 million acre-feet of groundwater flows from major and minor aquifers to surface water in an average year. This represents about 30% of the average surface water flow in Texas.
- Aquifer interactions with surface water vary regionally and within each aquifer. Between 14% and 72% of streamflow over aquifer outcrop areas is due to groundwater discharge from major and minor aquifers.
- The largest groundwater contributions to surface water occur in East Texas, the Hill Country, and around major springs in West Texas.
- The aquifer with the most groundwater discharge to surface water is the Gulf Coast Aquifer, with an estimated 3.8 million acre-feet per year.

Besides indicating that SW-GW interactions can significantly affect streamflow, the TWDB (2016a) shows that local geology and meteorological conditions are important factors that affect SW-GW interactions.

Baseflow and bank flow

TCEQ Rule §297.1 defines baseflow as "[t]he portion of streamflow uninfluenced by recent rainfall or flood runoff and is comprised of springflow, seepage, discharge from artesian wells or other groundwater sources, and the delayed drainage of large lakes and swamps." This definition implies that bank flow is not a part of baseflow. As discussed by Freeze and Cherry (1979), bank storage effects and bank flows can complicate the process of defining and determining baseflow. Bank storage refers to the variable amount of water stored temporarily in the stream banks during rising flood stage (Todd 1955). Bank flow is the release of bank storage back to the stream that occurs following high river stage. Despite being potentially important to characterizing SW-GW interactions, bank flow and bank storage are not recognized in TCEQ rules and are not considered in the water balance simulated by water availability models (WAMs) and groundwater availability models (GAMs).

Bank flow is the flow of water into and out of the banks along a stream (Figure 2). Figure 2A shows water levels under conditions for a gaining stream where the water level is higher in the aquifer than in the stream. Figures 2B and 2C show the effects of a rainfall event on water levels in the stream, causing them to become temporarily higher than the water level in the aquifer that is in contact with the stream. During this time, stream water flows into the aquifer and is stored in the banks of the aquifer as bank storage. After the flood event has passed and the stream becomes a gaining stream again (see Figure 2D and 2E), the water held as bank storage returns to the stream and mixes with the water that originated from the aquifer. After bank flow has ceded, the stream and aquifer water levels eventually return to conditions typical for a gaining stream.

Significant bank storage and flow occurs when (1) a stream reach is subject to stage increases, (2) bank materials have a high permeability, and (3) sufficient volumes of permeable bank material or alluvium provide storage (Rassam and Werner 2008). The abundance of high permeability alluvium will also promote the occurrence of underflow. In general, downstream reaches are more favorable to bank storage than headwater reaches (Kondolf et al. 1987) because they have greater drainage areas that produce large flood peaks and are more likely to be flanked by alluvium with a large capacity to store water relative to streamflow. Kunkle (1962) showed, in some cases, annual discharge from a groundwater basin can be less than the annual discharge from bank storage.

The identification and calculation of bank flow requires at a minimum measured water-level elevations and water quality parameters from a river gage and wells in the aquifer underlying and adjacent to the stream. Figure 3 shows water levels measured in 2007 at a Colorado River gage and a water well located about 200 feet from the Colorado River (URS and Baer Engineering 2008). These data are from a monitoring program performed by the Lower Colorado River Authority (LCRA) to investigate SW-GW interactions near the City of Wharton from 2006 to 2008. Over that period, the groundwater level in the aquifer was higher than the stream water level in the Colorado River over 80% of the time, which means the Colorado River was a gaining stream (see Figure 1) over 80% of the time. However, during multiple high stream stage events, the increase in stream water levels caused significant increases in the groundwater level that represent bank storage in the aquifer (as illustrated in Figures 2B and 2C). On several occasions, the bank storage became great enough to cause a reversal of groundwater flow direction 200 feet from the stream. Following the peak stream stage and the accumulation of bank storage, bank flow (as illustrated in Figures 2D and 2E) occurs as water levels recede in both the aquifer and the stream until another high stage ensues.

Although the data in Figure 3 can be used to demonstrate the occurrence of bank storage and bank flow to SW-GW interactions, additional information is needed to determine the amount of water transferred between the stream and the

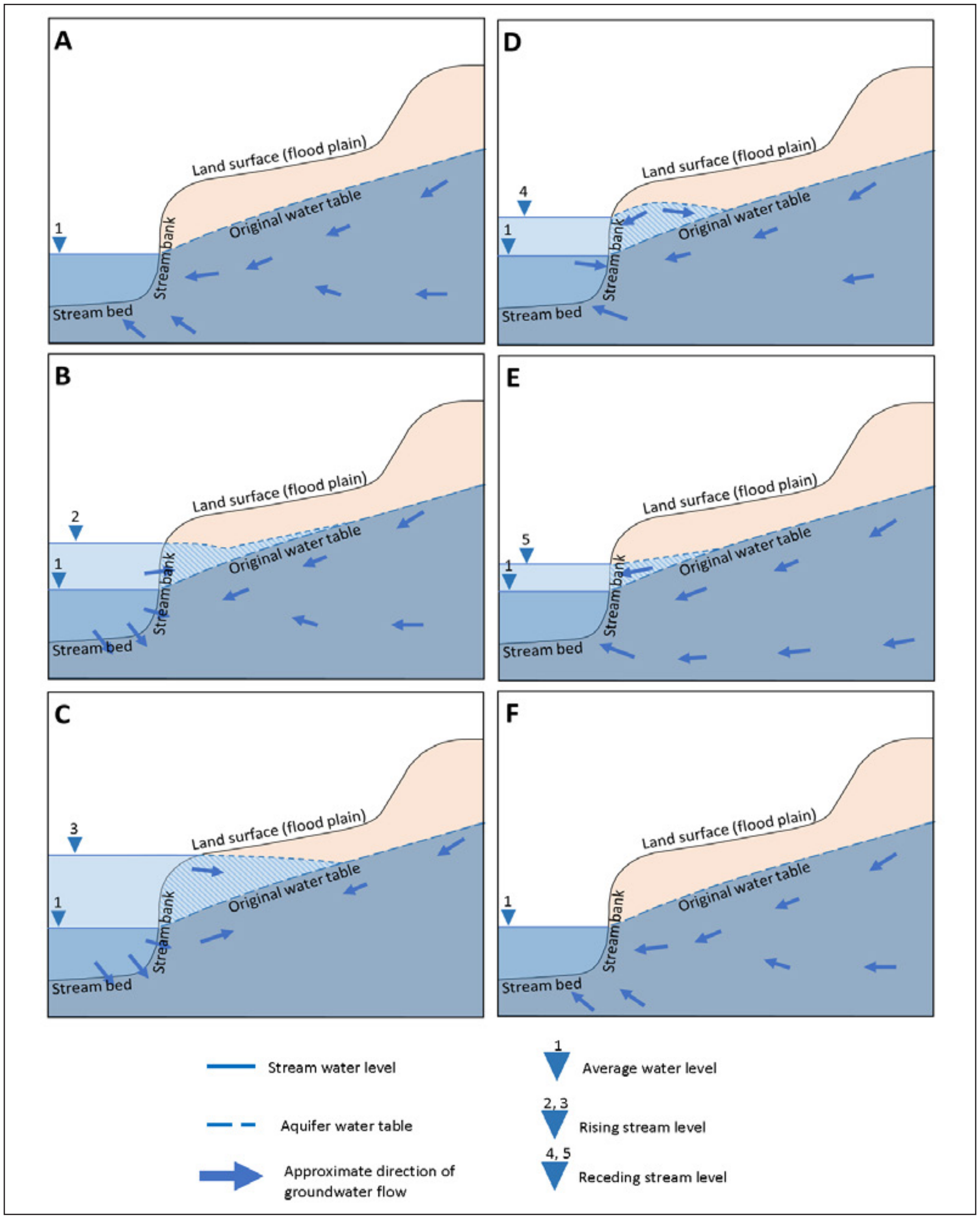

Figure 2. Schematic showing groundwater flow toward a stream at sequential times. Water levels during average flow conditions at a gaining stream (A). Increase in stream elevation during a flooding event causes hydraulic gradient reversal at stream-aquifer interface. Streamflow enters aquifer and becomes bank storage in stream bank (B and C). Decrease in stream elevation after a flooding event. Bank storage flows back to the stream as water level in the streams lowers over time (D and E). Water levels in stream and aquifer return to conditions that existed prior to flood event (F).

