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Cover photo: Tres Palacios River at FM 1468 near Clemville, Texas. ©2019 Ed Rhodes, TWRI.

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Policy Review: State Legislature, Voters Move to Eighty-Six Texas's Flooding Challenges

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Abstract: Even before the 86th Texas Legislature began, it was clear the session would feature a deluge of activity focused on addressing Texans' experience with flooding. Elected representatives from across the state floated solutions for Hurricane Harvey and long-term issues alike, featuring a mix of both recovery projects and future planning efforts. Much attention has been paid to Senate Bill 7 and Senate Bill 8, which create major new statewide programs. Significant questions remain regarding the implementation of these bills. We wade into these uncertainties and the larger trends behind the legislative session. In all, 128 introduced bills specifically mentioned "flooding" or "flood," far exceeding anything from the previous 10 sessions. Even more, 240 total introduced bills addressed issues with a clear connection to flooding. Of these, 67 (28%) went on to become legislation. As new laws go into effect, implementation ramps up, and funds trickle out, strong, sustained stakeholder engagement and communication will be key to making sure these programs hold water.

Keywords: flood, planning, infrastructure, recovery, resiliency

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Terms used in paper

Acronym	Descriptive term
FEMA	Federal Emergency Management Agency
GLO	General Land Office
HB	House Bill
HCFCD	Harris County Flood Control District
HJR	House Joint Resolution
HUC	Hydrologic Unit Code
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
SB	Senate Bill
SJR	Senate Joint Resolution
SWIFT	State Water Implementation Fund for Texas
TCEQ	Texas Commission on Environmental Quality
TDEM	Texas Division of Emergency Management
TSSWCB	Texas State Soil and Water Conservation Board
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
VFD	Volunteer Fire Department

LEGISLATURE OVERVIEW

Hurricane Harvey was a powerful and effective catalyst, but the pressure to address Texas's unfortunate struggles with flooding had been growing for some time. Texas leads the nation in declared flooding disasters (FEMA 2019). Peak flows in a number of the state's rivers and streams have been trending upward (Berg 2018). NOAA released its analysis indicating increased estimates of heavier downpours across a wide swath of the state (Perica et al. 2018) (Figure 1). With clear interim charges added to the mix (Patrick 2017a; Patrick 2017b; Straus 2017), it was a perfect storm of legislative motivation. As momentum built toward the convening of the 86th Texas Legislature, the only question was where it would all lead.

It did not take long to start finding out. Several bills had been pre-filed by the end of November 12, the very first day legislators could file, and a steady stream continued to flow well into the session itself. Meanwhile, in a poetic twist, the 6 months leading up to the session were the wettest July-December period ever recorded in Texas (NOAA 1895–). This soggy reminder had an effect. Introduced bills with the words "flood" or "flooding" (128 bills) set a new high-water mark for a single legislative session and significantly overtopped those addressing "drought" (28 bills) considerations (TLO 2019) (Figure 2).

Taking a broader view, the number of bills with a substantive, material connection to flooding was far larger. By the filing deadline, a raft of 240 flood-related bills had been introduced. These came from districts all across the state, with a clear concentration in a band running from the Beaumont-Port Arthur area through the southern Hill Country (Figure 3). In terms of primary authorship, the greatest numbers of such bills were introduced by Senator Lois Kolkhorst and Senator Carol Alvarado in the Senate and Representative Armando Walle and Representative Ed Thompson in the House of Representatives. If the frequency of discussion indicates the importance of a topic, flooding was very much a focus of the 86th legislative session.

This was not a surprise. As expected, many introduced bills focused on adjusting ad valorem taxation in the wake of natural disasters. There was also significant competition among bills regarding the communication of flood risk in property transactions. What was breathtaking, however, was the staggering scope of additional issues touched on by flood legislation. Wading into the bills reveals so much more (Appendix A). This does not even include those bills, such as House Bill (HB) 3167 (Oliverson), that impact the ability of local political subdivisions to plan for and respond to the threats posed by flooding. Yet more bills were slightly less connected with