aquifer. Among the additional information required to make such a determination are hydraulic properties of the aquifer and measurements of water quality parameters. The chemical data is used to partition flow based on mass-balance considerations. Numerous studies have successfully used geochemical analysis of stable isotopes, anions, and salinity to estimate baseflow (Boulton et al. 1999; Porter 2001; Oxtobee and Novakowki 2002; Brodie et al. 2005; SKM 2012; Scholl et al. 2015; Rhodes et al. 2017; Cook et al. 2018).

The importance of bank storage to SW-GW interactions is difficult to assess in most Texas rivers because of the sophisticated level of analysis and large quantity of data required to derive definitive answers. In order to thoroughly quantify bank storage effects, evaluations of flow exchange should include both

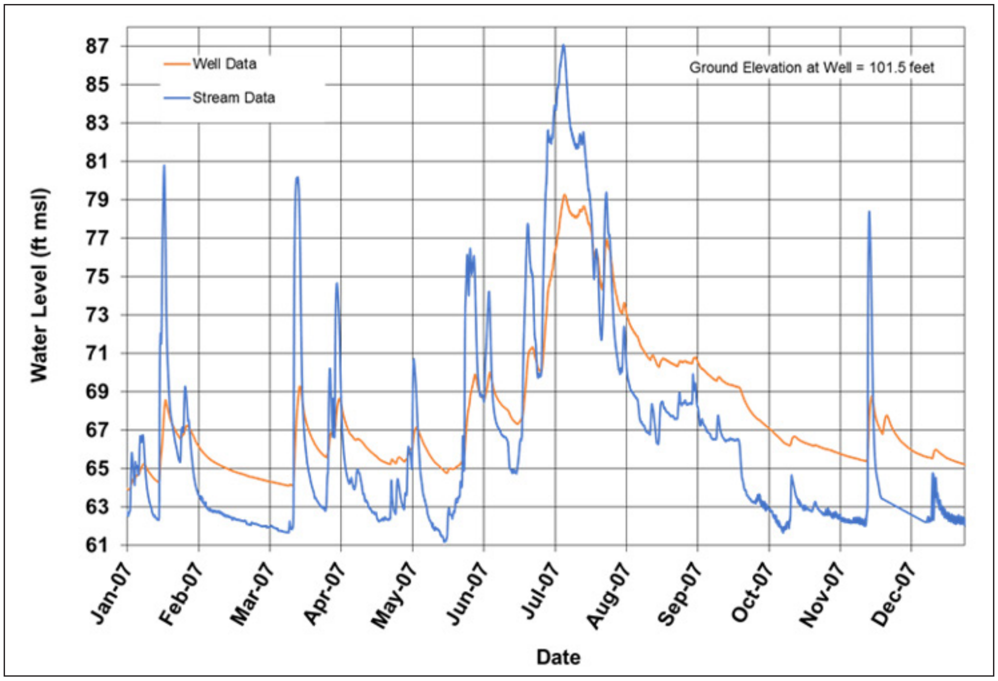

Figure 3. Comparison of measured water levels in the Colorado River and in the Colorado River Alluvium near the City of Wharton in 2007 (from URS and Baer Engineering 2007).

calculations based on hydraulic data and geochemical data. One Texas river that has a relatively large amount of permeable bank material is the Brazos River. A recent study by Rhodes et al. (2017) that includes both hydraulic and geochemical analysis demonstrates that bank storage can be a significant component of groundwater flow to the Brazos River. During a four-month river stage recession following a high stage event, less than 4% of the water discharged from the subsurface resembled the chemical fingerprint of the alluvial aquifer. Instead, the chemistry of the discharged water closely resembled the high stage event river water. Rhodes et al. (2017) concluded that the Brazos River is well connected to rechargeable bank storage reservoirs but disconnected from the broader alluvial aquifer.

SURFACE WATER AND GROUNDWATER AVAILABILITY IN TEXAS

In 1997, Senate Bill 1 of the 75th Texas Legislature directed the TCEQ (then called the Texas Natural Resource Conservation Commission) to develop WAMs for river basins in Texas. A WAM "is a computer based simulation program used to evaluate the amount of surface water in a river or stream that would be available to existing or proposed water rights under specified basin operations and hydrologic conditions"(HDR 2007). WAMs consist of two parts: the modeling program called the Water Rights Analysis Package (WRAP)(Wurbs 2001) and the text files that contain basin-specific information for the WRAP to process. WAMs do not explicitly simulate water fluxes associated with stream-aquifer interactions, but they can indirectly account for the effects of a losing stream through a channel loss function or a naturalized flow adjustment file (HDR 2007). As noted by HDR (2007), however, the majority of WAMs do not include channel losses because the losses are typically small relative to streamflows.

The authors believe that a potentially more valuable surface water model for investigating SW-GW interactions than WAMs are flow-routing models for the stream basin. Flow-routing models solve hydrologic equations that describe how a pulse of water moves downstream. Flow-routing models calculate flow as a function of space and time using equations based on flow continuity and momentum. Two examples of routing models are the LCRA's Daily Operational Routing Model (DORM) (Carron et al. 2010) and the Upper Rio Grande Water Operation Model (Boroughs 2013). These and other routing models can be used to estimate SW-GW interactions by performing water budget calculations that account for all losses and gains along a stream reach except for those associated with SW-GW interaction. Data used by DORM for its water budget calculations include hourly data from gaged tributaries, return flows, releases from Lake Travis, releases from Lady Bird Lake, and known diversions. Working with LCRA to find two- to four-week periods of stable low-flow conditions with high quality data, Young et al. (2017) found that DORM simulations provided credible estimates of SW-GW interaction for low-flow periods in 2012, 2013, 2014, and 2015. Based on DORM results that were generally consistent with previous estimates of SW-GW interactions (Saunders 2009, 2012), Young et al. (2017) recommends that DORM simulations be incorporated into field studies aimed at measuring SW-GW interaction along the Colorado River.

In 2001, Senate Bill 2 tasked the TWDB with developing GAMs of all major and minor aquifers in Texas. The TWDB defines groundwater availability modeling as "the process of developing and using computer programs to estimate future trends in the amount of water available in an aquifer and is based on hydrogeologic principles, actual aquifer measurements, and guidance from persons with interest in the models and the program" (TWDB 2016b). The goal of the GAM program "is to provide useful and timely information for determining groundwater availability for the citizens of Texas" (TWDB 2016b). GAMs are constructed using the family of USGS MODFLOW codes that simulate groundwater flow (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996; Harbaugh et al. 2000; Harbaugh 2005; Niswonger et al. 2005; Panday et al. 2013).

GAMs, in their current capacity, simulate water movement based on the physics of water flow and can simulate the exchange of water between aquifers and streams. Among the factors that limit the ability of GAMs to accurately simulate SW-GW interactions is that they were developed to address water issues at a relatively large spatial scale and are not readily suitable to simulate SW-GW interactions at a local scale of a few miles and less (Scanlon 2005; HDR 2007; Kelley et al. 2008). Another issue that limits GAMs' capability for accurately simulating SW-GW interaction at the local scale is that they use time periods of months to years; whereas, accurate modeling of SW-GW interaction will usually require time periods of hours to days (Scanlon 2005). Besides having the limitations associated with spatial and temporal scales that are large compared to scales that drive SW-GW interactions, GAMs are also limited because GAMs cannot simulate unsaturated flow, which can be an important process for accurate modeling of SW-GW interaction. Recognizing that these are GAM limitations and not necessarily a limitation of MODFLOW, as packages to include unsaturated flow processes exist, highlights one of the ways to enhance GAMs, or a modification of a GAM, to improve simulations of SW-GW interactions.

Despite the inherent limitations with GAMs for simulating SW-GW interaction at the local scale of a few miles, GAMs will not necessarily provide reasonable estimates of SW-GW interaction even at the regional scale unless considerable care is taken with its development. Specifically, the model calibration process for a GAM is particularly important because of the wide range of factors affecting SW-GW interactions. These factors include how recharge, evapotranspiration, streamflow, stream channel geometry, stream-bed hydraulic properties, and runoff are represented in the model. Additionally, another major issue affecting GAM simulation of SW-GW interaction, discussed by Mace et al. (2007), is the vertical resolution (i.e., the layer thicknesses) of the groundwater model:

> "One of the difficulties in accurately representing surface water-groundwater interaction is the vertical resolution in the groundwater availability model. The interaction of a stream and an aquifer is an intimate affair that occurs locally on the order of feet to tens of feet. In many cases, the current groundwater availability models are too coarse, both laterally and vertically, to accurately represent surface water-groundwater interaction. The difference between a gaining stream and a losing stream can be the difference of a few feet of groundwater level change, especially for the aquifers along the Gulf Coast where there is not much topography."

The importance of vertical resolution (inclusion of shallow model layers) at the regional scale is twofold. One reason is that the vertical resolution affects a GAM's capability to represent a shallow groundwater flow zone. This shallow flow zone is the primary conduit in the real physical aquifer system for much of the recharge that enter the groundwater system to move relatively quickly to discharge locations in the aquifer's outcrop, which includes seeps, springs, and surface water bodies. A second reason is that the vertical resolution prevents deep pumping wells that are nearly hydraulically isolated from water table near ground surface from being represented in the same model layer that is a river or a lake.

One of the first applications of shallow model layers to represent a shallow, local flow system in a regional groundwater model was the Lower Colorado River Basin (LCRB) model (Young et al. 2009). The LCRB model sought to improve the accuracy of both recharge and SW-GW interaction by including a shallow and relatively thin model layer near the water table to represent the shallow groundwater flow system. The incorporation of the shallow groundwater layer was made with considerations toward improving how the model represents the aquifers and alluvium. The geology representation was guided by using maps of surface geology including alluvium developed by Barnes (1974).

Figure 4 shows that the county-scale LCRB model provides a significantly better match to historical estimates of groundwater contributions to the Colorado River than the regional-scale Central Gulf Coast GAM (Chowdhury et al. 2004). With regard to the source for pumped groundwater for Matagorda, Wharton, and Colorado counties from 1980 to 2000, the Central Gulf Coast GAM predicts that 66% is leakage from streams whereas the LCRB model predicts 71% is from recharge from precipitation (Young et al. 2009). The large differences in the source for the pumped groundwater illustrate that at a regional scale, model layering can have a significant effect on simulated SW-GW interactions. Among the GAMs that include a thin model layer near the water table to represent shallow ground-

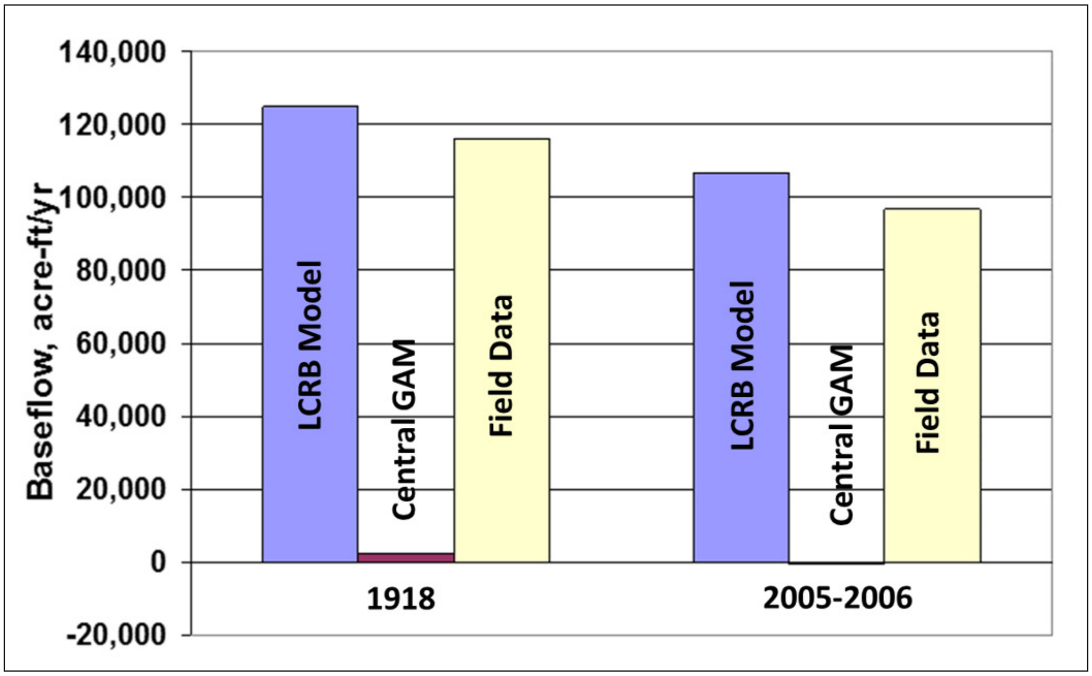

Figure 4. Comparison of measured baseflow along the Colorado River (Field Data) with simulated baseflow values from the LCRB groundwater model and from the Central Gulf Coast Groundwater Availability Model (data from Young et al. 2009; LCRB = Lower Colorado River Basin, GAM = groundwater availability model). The Field Data includes gain-loss studies performed with river gage data reported by Slade (2002) and Saunders (2006).

water flow system are a GAM for the Yegua-Jackson Aquifer (Deeds et al. 2010), a GAM for the Northern Trinity and Woodbine Aquifers (Kelley et al. 2014), and a GAM for the central portion of the Sparta, Queen City, and Carrizo-Wilcox aquifers (Young et al. 2018).