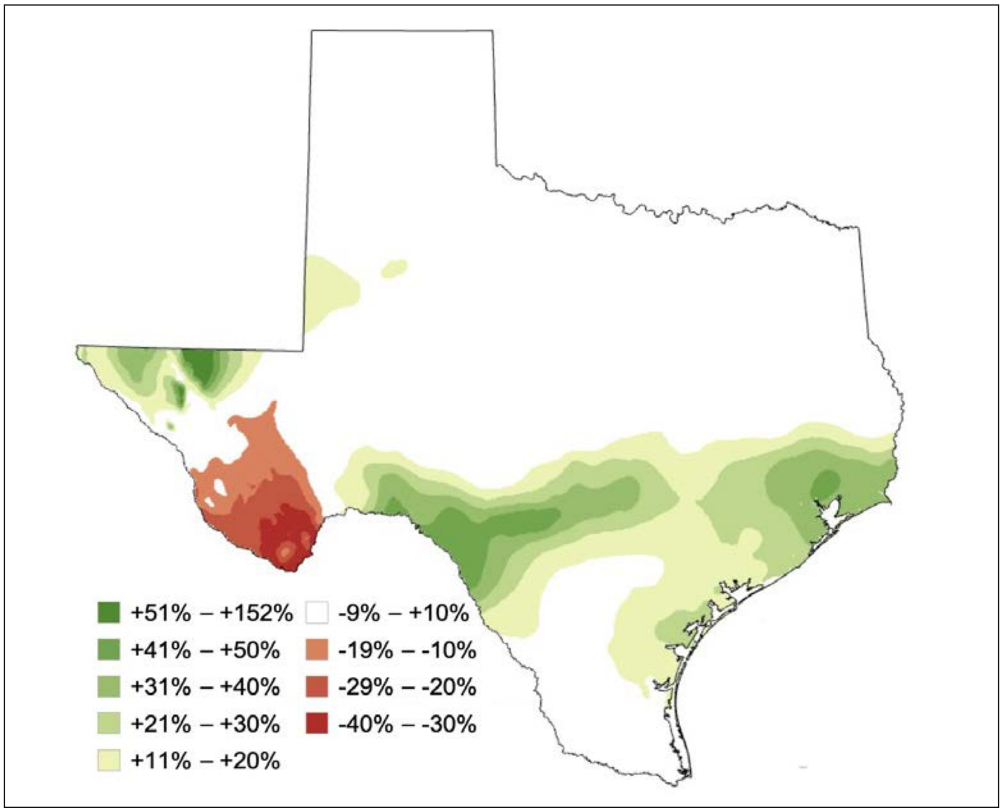

Figure 1. Extending from southeast Texas along the Louisiana border to just east of the Big Bend region and also including the northern portion of the Trans-Pecos, a swath of Texas registered significant increases in the so-called 100-year (1% annual chance) storm since the last time these estimates were calculated. The map indicates percent differences in 100-year, 24-hour rainfall depths between Weather Bureau Technical Paper No. 40 (Hershfield 1961) and NOAA Atlas 14 (Perica et al. 2018). Adapted from NOAA Atlas 14 with permission from authors.

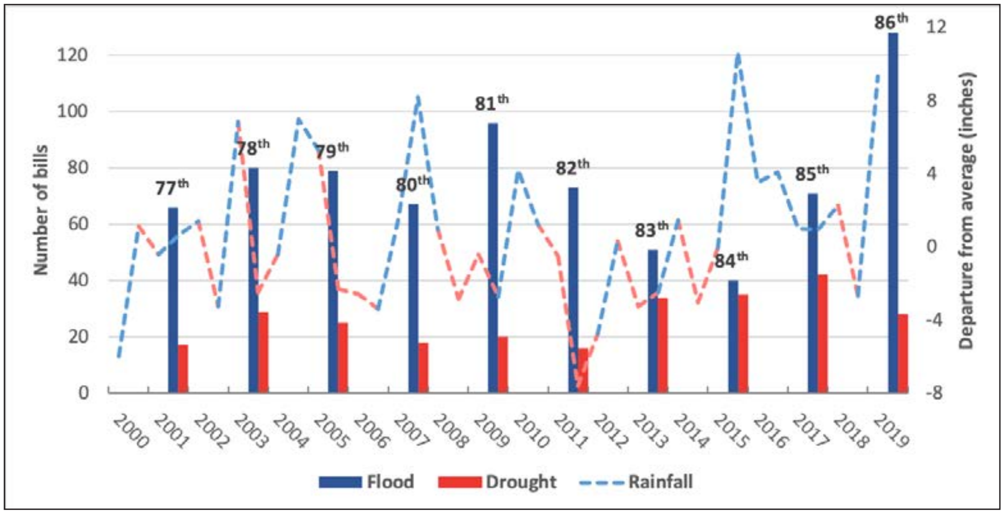

Figure 2. Frequency of bills introduced in Texas Legislature specifically addressing "drought" (red bars) and "flooding" (blue bars) in relation to statewide precipitation trends. Light red dashed lines signify a six-month period ending with below average statewide precipitation. Light blue dashed lines signify a six-month period ending with above average statewide precipitation. Extremely wet periods often translate to flood-related bills in the following session, but nothing comes close to the 86th Legislature in terms of bill volume.

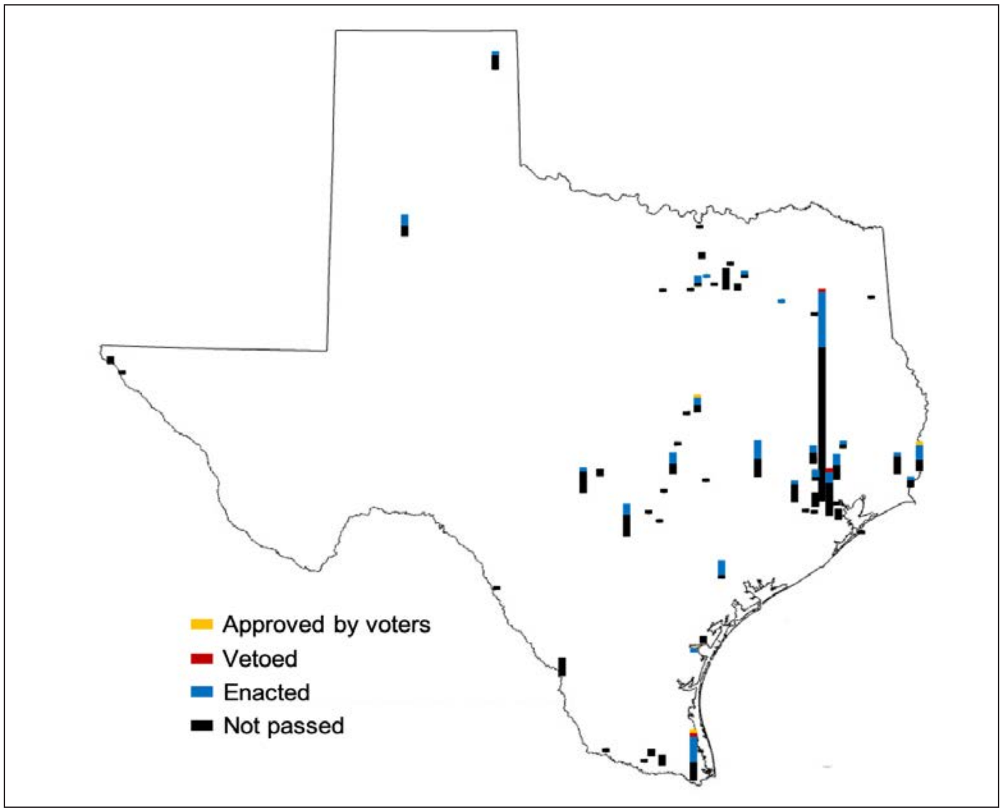

Figure 3. Map of flood bills and their respective fates by the primary district office location of the bill's primary author. Bills with a substantive, material connection to flooding were introduced by elected representatives from across the state. However, far and away the greatest numbers were introduced by representatives from southeast Texas near the Louisiana border, through the Houston metropolitan area and to the southern Hill Country.

flooding concerns but still tangentially relevant. Clearly rising waters had permeated essentially every aspect of Texans' lives.