Independent studies funded by the TWDB (HDR 2007) and the TCEQ (Scanlon et al. 2005) have investigated the ability of models to predict SW-GW interactions. Both studies emphasized that there is a critical need for field data that can be used to develop appropriate conceptual models and guidelines for developing GAMs to help standardize and improve the approaches used to simulate SW-GW interactions. Before significant improvements in simulating SW-GW interactions with GAMs and other groundwater can occur, additional field studies need to be conducted. Scanlon et al. (2005) recommended that additional field studies be performed that include (1) co-locating groundwater monitoring wells with stream gages, (2) characterizing stream morphology and aquifer hydraulic properties, (3) collecting water-level and water quality data, (4) evaluating streamflow gains and losses and aquifer bank storage and bank flow, (5) conducting aquifer tests near streams, and (6) evaluating the time it takes water to travel between streams and wells.

STREAM HYDROGRAPHS

Besides using models that simulate the movement of surface water or groundwater, SW-GW interactions can be estimated by using hydrograph-separation methods. Stream hydrographs show changes in measured water levels (that is, stream height or stage) at river gages as a function of time. Hydrograph-separation methods (sometimes called baseflow separation) aim to distinguish a streamflow hydrograph into two components:

1) Quickflow – flow in direct response to a rainfall event including overland flow (runoff) and direct rainfall onto the stream surface (direct precipitation).
2) Baseflow – the steady flow derived from groundwater discharge to the stream and lateral movement in the soil profile (interflow).

Many hydrograph-separation methods have been developed to estimate the baseflow and runoff components of streamflow, and these methods have been implemented in a number of computer programs that facilitate the estimation process (Pettyjohn and Henning 1979; Nathan and McMahon 1990; Wahl and Wahl 1995; Sloto and Crouse 1996; Rutledge 1998; Arnold and Allen 1999; Eckhardt 2005; Lim et al. 2005; Piggott et al. 2005). Although each of the methods is based on formalized algorithms for identifying the baseflow component

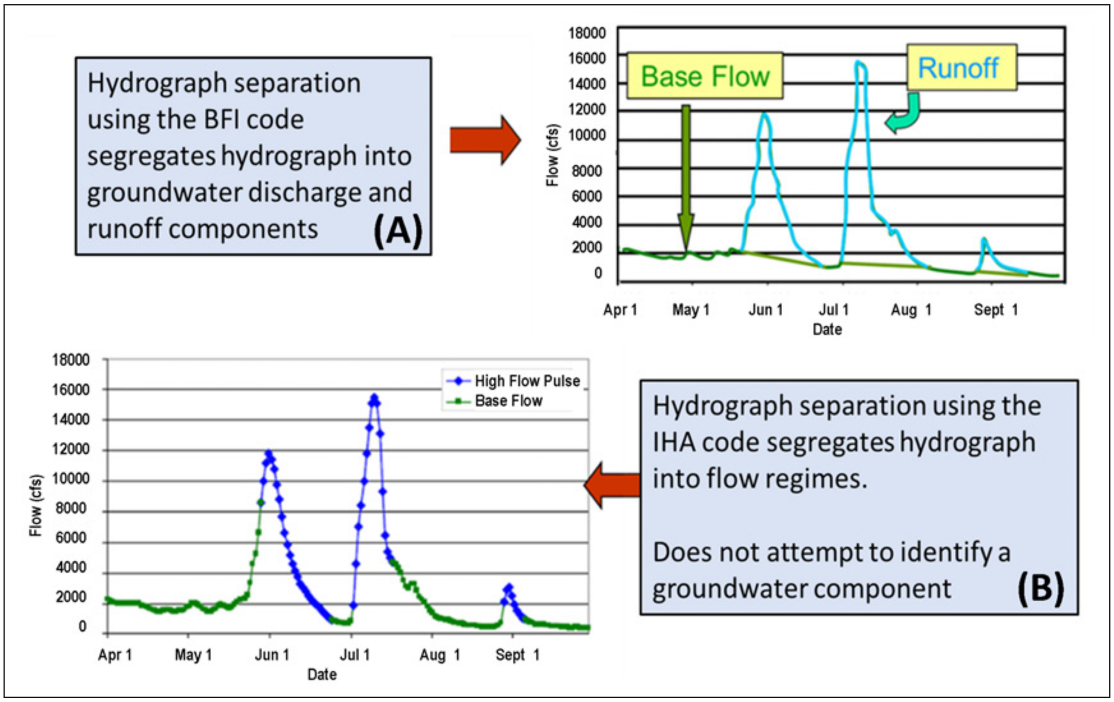

Figure 5. Analysis of a stream gage hydrograph by a surface water hydrologist using the IHA software (A) and by a groundwater hydrologist using the BFI software (B) (IHA = Indicators of Hydrologic Alteration; BFI = baseflow index).

of total streamflow, they can differ substantially in their underlying assumptions and degree of freedom in their application. Because of the different underlying assumptions with the different methods, there are advantages to using more than one hydrograph-separation method to analyze a streamflow record to assess uncertainty.

Hydrograph-separation methods have been widely used to estimate SW-GW interaction and recharge across watersheds in Texas (Young and Kelley 2006; Deeds et al. 2010; Scanlon et al. 2012; Kelley et al. 2014; Ewing et al. 2016; TWDB 2016a; Young et al. 2018). Most of these Texas studies have used either the Base-Flow Index (BFI) Program (Institute of Hydrology 1980; Wahl and Wahl 1995) or the Baseflow Program developed for use with the Texas A&M University's Soil and Water Assessment Tool (Nathan and Mahon 1990; Arnold and Allen 1999). A potential concern with these two methods and other hydrograph-separation techniques is that they do not explicitly account for discharge that did not originate from the groundwater basin (Scanlon et al. 2005) and thus will likely overestimate baseflow. Scanlon et al. (2005) identify these sources as in-stream detention and subsequent discharge of surface water, alluvium aquifer recharge such as bank storage/release following flood events, perched groundwater zones, or fractured zone recharge/discharge in the near subsurface.

In addition to the type of hydrograph-separation programs used by hydrogeologists to identify groundwater contribution to a stream, there are other types of hydrograph-separation programs used by surface water hydrologists to identify flow regimes. These type of hydrograph separations are performed to support the Texas Instream Flow Program (TIFP). The purpose the TIFP is to perform scientific and engineering studies to determine flow conditions necessary for supporting a sound ecological environment in the river basins of Texas (TCEQ, TPWD, TWDB 2008). To identify flow regimes, surface water hydrologist use either the Indicators of Hydrologic Alteration (IHA) program (Richter et al. 1996) or the Modified Base Flow Index with Threshold (MBFIT) (Brandes et al. 2011) to class a portion of a hydrograph into one of four flow regimes: subsistence flow, baseflow, high flow pulses, or overbank flows.

Figure 5A shows the results of a stream hydrograph analysis performed using the BFI program. The BFI program is used to partition a streamflow into a runoff component comprising diffuse surface water flow and a baseflow component comprising groundwater flow into a stream. Figure 5B shows results from applying IHA to the same stream hydrograph in Figure 5A to identify baseflow regimes and high flow pulse regimes. The application of the BFI and the IHA programs illustrate the different type of results produced by each program. Because the two programs use very different sets of underlying assumptions, there is not a common set of information on which the two disciplines can rely to develop a shared understanding and quantification of SW-GW interactions.

Halford and Mayer (2000) share some of the same concerns that Scanlon et al. (2005) state regarding the reliability of the hydrograph-separation techniques without some type of third-party dataset or analysis to ground truth the estimated groundwater contribution calculated from the hydrograph separation. Halford and Mayer (2000) question the accuracy of the hydrograph-separation technique when the underlying assumptions of the technique have not been validated. Based on their analysis of 14 studies in nine states, Halford and Mayer (2000) say that:

- "The recession-curve displacement method and other hydrograph-separation techniques are poor tools for estimating groundwater discharge or recharge when major assumptions of the methods are violated."
- "The identification of groundwater discharge in stream discharge records can be ambiguous because drainage from bank storage, wetlands, surface water bodies, soils, and snowpacks also decreases exponentially during the recession period."

USGS (2017) noted that an important limitation of the BFI program, as well as other hydrograph-separation methods, is that "In general, the method [BFI program] interprets most regulated releases as baseflow. If the program is used for regulated streams, the effects of regulation must be carefully accounted for thorough manual adjustment of the program output." Even when underlying assumptions of the baseflow separation methods are met, the applications of the methods can still be problematic. This situation is illustrated by results from Partington et al. (2012) who analyzed numerically simulated river hydrographs with automated baseflow separation techniques. Partington et al. (2012) found that the automated baseflow separation underestimates the simulated baseflow by as much as 28% or overestimates it by up to 74% during rainfall events. They also concluded that no separation method was clearly superior to the others, as the performance of the various methods varies with different soil types, antecedent moisture conditions, and rainfall events.

Some of the concerns documented by Halford and Mayer (2000) and Scanlon et al. (2005) are confirmed by Young et al. (2018) who estimated baseflow from 35 stream gages in Groundwater Management Area 12. For the 35 stream gages, the average recharge rate across the watershed estimated using the BFI method and the program developed for use with the Texas A&M's Soil and Water Assessment Tool was 2.70 inches and 3.78 inches, respectively, which is about a 140% difference. Such a large difference is evidence that additional work is needed to vet and ground truth the applications of baseflow-separation techniques to quantify SW-GW interaction.

In our opinion, TWDB (2016a) further illustrates the importance to vet and ground truth the approaches used for interpreting stream hydrographs in Texas. This study, prepared in response to House Bill 1232 of the 84th Texas Legislature, estimated the volume of flows from aquifers to surface water in Texas. TWDB (2016a) used the results from several U.S. Geological Survey (USGS) studies (Wolock 2003a, 2003b; Wolock et al. 2004) to spatially distribute groundwater contributions to surface water for the outcrop areas of the major and minor aquifers. Wolock (2003a) analyzed hydrographs from approximately 19,000 stream gages across the United States using the BFI program (Wahl and Wahl 1995). One output of the BFI program is the BFI Index, which is the average percentage that groundwater contributes to streamflow. Figure 6 shows the BFI values from Wolock (2003a) for the Lower Colorado River downstream of Tom Miller Dam in Austin. These nine values indicate that average annual groundwater contributions range from 40% to 65% of the total surface water flow in the Colorado River. Among other SW-GW studies performed in the region are stream low-flow gain-loss studies by Saunders (2009, 2012). Results from these studies can be used to generate BFI values. The analysis of Saunders' data produces BFI values that are up to four times smaller than those presented by Wolock (2003a) at some of the gages shown in Figure 6.

Comparisons of studies involving SW-GW interaction that provide different water budgets show that the variability is not only caused by using different types of data over varying time periods but also by using different assumptions for interpreting the data. Among the assumptions that could be important to an analysis are those related to flow diversions, flow returns, regulated flows upstream, seeps from perched groundwater tables, pumping in or near the alluvium, alluvial recharge, and bank storage/bank flow. The need for well documented and vetted approaches for interpreting stream hydrographs is cited in previous studies funded by TWDB (HDR 2007; Young et al. 2017) and TCEQ (Scanlon et al. 2005) as an important and necessary step toward improving the understanding and modeling of SW-GW interaction in Texas.

WATER RESOURCE MANAGEMENT DECISIONS AFFECTED BY SW-GW INTERACTION

The TWC recognizes that surface water and groundwater resources are hydrologically connected, at least locally, and requires that regulatory authorities consider this when issuing permits. TWC §36.113(d)(2) requires that GCDs, when evaluating groundwater permits, consider whether "…the proposed use of water unreasonably affects existing groundwater and surface water resources or existing permit holders…" Similarly, TWC §11.151 states "in considering an application for a permit to store, take, or divert surface water, the commission [TCEQ] shall consider the effects, if any, on groundwater or groundwater recharge." Statute recognizes the potential inter-

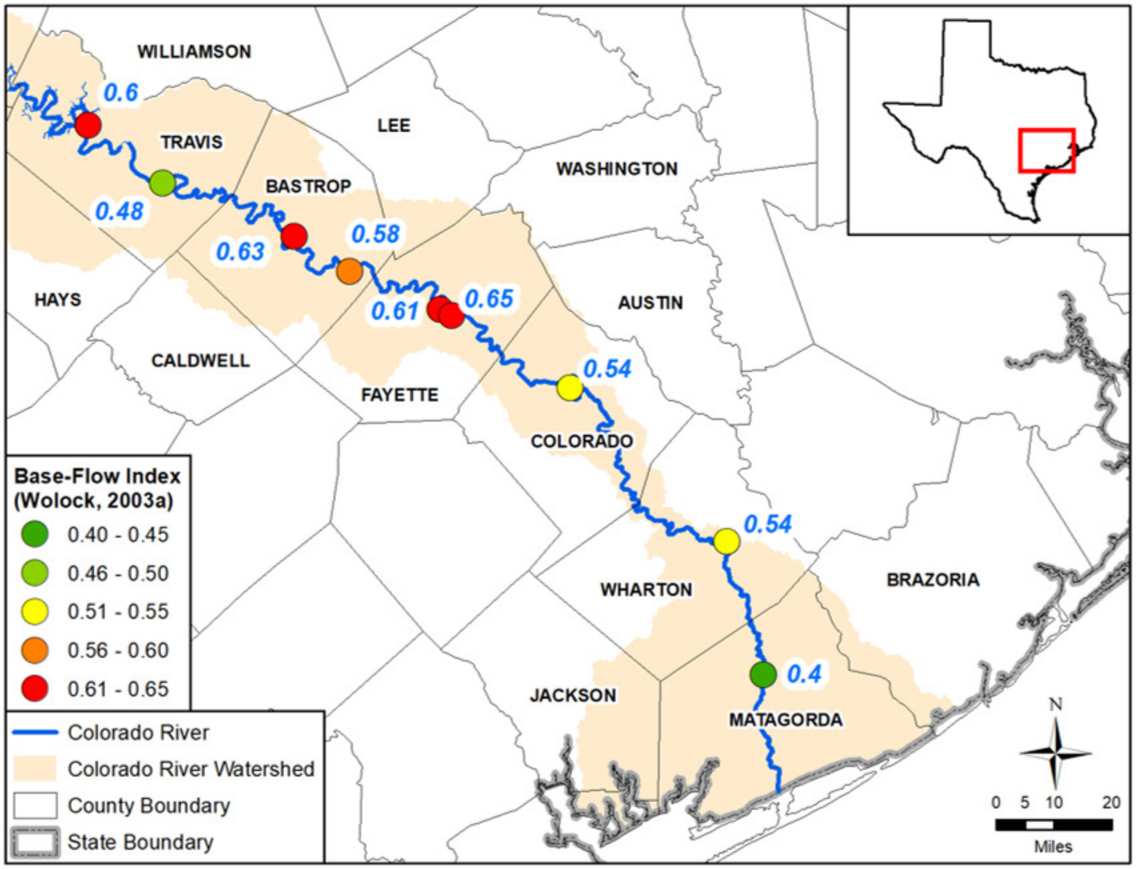

Figure 6. Baseflow index (BFI) from Wolock (2003a) for stream gages on the lower reach of the Colorado River. The BFI figures are percentages of groundwater contribution to streamflow.

connectivity between groundwater and surface water but (1) doesn't specify what level of interaction would spark action on a permit, (2) doesn't require any action by the regulating body, and (3) doesn't coordinate the regulatory realms of TCEQ from the surface water perspective or GCDs from the groundwater perspective.