Perhaps just as fascinating as the bills enacted are the contents of those that did not make it that far. A whopping 167 flood-related bills (70%) were introduced but did not progress to the Governor's desk. This list was heavily populated by competing versions of related bills that failed to become the preferred legislation. Other dead bills include the potential use of U.S. Postal Services workers during natural disasters, an examination of the flooding impacts of border wall construction, the development of a list of voluntary best practices for aggregate production operations, and the location of solid waste facilities in relation to floodplains, among many, many more.

There were also several bills prescribing studies and authorizing commissions to address changing weather patterns and climate issues. None passed. Interestingly, the overwhelming majority (71%) of all flood-related bills were from legislators with district offices within areas identified by NOAA's Atlas 14 as having experienced significant increases in 100-year rainfall depths (Figure 4).

A handful of additional bills were passed by the legislative branch but received Governor Abbott's veto. HB 2112 (Ed Thompson) addressed the salvage of flood-damaged vehicles but was disapproved in favor of procedures laid out in HB 2310 (Vo) (Abbott 2019c). Senate Bill (SB) 1575 (Alvarado) addressed municipal immunity for pass-through administration of state and federal disaster recovery funds. Governor Abbott determined this legislation to be too protective and vague (Abbott 2019b). HB 1059 (Lucio III) prescribed a biennial report on green stormwater infrastructure through the Texas Commission on Environmental Quality (TCEQ). This bill was declared redundant and unnecessary, and it was suggested that a combination of current efforts by local governments and higher education institutions is sufficient (Abbott 2019a).

The fate of three additional legislative proposals was settled later in the year. House Joint Resolution (HJR) 4 (Phelan), HJR 34 (Shine), and Senate Joint Resolution (SJR) 79 (Lucio) accompanied additional bills already passed by the Legislature and received overwhelming approval as constitutional amendments by Texas voters in the November 5 general election. HJR 4 (Proposition 8) proposed the creation of a dedicated Flood Infrastructure Fund to finance drainage, flood mitigation, and flood control projects. HJR 34 (Proposition 3) proposed a temporary partial exemption from ad valorem taxation of

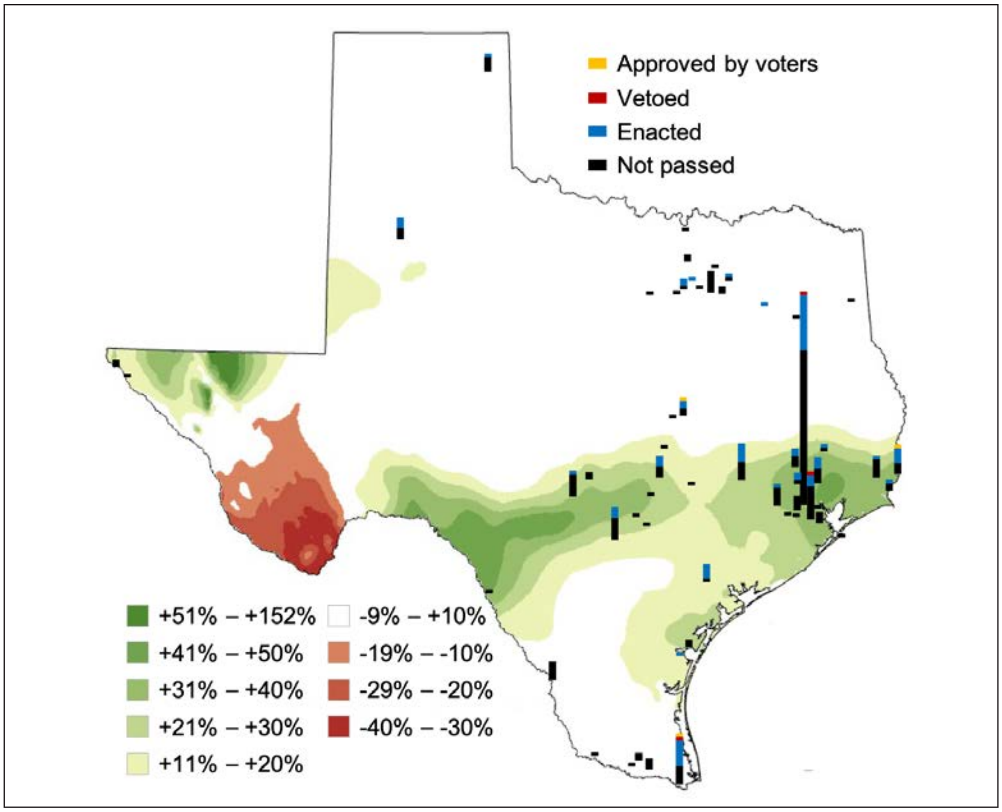

Figure 4. Map of introduced bills and their respective fate in relation to precipitation changes identified in NOAA Atlas 14 (Perica et al. 2018), a combination of Figures 1 and 3. The vast majority (71%) of flood-related bills were introduced by representatives whose districts experienced significant increases in 100-year (1% annual chance) rainfall depths. Legislative initiatives appear to reflect changing precipitation conditions.

disaster-damaged property. SJR 79 (Proposition 2) proposed the issuance of bonds by the Texas Water Development Board (TWDB) to fund projects in economically distressed areas, though this was amended by legislators from its introduced form to exclude drainage projects.