Pumping near streams

In Texas, there are thousands of shallow wells with depths less than 100 feet that are located near streams. Some of these wells, and those located in the river alluvium within a few hundred feet of the river, pump sufficient water to impact the flow between the stream and the aquifer. Historically, there have been relatively few cases where regulators curtailed pumping. The general lack of action by parties affected is likely the result of a combination of several factors including (1) the lack of clarity in the TWC with regard to how to characterize underflow and how to assess pumping impacts, (2) the dearth of field measurements characterizing SW-GW interactions, (3) the absence of a demonstrated and standardized approach for analyzing stream hydrographs, (4) the reluctance of GCDs to require well owners to meter and report water use, and (5) the inaccuracies associated with many historical gain/loss studies on stream reaches and the inability of WAMs and GAMs to evaluate SW-GW interactions.

The drought-induced periods of lower surface water availability during the last decade have created conditions such that affected parties or stakeholders have requested regulatory assistance to protect state waters from adverse impacts caused by groundwater pumping. This has occurred on the Rio Grande, San Saba, Brazos, and Colorado rivers.

Rio Grande in New Mexico

In January 2013, Texas submitted a complaint to the Supreme Court of the United States (SCOTUS) alleging that New Mexico was in violation of the 1938 Rio Grande Compact. Specifically, Texas alleged that New Mexico had violated the Compact by allowing the diversion of surface water through the pumping of groundwater that is hydrologically connected to the Rio Grande, thereby diminishing Texas' ability to obtain the water the Compact apportioned to it. The New Mexico wells, which are estimated to number 3,000, pump as much as 270,000 acre-feet/year (TLO 2018). In addition, New Mexico has permitted wells that will facilitate additional water use in the future. In January 2017, New Mexico requested that SCOTUS dismiss the complaint from Texas and dismiss a request from the United States to intervene as a party to the litigation. The Special Master appointed by the Supreme Court on this case ruled against New Mexico's motion to dismiss Texas' complaint and to hear oral arguments for the United States complaint. In early 2018, SCOTUS heard arguments by the United States to intervene as a party and to essentially make the same claims as Texas. In March 2018, the SCOTUS ruled that the United States can be a party to the litigation. Litigation will likely proceed well into 2019 to discovery, motions, and eventually a hearing of the merits before the Special Master. The Special Master will then make recommendations to SCOTUS on the merits of the case (SCOTUS 2013).

San Saba River

Since 2011, the TCEQ has received complaints alleging shallow groundwater wells are being used to pump surface water in the form of underflow from the San Saba River. The area identified is a 40-mile reach between Menard and Brady (House Committee on Natural Resources 2018; Sadasivam 2017; 2018), where numerous wells within one mile of the river are completed in the alluvial deposits, which are believed to be a lateral extension of the river. Before 2000, the San Saba River was never known to cease flowing—not even during the record drought of the 1950s. From July to October in six of the past 15 years, and for every summer from 2011 to 2015 (House Committee on Natural Resources 2018; Sadasivam 2017; 2018), the river has gone dry along the 40-mile reach. In 2015, TCEQ Investigation Report Number 1254241 (TCEQ 2015) presented findings from its hydrogeological investigation and determined that some of the groundwater wells were illegally capturing state waters and that, for future pumping to continue, the well owners needed to obtain the appropriate surface water rights. In May 2018, the Texas House Natural Resources Committee conducted a public hearing in Brady, Texas that included both local and statewide perspectives on issues related to SW-GW interactions. During the hearing, arguments were heard from upstream users that natural climate changes and decreased springflows are reasons for the low surface water flows whereas the downstream users claim that wells drilled close to the rivers are pumping the San Saba dry. Among the factors that could affect future actions is the threat of federal regulation. The San Saba is home to five species of mussels that the U.S. Fish and Wildlife Service (USFWS) is considering listing as endangered. If any one of those mussel species is found to be endangered, it could mean restrictions on water use from the San Saba.

Brazos River

In 2009, surface water rights holders in the Brazos River Basin were subject to the first of several calls from the Dow Chemical Company to exercise its senior priority water right. These water calls sparked a series of water diversion curtailments and associated actions that led the TCEQ to, in response to a petition from affected water right holders, establish a watermaster program to regulate diversion from the Brazos River starting in 2015. Curtailments have heightened awareness that groundwater pumping in the Brazos River Alluvium could be affecting surface water availability. Within Robertson, Brazos, and Burleson counties, the GCDs have issued permits totaling more than 130,000 acre-feet/year, and the TWDB has reported pumping greater than 100,000 acre-feet/year for several years in the Brazos River Alluvium. Recently, the TWDB (Wade et al. 2017) used the Brazos River Alluvium GAM (Ewing and Jigmond 2016) to establish 210,536 acre-feet/year as the minimum modeled available groundwater (MAG) for Groundwater Management Area (GMA) 12 between 2013 and 2070. The concern that groundwater pumping could affect surface water availability can be investigated by evaluating the water budget for the TWDB GAM simulations (Wade et al. 2017) and additional GAM simulations that involved no pumping. The joint analysis of these GAM simulations indicate that nearly all of the groundwater pumped from the Brazos River Alluvium wells originates from the Brazos River.

Colorado River

During the first joint planning cycle, Environmental Stewardship (ES) petitioned GMA 12 (ES 2011) to argue that the desired future conditions (DFCs) did not adequately consider SW-GW relationships and did not include protection for the Colorado River, Brazos River, and associated streams and springs. During the second joint planning cycle, ES (2016) presented results from GAM and WAM simulations to argue that future groundwater pumping would lead to declines in Colorado River flow to impact over 1,100 water rights. ES (2016) stated:

> "Critical environmental flow standards for the Colorado and Brazos rivers are threatened by groundwater pumping and must be considered and mitigated in establishing DFCs for aquifers that impact the Colorado and Brazos rivers and their tributaries."
>
> "There are logical arguments and credible evidence that the groundwater pumping in the proposed DFCs will have an adverse impact on surface water permits making it proper that the impact on surface water rights be considered under Section 36.108(c)(7)."

In finding that the GMA 12's DFCs were reasonable and GMA 12 did not need to account for SW-GW interactions, the TWDB (2012) stated the following:

1. "Senate Bill 3 does not place the responsibilities discussed by Environmental Stewardship on the Districts. Before granting or denying a permit, a district must consider, among other things, whether 'the proposed use of water unreasonably affects existing groundwater and surface water resources or existing permit holders.' But that requirement is part of the permitting process; there is no explicit requirement in the statutes under which this petition was brought for the Districts to consider impacts on spring flow and other interactions between groundwater and surface water."
2. "A number of factors affect instream flow and outflows from the Colorado and Brazos rivers and technical work remains to be done to better monitor, analyzed, and manage that interaction."…"But, the issue at hand is whether the DFCs are reasonable as expressions of the desired future conditions of the aquifers."

An overarching concern expressed by ES (2011) is that GMA 12 did not use the science and technology necessary and appropriate to simulate SW-GW impacts and evaluate groundwater pumping impacts on streamflows. During the second joint planning session, ES (2016) maintained that the DFCs are not protective of the environment and recognized that the currently adopted DFCs are the current legal standard and, as such, should not be significantly changed until the GAM has been improved and better data are available to assess SW-GW interactions. To help correct this situation, ES, the LCRA, the Brazos River Authority, and the GCDs in GMA 12 have worked with the TWDB to update the GAM for the central portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers (Young et al. 2018), which includes improved SW-GW interactions.

The GAM update included several modifications to better represent a shallow groundwater flow system. One of these modifications was to explicitly represent the Colorado River Alluvium and the Brazos River Alluvium as independent hydrostratigraphic entities with thicknesses and hydraulic properties based on hydrogeological studies and with pumping rates based on wells screened across the alluviums. Another modification was to represent aquifers using two model layers instead of a single model layer where they outcrop and receive recharge from rainfall. In addition, the GAM grid spacing in the vicinity of the Colorado River and Brazos River was changed from 1 mile by 1 mile to as small as 0.25 mile by 0.25 mile in order to more accurately represent well locations and the location and bathymetries of the Colorado and Brazos rivers.

Rio Grande at El Paso

While pumping near El Paso has not recently been a concern for regulatory agencies with regard to SW-GW interactions, it has been historically and may likely be in the future. In the first half of the 1900s, estimated pumping from deep wells in the El Paso area increased from about 2,200 acre-feet/year in 1910 to about 31,000 acre-feet/year in 1953 (Knowles and Kennedy 1956). This caused a reversal of flow between the Rio Grande Alluvium and the deeper aquifers. Hutchison (2006) noted that in the El Paso area, groundwater flow was generally toward the alluvium until about 1940, then away from the alluvium after 1960. Hutchison (2006), using the groundwater model developed by Heywood and Yager (2003), showed groundwater pumping in the El Paso area caused a switch from an overall flow of groundwater to surface water of about 3,000 acre-feet/year to 5,000 acre-feet/year before 1925 to an overall flow of surface water to groundwater after 1925. Over the last 20 years, the net losses from the Rio Grande have stabilized at about 33,000 acre-feet/year (Mace et al. 2007). With regard to the reported SW-GW interaction for the Rio Grande at El Paso, it is important to recognize that these fluxes contain biases introduced by the uncertainties associated with using regional models.

Bed and bank permits, environmental flows, endangered species and desired future conditions

Besides surface water rights, other regulatory issues that could be affected by SW-GW interactions are environmental flows, habitat for endangered species, bed and bank permits, and desired future conditions.

Environmental flows

Senate Bill 2 passed into law by the 77th Texas Legislature in 2001 established the TIFP. TIFP is jointly administered by the Texas Parks and Wildlife Department (TPWD), the TCEQ, and the TWDB in collaboration as appropriate with other entities. The goal of the TIFP is to identify flow regimes (quantity and timing of flow) that are adequate to maintain an ecologically sound environment, conserving fish and wildlife resources while also providing sustained benefits for other human uses of water resources. One of the objectives of the instream flow program is to mimic the natural flow regime as closely as possible.

Streamflow requirements (standards) for particular locations in specific stream systems are defined in terms of flow regimes. TWC §11.002.16 defines an environmental flow regime as "quantities that reflect seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies." The development of an instream flow regime includes four components: subsistence flows, baseflows, within-bank high flow pulses, and overbank high pulse flows.

For some streams, SW-GW interactions can become an important process that impacts the quantity and quality of streamflow during subsistence flows or baseflows. Subsistence flows occur during drought or very dry conditions. The primary objective of subsistence flow standards is to maintain tolerable water quality conditions to provide minimal aquatic habitat space for the survival of aquatic organisms. Baseflows represent the range of average or normal flow conditions without the effects of recent rainfall. A primary objective of baseflow standards is to provide adequate habitat for the support of diverse, native aquatic communities and maintain groundwater levels to support riparian vegetation.

Endangered Species Act

The ESA took effect in 1973. Its purpose is to conserve and recover listed endangered species and the ecosystems upon which they depend. SW-GW interactions are potentially important to the ESA in the execution of ESA's Section 9—the taking provision. This section makes it a felony to "take" a threatened or endangered species without specific authorization from the USFWS. The ESA provides for both civil and criminal prosecution for illegal "takes." The U.S. Supreme Court has expanded a "take" to include activities that disrupt the habitat of the threatened or endangered species or interfere with usual feeding and breeding activity. Species in Texas that have protection under the ESA are listed in the Texas Parks and Wildlife Code 68.002 and the Texas Administrative Code. The aquatic animals under ESA protection includes birds, fish, and amphibians. The Texas hornshell mussel is under ESA protection in Texas (Federal Register 2018) and 11 other freshwater mussel species are currently under review by the USFWS for ESA listing (Ingram 2017).

As a result of legal threats of a federal takeover of the Edwards Aquifer under the ESA, the Texas Legislature adopted the Edwards Aquifer Authority (EAA) Act in 1993 (Votteler 1998). The EAA was created to preserve the Edwards Aquifer while protecting threatened and endangered species in the aquifer-fed Comal and San Marcos springs. The creation of the EAA clearly demonstrates that SW-GW interactions can be important to maintaining habitat for endangered species.

The ESA was also a key component of lawsuits involving the deaths of an unknown number of whooping cranes in Aransas Bay during the drought of 2008 and 2009 (USCA 2014; Votteler 2017). Plaintiffs argued that the deaths were indirectly a result of insufficient freshwater flows into Aransas Bay caused by diversion of water, authorized under water rights issued by the TCEQ, from the San Antonio and Guadalupe river basins. An initial court ruling by a Corpus Christi district judge stated that the ESA had been violated by TCEQ's administration of water rights, but a later ruling by the 5th Circuit Court of Appeal in 2014 stated that the TCEQ did not violate the ESA based on the narrow issue of proximate cause. Proximate cause is a legal concept providing that a person should only be held liable for that sequence if the outcome would have been reasonably foreseeable. Despite the 5th Circuit ruling exonerating the TCEQ of violating the ESA, the ruling confirms that ESA considerations need to be properly evaluated as part of water resource planning.

Bed and banks permits

TWC §11.042 and TCEQ Rule §295 allow the bank and bed of any flowing natural stream in Texas to convey water from the place of storage or discharge to the place of use or diversion. This can include wastewater discharges that are derived from a groundwater source where ownership may be maintained. A bed and bank permit requires the applicant to indicate the source, amount, and rates of discharge and diversion (TCEQ 2017). This information is necessary for the agency to calculate conveyance losses that may result from the bed and banks transfer. Per TCEQ §295.114(b)(6) conveyance losses include the loss to transportation, evaporation, seepage, channel, or other associated carriage losses from the point of discharge to the point of diversion. SW-GW interactions are important to conveyance losses where streams lose flow to the adjacent aquifer. Such losses would occur where the stream stage is at a higher elevation than the water table and the amount of conveyance losses would depend on the geometry of the stream channel, the hydraulic gradient away from the stream, the hydraulic properties of the streambed, and the hydraulic properties of the aquifer.