Some 67 bills related—as filed—to flooding (28%) did successfully navigate the legislative process to become law, with the greatest number authored by Senator Kolkhorst and Senator Lucio in the Senate and Representative Morrison and Representative Phelan in the House. At least one more of these, SB 2452 (Lucio), which enabled SJR 79, initially included fund eligibility for drainage projects but was pared down over the course of the legislative process. As with the number of bills introduced overall, the scope of passed bills is incredibly extensive. Bill language was awash in acronyms of almost every state agency. A brief summary of passed legislation is found in Appendices B and C.

While all of these will bring changes to the lives of Texans, a handful of bills have received outsized attention. SB 7 (Creighton), in conjunction with HJR 4, and SB 8 (Perry) continue to dominate flood conversations in the state and were the focus of statewide stakeholder meetings in 2019. They are also the bills with perhaps the greatest amount of uncertainty. Yet significant work is underway to clear up the unknown.

SMALL BILL NUMBERS, HUGE EXPECTATIONS

As has been made very clear by essentially all stakeholders and outlined in the State Flood Assessment (TWDB 2019b), significant funding is the biggest need in order to mitigate flooding and manage floodplains across the state. SB 7 and SB 8 in particular make meaningful progress toward meeting that need by establishing a process to identify projects and target resources.

The applause accompanying the passage of SB 7 and HJR 4 in the legislative chambers reflects the hope both legislators and private citizens place in these bills. Discussion on the floor featured abundant reflection on Hurricane Harvey and personal war stories of flooding. These bills work hand in hand with SB 8 and the supplemental appropriations bill SB 500 (Nelson) and seek to accelerate recovery from the most recent storms while aiming to build a foundation of resilience to future events.

Senate Bill 7

SB 7 provides a significant retooling of flood projects and disaster recovery for Texas. And since doing anything costs money, the legislation importantly establishes the Flood Infrastructure Fund to finance all phases of flood and drainage projects in the form of grants and low-cost loans. Through an appropriation from the Economic Stabilization Fund, SB 500 assigns $793 million for this purpose. These funds will be directed to political subdivisions (counties, municipalities, river authorities, and other special districts). It is hoped that this mechanism will help communities overcome the cost hurdles and lengthy timelines associated with large infrastructure projects.

The adoption of the first state flood plan looms as a major milestone for the Flood Infrastructure Fund. Before that time, this fund will be used to finance flood projects that are developed through a cooperative planning process (TWDB 2019a). After regional flood plans are compiled into a state flood plan in 2024, the Flood Infrastructure Fund must be used exclusively for projects featured in the state flood plan. With 78% of more than 1.5 million Texas voters supporting Proposition 8, the Flood Infrastructure Fund is officially created outside the general revenue fund and will be carried forward in future budget cycles.

In addition to the statewide referendum, SB 7 also establishes the $857 million Texas Infrastructure Resiliency Fund through an appropriation from the Economic Stabilization Fund. A major goal of the Texas Infrastructure Resiliency Fund is to provide the Texas Division of Emergency Management (TDEM) with matching local funds ($638 million) to leverage the multitude of different federal funds in ongoing recovery from Hurricane Harvey. An additional $47 million will be directed toward data collection and analysis, including the updating of flood hazard information across the state, development of the state flood plan, and public outreach efforts. In sum, the "rainy day fund" is finally allowed to live up to its nickname. The bill also lays out agency requirements for reporting use of federal funds and for transparency in flood project progress.

The rollout of SB 7 was very much in progress even before the Flood Infrastructure Fund was approved by voters. It was clear that a number of issues would require a great deal of deliberation, from the broad (the pathway that funds take, whether match for federal programs, complement to federal buyout programs, or implementing local projects that lack funding) to the specific (criteria for project prioritization). One of the key questions was the precise mix of grants and low-interest loans to be disbursed from the Flood Infrastructure Fund, which would affect the number of applicants who receive funding. The prioritization of repairing and rehabilitating existing infrastructure versus implementing new projects and activities also was a big question mark. Answers to all these have been provided for the first year of the program, but significant evolution is expected over the long term. Importantly, TWDB determined that establishing program guidelines through an annual Intended Use Plan rather than codifying them in rule preserves the flexibility to adjust based on experience as the program matures (TWDB 2019c).

Portions of the Texas Infrastructure Resiliency Fund will require significant coordination with TDEM, but TWDB will administer both this fund and the Flood Infrastructure Fund. This charge represents a major expansion in responsibility for the agency. And that is nowhere near the end of new assignments for TWDB.

Senate Bill 8

While SB 7 mobilizes new resources for flood projects, SB 8 builds a long-term framework to identify these projects and guide their development through a stakeholder-driven process. This bill drives toward what many optimistically hoped would be delivered by what ultimately became the State Flood Assessment: a comprehensive statewide plan to protect life and property from flooding.

What the State Flood Assessment did make clear, however, is that Texans strongly prefer that flood planning be conducted at a watershed scale to improve efficiency and capitalize on solutions that offer multiple benefits (TWDB 2019f). The new regional flood planning process will follow this approach, with 11 planning regions organized by river basin.

Within each planning group, stakeholders representing different unique local interests will hold public meetings and cooperatively develop regional plans to be completed by January 10, 2023. These evaluations of existing infrastructure and rankings of flood projects will be compiled into the first state flood plan no later than September 1, 2024 and every 5 years thereafter.

The regional and state plans will go through an approval process with TWDB, which will also provide ongoing facilitation, updated mapping, and data collection assistance. Thankfully, this major new program is right in TWDB's wheelhouse. The agency is already quite familiar with the state and regional water planning model from which it can draw inspiration. A major part of new flood work will lead to the development of new models and other technical tools. The completed plan will also feature an analysis of development in FEMA-defined "100-year" floodplains and recommendations on state policy changes to facilitate ongoing planning and implementation.

While the flood planning process has received most of the attention, SB 8 also delivers an important provision for improving the integrity of dams in Texas, some of which are nearing

80 years of age. The Texas State Soil and Water Conservation Board (TSSWCB) will be required to develop a plan for the flood control dams constructed through federal programs that the state agency now oversees. SB 500 provides $150 million to implement the resulting repair, rehabilitation, and maintenance plan, which will be updated every 10 years. TSSWCB will also provide annual updates to TWDB and work with TCEQ to identify the needs of certain non-federal dams.

As with SB 7, the rulemaking process provided significant clarification, but a great deal of detail remains to be worked out regarding SB 8 implementation. Legislation required TWDB to finalize flood planning regions before September 1, 2021, but this will happen much sooner. The initial candidates for regional alignment differed only with respect to the division of basins in the Panhandle, the partition of the Guadalupe and San Antonio rivers, and the affiliation of the Lavaca River Basin. Coastal basins are tricky! The preferred approach resulted in Brazos-San Bernard, Canadian-Red, Colorado-Lavaca, Guadalupe, Neches, Nueces, Rio Grande, Sabine, San Antonio, San Jacinto, and Trinity flood planning regions (TWDB 2019d). Neighboring regions along the Gulf coast are also encouraged to coordinate with one another (TWDB 2019e). With group finalization, adequate representation and the precise mix of regional interests and ex-officio agency representatives will be key.

Additional questions revolved around both the spatial and temporal scale of flood planning. Rules limit planning regions to considering flood strategies and projects with a drainage area of at least 1 square mile. Where portions of larger basins are worthy of special focus, groups may assign subgroups to look at watersheds at the Hydrological Unit Code (HUC)-8 level. These subgroups will also require the same stakeholder representation as the full group (TWDB 2019e). It will be interesting to see where local stormwater and drainage issues fit in. Regional water planning currently uses a 50-year time horizon. Regional flood plans will adopt a 30-year planning period and use associated development and population scenarios. They will also identify 10-year goals. These shorter timespans may provide the agility to incorporate further anticipated changes like those demonstrated in NOAA Atlas 14 (Perica et al. 2018) and data on changing sea levels, which groups are required to consider (TWDB 2019e).

Given the built-in flexibility and learning curve for SB 7 and SB 8 rules, public input will be a key feature throughout the process. In the mold of its development of the State Flood Assessment, TWDB wrapped up an ambitious series of statewide stakeholder workshops and a public feedback period in summer 2019. Additional public comments were invited as part of the required formal rulemaking procedures. This will be a long-term process, and there will be a great need for ongoing public participation in the regional planning process as groups are formed and begin work (TWDB 2019a).

UNCHARTED WATERS

Differences with Existing State Programs

A number of comparisons have been drawn between these new bills and both the regional water planning process and the State Water Implementation Fund for Texas (SWIFT). Indeed, flood planning guidance principles are similar to the guidance for regional and state water planning (TWDB 2019b). There are certainly similarities, but there are also key differences.

Unlike SWIFT, one unique aspect of the Flood Infrastructure Fund is the provision for grants that do not require repayment over time. Initial scenarios, such as a 75% grant/25% loan or 25% grant/75% loan breakdown, involve major tradeoffs in terms of debt burden versus how far funds can be stretched. Depending on the approach taken and the interest rate of loans, anywhere from $198 million to $731 million would be available over 20 years. For the 2020 Intended Use Plan, TWDB proposed several project categories with different financing breakdowns. Broadly, these represent a mix of grants (most requiring local match) ranging from 50 to 100%, with 0% interest loans available in all categories (TWDB 2019c).

The dynamics of the fund depend heavily on what criteria are applied to potential recipients. Prioritizing community financial need versus basing benefit-cost analyses on property values can yield very different results that often point in opposite directions. Additionally, roughly 47% of Texans reside in municipalities with a population over 100,000. Considering cities over 50,000, this rises to 54%. While these are much larger numbers than previous decades, this still means almost half of all Texans live in smaller political subdivisions that tend to lack the capacity to repay loans for expensive infrastructure projects and that also generally lack the dedicated staff to identify, plan, and coordinate the implementation of such projects. Such questions of how to address financial means promises to be a hot button issue in project selection. The statewide need is so vast, and the number of fault lines across flood history and socioeconomic factors is not small. For 2020, proposed categories are highly responsive to these questions, with highest grant percentages and highest prioritization going to areas outside a Metropolitan Statistical Area and those with annual median household income less than the statewide average (TWDB 2019c). In fact, consideration of Social Vulnerability Index scores is required. Other prioritization criteria include watershed planning and mapping updates, projects immediately protecting life and property, emergency need due to recent or imminent failure, regional benefit, completion date, existence of water supply benefit, and removal of structures from the floodplain. Project cost will be used as a tiebreaker, with preference going to the lower cost.

Once the application period opens, one of the big questions to watch will be the appetite for loans compared to grants. A loan with an interest rate of 0% will be difficult to beat. For future cycles, interest rates likely will come more into play. Some outside sources of financial assistance also offer low-interest loans, and political subdivisions may look elsewhere. Even if grants are the preferred path forward in 2020, will applicants be able to provide the 25-50% local matching funds required for most project categories? Critically, unlike financial assistance for water projects, most entities do not have a dedicated mechanism for recovering the cost of flood project loans. Water utility rates can foot the bill for funds through SWIFT, but that structure is generally not in place for funding flood projects outside of a relatively small number of special districts with taxing authority and those municipalities that have enacted a drainage charge. Where a cost recovery mechanism does exist, will those entities use funds directly for projects rather than pursuing loans? The regional planning process requires an examination of potential funding mechanisms for not just project development but also for operation and maintenance costs (TWDB 2019e). Expect serious discussion on the establishment of local revenue streams.