Desired future conditions

House Bill 1763 of the 79th Texas Legislature requires joint planning among GCDs in a GMA to establish DFCs every five years. TWDB rules define DFCs as "[t]he desired, quantified condition of groundwater resources (such as water levels, water quality, spring flows, or volumes) at a specified time or times in the future or in perpetuity…" TWC §36.1008 (2)(d)(4) requires that, as part of the process for setting DFCs, GMAs consider "environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water" among other factors. GMAs have different interpretations of what "consider" means, which have generally been informed by overall management goals. For example, the GCDs in GMA 9 have developed a DFC in the Edwards Group of the Edwards-Trinity (Plateau) Aquifer that "provides maximum, reasonable and achievable protection for springs and baseflow to creeks and rivers (GMA 9 et al. 2016). Other GMAs have chosen DFCs that do not maintain baseflow and springflow.

In GMA 12, GCDs, river authorities, and the Colorado-Lavaca Basin and Bay Area Stakeholder Committee (BBASC) co-funded work on the Central Sparta-Queen City-Carrizo-Wilcox GAM to improve the capability of the GAM to simulate SW-GW interactions. The improved capability is primarily achieved by creating a shallow groundwater flow zone in the aquifer outcrops, through the addition of model layers, which interacts with streams independently of the deeper groundwater flow zone. To help address their concerns with improving the management of the shallow groundwater flow system, the GCDs in GMA 13 have adopted a DFC that limits drawdown in the outcrop of the Carrizo-Wilcox Aquifer (Hutchison 2017).

DEVELOPING BETTER SCIENCE

A number of activities could be accomplished to improve the science—and thus the regulatory tools—for quantifying SW-GW interactions.

Conduct field studies

Lack of field data is perhaps the greatest obstacle to improving the capability of GAMs to simulate SW-GW interactions, as data are required to develop and validate approaches for modeling this interaction. Field studies are lacking because they are relatively expensive and no state programs currently mandate these studies. As part of a TCEQ study concerning SW-GW interactions, Scanlon et al. (2005) recommended that future studies include (1) co-locating groundwater monitoring wells with stream gages, (2) evaluating streamflow gains and losses, (3) evaluating stream channel morphology, (4) conducting aquifer tests near streams, and (5) evaluating the time it takes water to travel between streams and wells.

An important aspect of any field study is that it collects the necessary information to support the development and testing of models that can be used by state agencies, river authorities, private or public utilities, and hydrogeological consultants to simulate SW-GW interactions. Specifically, field studies should be evaluated in light of anticipated statutory issues that could be before the Texas Legislature in future sessions. Such studies should include the measurements of water levels and water quality parameters, the evaluation of stream hydrographs, the quantification of bank storage and bank flow, and the modeling of SW-GW interactions.

Vet approaches for calculating baseflow using hydrograph separation

Because of the wide range of conditions that exists along rivers and the relatively simple algorithms used by most hydrograph-separation techniques to estimate baseflow, there is considerable opportunity in the analysis for introduction of error into the estimate for baseflow. As such, when estimates of baseflow are important to understanding SW-GW interactions, the baseflow estimate should be properly vetted and uncertainties should be identified and quantified. The vetting process should include a thorough discussion and analysis of factors that could affect the application such as return flows, diversions, dam flows, groundwater pumping, and bank storage. This discussion should quantify, to the extent possible, the potential for each of these factors to impact the stream hydrograph and to introduce uncertainty into the calculated baseflow. The analysis should include multiple and even alternative methods for estimating baseflow in order to help account for the uncertainty associated with any one technique and the sensitivity of the calculated baseflow to the actual mechanics used to implement a particular technique.

Update and improve groundwater availability models

GAMs were originally designed to address large regional-scale groundwater issues and provide information to regional water planning groups and for GCD management plans. Since the start of joint planning, there has been increased interest on the part of GCDs and other stakeholders to use GAMs to address groundwater management issues at the local scale. Among the reasons for the expanded interest are that GAMs are generally considered to represent the best available science, and the prolonged periods of low surface water availability in 2009 and 2011 created additional interest in using groundwater as a water supply. The application of GAMs to evaluate the impacts of specific well fields usually requires discretization and additional field data to better represent site conditions. Such modifications increase the costs for developing a GAM and can complicate its use in regional planning.

Given that GAMs are increasingly being used for much more than what the original TWDB GAM program intended, we make two recommendations to improve the GAMs. The first is to evaluate whether the mission of the GAM program should be modified to better address issues associated with SW-GW interactions. The second is to develop more standardization among the GAMs, where appropriate, for representing interactions that occur in aquifer outcrops such as recharge, evapotranspiration, and SW-GW interactions. Along with this standardization comes the case-by-case analysis of which analytical and numerical methods best represent SW-GW interaction and whether these representations can be accurately included in appropriately-scaled GAMs. The better science derived from WAMs and GAMs as well as increased capabilities may result in less contested issues relative to water permitting activities.

Develop science to better define baseflow, bank flow, underflow

Among the key needs for improving the regulation of SW-GW interactions are the science and data necessary to define the terms used to characterize SW-GW interactions. These terms include baseflow, bank flow, and underflow. There are two significant technical problems associated with defining these terms. The first problem is that these three terms define quantifies that are transient and spatially variable. The second problem is the lack of science to demonstrate how to appropriately accommodate temporal and spatial variability into the measurement of each term. Because of these two technical problems, regulatory agencies called upon to mitigate disputes involving SW-GW interactions may not have, or in most cases do not have, sufficient information to make appropriate regulatory distinctions and determinations.

With respect to developing a science program to better characterize SW-GW interactions, there are two important considerations. One consideration is that the environmental conditions, which include geology, hydrogeology, and meteorology, have a significant impact of SW-GW interactions. As a result, there is no need to study every stream because streams with similar environmental conditions should have similar type of SW-GW interactions. A second consideration is that because SW-GW interactions are not equally important across Texas, a science program should prioritize the critical areas for study based in part on their environmental conditions.

CONCLUSIONS

SW-GW interactions can be important for managing water rights along a river, complying with the ESA, implementing environmental flow recommendations, and obtaining bed and banks permits. A key issue to these regulatory and management concerns is how to quantify the exchange of water between streams and aquifers and to what extent does groundwater pumping impact this exchange and the availability of surface water. Currently, Texas does not possess a sufficient understanding of SW-GW interactions to readily address these concerns at the granularity necessary to facilitate permitting determinations.

The uncertainties associated with quantifying SW-GW interactions have contributed to disputes regarding actual ownership and rights to water. Locations where these disputes have recently occurred or are occurring include the Rio Grande, the San Saba River, the Colorado River, and the Brazos River. To help effectively integrate, regulate, and manage surface water and groundwater resources in Texas, recommendations include conducting field studies focused on quantifying SW-GW interactions, performing additional vetting and ground truthing on hydrograph-separation techniques, improving the capability of GAMs to simulate SW-GW interactions, and developing the science and tools necessary to define and quantify underflow, bank flow, and baseflow.

Communication and cooperation among river authorities, GCDs, the TCEQ and TWDB must also be improved. Such cooperative efforts recently occurred while updating the GMA 12 Carrizo-Wilcox GAM, for which appreciable funding was contributed by the LCRA and Brazos River Authority and by the Post Oak Savannah GCD and Brazos Valley GCD to specifically address SW-GW interactions in the GAM. This jointly funded project clearly shows that proper modeling of SW-GW interactions is a concern and an interest for both river authorities and GCDs.

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