Another major contrast between water planning and flood planning is what some perceive as the overall objective itself: getting water versus getting rid of water. It appears that legislators have noticed the tensions that can arise between regions in the water planning process. SB 8 outlines requirements that no regional plan "negatively affects a neighboring area" (2019). Using a watershed approach and thanks to gravity, this is far less likely to occur between regions in the flood planning process. Unlike in water planning, the strongest tensions will likely arise within regions but between upstream and downstream interests. There are indications that this is already developing in some river basins. Rules reflect this reality by defining neighboring areas to include upstream and downstream portions of a given basin (TWDB 2019e). The preference between detention and conveyance is frequently tied to one's location in a watershed, and these preferences are strong. Planning flood projects without negative impacts on upstream or downstream areas will be a fine line to walk.

Given this potential reverse tug-of-war, it will also be interesting to watch what water planning-flood planning nexus develops. Water is water. "Too much" can quickly become "not enough," and flood waters pushed downstream may be less available to meet water supply needs.

The proposed list of representative flood planning stakeholders is a mirror image of that used in regional water planning, though stakeholder workshops did reveal a healthy appetite for including land trust and academic representation as well (TWDB 2019b). Like water planning, legislation for flood planning groups requires representation of the public interest. While some water supply projects can indeed skyrocket to become hot button issues, the majority of water planning concerns are likely keyed into much longer time horizons among the public. Water supply issues tend to take longer to express themselves. In contrast, devastating flood impacts can unfold in a matter of a few hours in a single afternoon.

When even one community is flooded, that can generate energy in a hurry, and that energy surely can endure. More than 2 years after the landfall of Hurricane Harvey, flood-related public meetings continue to experience capacity crowds in many locations. As a result, the communication process in the implementation of SB 8 will be critical. Ensuring all stakeholders feel genuinely heard and included will require an expert touch, with consistent response strategies after every future flood event. Whittling massive public interest down to a single representative will also be a real challenge. Expect a great deal of demand for additional planning group spots representing the public interest, and for some groups to expand membership further to include additional interests.

Amidst this complex dynamic, the role of thorough technical analysis will be paramount. The sense of urgency and hunger for visible action after a disaster are powerful. Yet in the wake of Hurricane Harvey, certain proposed solutions did not address the actual cause of flooding, and some ideas, if implemented, may actually cause an increase in flood risk.

Preliminary flood planning guidelines require that flood projects be based on the "best available" science and data (TWDB 2019a, TWDB 2019c). Maintaining this foundation, with consistent updates on an ongoing basis, should ensure strategies move in the right direction. Yet given the frequent need for adequate study to bump against the public desire for immediate project implementation, this evidence-based approach can involve a degree of tension. Clearly, navigating this process will demand superior communication, facilitation, and mediation prowess across every dimension.

A Rising Tide of Conservation Projects?

In floor discussion of the first amendment to SB 7, Senator Brandon Creighton acknowledged the work of his district's Bayou Land Conservancy in crafting a key component of the bill's language. A number of conservation organizations worked to amend language to include "nonstructural projects, including projects that use nature-based features to protect, mitigate, or reduce flood risk" (2019). TWDB stakeholder meeting materials reflect this mandate, and preliminary guidance principles included this suite of approaches prominently (TWDB 2019b). In fact, non-scientific audience polling at public meetings also indicated a strong preference for floodplain preservation and other nature-based solutions among all flood mitigation strategies.

Some intriguing possibilities revolve around such nature-based approaches. SWIFT legislation included sizable program targets for funding of water conservation and rural water projects (Jackson and Walker 2017). TWDB even prescribes water conservation as a tiebreaker in scoring water project applications (TWDB 2019g). SB 7 already makes specific provisions for the Flood Infrastructure Fund to support projects that "serve an area outside of a metropolitan statistical area" (2019). That means SWIFT and the Flood Infrastructure Fund differ in one last key aspect: targets for conservation. It would make sense that the water conservation programs emphasized in water planning be paralleled by a similar focus on a different kind of conservation in flood planning: land conservation. More than that, since TWDB also made the acquisition of land conservation agreements an eligible use of Clean Water State Revolving Fund resources, nature-based land conservation projects stand poised to be among the powerful few strategies that actually achieve the oft-emphasized goal of providing both flood mitigation and water supply benefits.

Nature-based, nonstructural approaches tend to be less expensive than structural approaches to implement and feature lower operation and maintenance costs over time (Dart 2019; Lightbody and Miller 2019). Furthermore, the performance of traditional infrastructure generally degrades over time, while natural strategies, particularly those with a restoration component, typically improve with project maturation. Additionally, land conservation approaches are far cheaper than acquisition (buyouts) after flooding of developed land has already occurred. Such projects also avoid the lengthy process of FEMA-supported buyouts that keeps flood survivors in limbo and sidestep the associated loss of life and property.

Among a multitude of conservation organizations across the state, there is no shortage of already-identified land conservation projects that could make a major dent in flood risk. The opportunity is even bigger. The U.S. Army Corps of Engineers (USACE) Engineering With Nature program acknowledges "nature offers us so many solutions to minimize flood risk" (Kuzmitski 2019). Including nature-based approaches as key elements of every flood project, as promoted by the Engineering With Nature initiative, seems a critical strategy.

Defining Success and Future Challenges

Regardless of the emphasis chosen by different regional groups, big conversations will revolve around how flood plan success is even defined. What is the appropriate standard (TWDB 2019b)? Water planning is based on a hypothetical repeat of the "drought of record," a historically severe dry period during the 1950s (TWDB 2017). However, investigation of long-lived Texas trees indicates this approach severely underestimates what the region has endured in previous centuries (Cleaveland et al. 2011).

A similar challenge exists with flooding. Despite the scarce probability of Hurricane Harvey's torrential rains, streamflows generated by even this storm were far less severe than would be expected in many watersheds (Watson et al. 2018). How, therefore, should regional groups think about managing risk to life and property? A much-needed change in terminology from the "100-year flood" to "1.0% annual chance flood" may help facilitate a better public understanding of flood risk (TWDB 2019e). Significant discussion will revolve around whether a historical benchmark or some stricter probabilistic measure is a better fit.

Over $1.6 billion was assigned to new flood mitigation initiatives by the 86th Legislature. An additional $200 million was allocated to the General Land Office (GLO) to support dredging and USACE studies. This is indeed a substantial withdrawal from the Economic Stabilization Fund. Yet even the State Flood Assessment acknowledged that a 10-year, $31.5 billion need means that communities face a shortfall of $18 billion to $26.6 billion in financial assistance, and these estimates do not even take into account projects associated with Hurricane Harvey (and Tropical Storm Imelda) recovery or certain major projects across the state (TWDB 2019f). Flood legislation passed in 2019 is an important first step, but the gap between appropriated funds and remaining needs is huge. Tremendous interest and pressure will be focused on future legislative sessions to maximize the productivity of these funds and follow through with significant additional resources. In addition to funds, will something more be required of Texans in the form of shifts in expectations and living with water? Through the flood planning process, what necessary changes to current floodplain management, land use regulations, and economic development practices will be recommended?

CONCLUSIONS

As implementation ramps up for all flood legislation, be prepared for an iterative process with plenty of learning opportunities. This is particularly true for SB 7 and SB 8. No other state has yet chosen to dive into flood risk management with such a systematic approach—one that simultaneously funds flood hazard identification, watershed-based planning, and mitigation projects. Even the current state water planning process has only been in place since 1997. SWIFT has been in action far shorter. SB 7 and SB 8 are each significantly shorter than the enabling legislation for both state water planning and SWIFT and leave much to be fleshed out. Lessons learned through these efforts will absolutely help smooth the road for flood planning, but it is fully expected that there will be some kinks to work through.

As with any massive and ambitious effort, the success of these new programs will depend on sustained stakeholder engagement at every single step in the process. Early signs suggest the beginnings of a move in the right direction. Yet from the initial stakeholder meetings all the way through the prioritization of funds and long-term activity within regional flood planning groups to future legislative action, the decision of whether the 86th Legislature becomes a watershed moment or is seen as yet another drop in the bucket ultimately rests with the people of Texas.

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REFERENCES

Abbott G. 2019a Jun 15. Governor Abbott vetoes HB 1059. Office of the Texas Governor. Available from: https://gov.texas.gov/news/post/governor-abbott-vetoes-hb-1059.

Abbott G. 2019b Jun 15. Governor Abbott vetoes SB 1575. Office of the Texas Governor. Available from: https://gov.texas.gov/news/post/governor-abbott-vetoes-sb-1575.

Abbott G. 2019c Jun 15. Governor Abbott vetoes HB 2112. Office of the Texas Governor. Available from: https://gov.texas.gov/news/post/governor-abbott-vetoes-hb-2112.

Berg M. 2018. Peak flow trends highlight emerging urban flooding hotspots in Texas. Texas Water Journal. 9(9). Available from: https://twj.media/peak-flow-flooding-texas/.

Cleaveland M, Votteler T, Stahle D, Casteel R, Banner J. 2011. Extended chronology of drought in south central, southeastern, and west Texas. Texas Water Journal. 2(1). Available from https://journals.tdl.org/twj/index.php/twj/article/view/2049.

Dart T. 2019 Jun 4. Will "gray" or "green" flood infrastructure protect Houston? CityLab. Available from: https://www.citylab.com/environment/2019/06/hurricane-season-texas-houston-storm-flood-resilience-funds/588868/.

[FEMA] Federal Emergency Management Agency. 2019. Data visualization: Disaster declarations for states and counties. Available from: https://www.fema.gov/data-visualization-disaster-declarations-states-and-counties.

Hershfield D. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Washington (District of Columbia): U.S. Weather Bureau. 65 p. Technical Paper No. 40. Available from: http://www.nws.noaa.gov/oh/hdsc/Technical_papers/TP40.pdf.

Jackson K, Walker J. 2017 Dec 20. Ready, set, SWIFT: Time for water utilities to save. The Texas Tribune: TribTalk. Available from: https://www.tribtalk.org/2017/12/20/ready-set-swift-time-for-water-utilities-to-save/.

Kuzmitski H. 2019 Jan 24. Engineering With Nature book launch is a resounding success. U.S. Army Corps of Engineers. Available from: https://www.usace.army.mil/Media/News-Archive/Story-Article-View/Article/1750150/engineering-with-nature-book-launch-is-a-resounding-success/.

Lightbody L, Miller Y. 2019 Jun 14. Flood readiness get bigger in Texas. The Pew Charitable Trusts. Available from: https://www.pewtrusts.org/en/research-and-analysis/articles/2019/06/14/flood-readiness-gets-bigger-in-texas.

[NOAA] Climate at a glance: Statewide mapping. 1895– . Washington (District of Columbia): National Oceanic and Atmospheric Administration National Centers for Environmental Information. [accessed 2019]. Available from: https://www.ncdc.noaa.gov/cag/statewide/mapping/110/pcp/201812/6/rank.

Patrick D. 2017a. 2017 Interim legislative charges. Austin (Texas): Texas Senate. Available from: https://senate.texas.gov/_assets/pdf/Senate_Interim_Charges_85_pt1.pdf.

Patrick D. 2017b. 2017 Interim legislative charges: 2. Austin (Texas): Texas Senate. Available from: https://senate.texas.gov/_assets/pdf/Senate_Interim_Charges_85_pt2.pdf.

Perica S, Pavlovic S, St. Laurent M, Trypaluk C, Unruh D, Wilhite O. 2018. NOAA Atlas 14: Precipitation-frequency atlas of the United States. Volume 11 Version 2.0: Texas. Washington (District of Columbia): National Atmospheric and Oceanic Administration. 283 p. Available from: https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume11.pdf.

S.B. 7, 86th Legislature, 86th session (Texas 2019). Available from: https://capitol.texas.gov/BillLookup/History.aspx?LegSess=86R&Bill=SB7.

S.B. 8, 86th Legislature, 86th session (Texas 2019). Available from: https://capitol.texas.gov/BillLookup/History.aspx?LegSess=86R&Bill=SB8.

Straus J. 2017. Interim committee charges. Austin (Texas): Texas House of Representatives. Available from: https://house.texas.gov/_media/pdf/interim-charges-85th.pdf.

[TLO] Texas Legislature Online. 2019. Text search. Available from: https://capitol.texas.gov/Search/TextSearch.aspx.

[TWDB] Texas Water Development Board. 2019a. Frequently asked questions: Flood legislation from the 86th Texas Legislative Session. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/home/tabs/doc/FAQ_Flood-Implementation-Fund.pdf.

[TWDB] Texas Water Development Board. 2019b. Implementation of flood legislation from the 86th Texas legislative session. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/flood/doc/Flood_Implementation_Issues_for_Stakeholder_Consideration.pdf.

[TWDB] Texas Water Development Board. 2019c. Proposed changes to Texas Administrative Code regarding funding of flood mitigation projects. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/board/2019/11/Board/Brd02.pdf.

[TWDB] Texas Water Development Board. 2019d. Proposed flood planning region boundaries to implement new flood planning requirements of Senate Bill 8. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/board/2019/12/Board/Brd03.pdf.

[TWDB] Texas Water Development Board. 2019e. Proposed new Texas Administrative Code Chapters 361 and 362 relating to Regional and State Flood Planning. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/board/2019/12/Board/Brd04.pdf.

[TWDB] Texas Water Development Board. 2019f. State flood assessment: Report to the Legislature, 86th Legislative Session. Austin (Texas): Texas Water Development Board. Available from: http://www.texasfloodassessment.com/.

[TWDB] Texas Water Development Board. 2019g. SWIFT: State Water Implementation Fund for Texas (SWIFT). Available from: http://www.twdb.texas.gov/financial/programs/swift/index.asp.

[TWDB] Texas Water Development Board. 2017. 2017 Texas state water plan. Austin (Texas): Texas Water Development Board. Available from: https://2017.texasstatewaterplan.org/statewide.

Watson K, Harwell G, Wallace D, Wellborn T, Stengel V, McDowell J. 2018. Characterization of peak streamflows and flood inundation of selected areas in southeastern Texas and southwestern Louisiana from the August and September 2017 flood resulting from Hurricane Harvey. Washington (District of Columbia): U.S. Geological Survey. 56 p. U.S. Geological Survey Scientific Investigations Report 2018–5070. Available from: https://doi.org/10.3133/sir20185070.

APPENDIX A. ISSUES AND CONCERNS ADDRESSED BY FLOOD-RELATED BILLS INTRODUCED IN THE 86TH TEXAS LEGISLATURE

- Property tax
- Debris removal
- Emergency alerts
- Dam operations
- Casino gaming
- Public meeting procedures
- Personal identification
- Climate change
- Infrastructure assessment
- Loan interest rates
- Mail carriers
- Property insurance
- Outreach programs
- Housing recovery
- Government contractors
- Buying a home
- Legal counsel
- Government assistance forms
- Aquifer storage and recovery
- Affordable housing
- Handguns
- Sand and gravel mining
- Border wall construction
- Feeding state employees
- Federal funds
- Business advisory council
- Recovery program audits
- Leasing property
- Education finance
- Health care volunteers
- State agency coordination
- Public office residency requirements
- Permit and inspection fees
- Volunteer repairs
- Supplemental nutrition assistance
- Health care accessibility

- Suspension of regulations
- Landfills
- Mosquito control
- Oil and gas spill prevention
- Alcohol disposal
- Immunization records
- Government communications
- Assistance case management
- Government expenditure records
- Road construction
- Internet access
- Aboveground storage tanks
- Peace officers
- Vehicle salvage, repair, and assembly
- Telecommunications
- City legal immunity
- Vocational apprenticeship
- Family and protective services
- Price gouging
- Vehicle registration
- Local drainage districts
- Trade service fraud
- Personal information privacy
- Growth of state expenditures
- Land banking
- State employee leave
- Green infrastructure
- Infrastructure security
- Disease prevention
- Emergency management personnel
- Recycling
- Food banks
- Strategic planning
- Drone operation
- Cemeteries
- Volunteer fire departments
- Faith-based disaster assistance
- Utility billing
- Land easements and rights-of-way
- Teacher salaries
- Luxury vehicles
- Elderly and disabled persons

APPENDIX B. FLOOD-RELATED BILLS ORIGINATING IN THE HOUSE PASSED BY THE 86TH TEXAS LEGISLATURE

HB 5 (Phelan) requires TDEM to develop a catastrophic debris management plan and model guide for political subdivisions in the event of a disaster and supports the creation of associated training programs and a wet debris study group.

HB 6 (Morrison) prescribes a disaster recovery task force within TDEM to provide specialized assistance and facilitate long-term recovery efforts.

HB 7 (Morrison) requires the Office of Governor to compile a list of statutes and rules that may be suspended in the event of disaster and prescribes TDEM to assist political subdivisions with common disaster-related service contracts.

HB 26 (Metcalf) requires dam operators to include a notice requirement in their emergency action plans dictating that affected persons and communities downstream from reservoirs receive detailed notice of water releases during natural disasters.

HB 137 (Hinojosa) requires TCEQ to provide a report on high and significant hazard dams to the emergency management representative in the area where the dam is located.

HB 492 (Shine) allows income-producing personal property and property improvements to qualify for a property tax exemption if they are located in a declared disaster area and sustain at least 15% damage.

HB 720 (Larson) allows unappropriated water, including stormwater and floodwater, to be used for aquifer recharge.

HB 721 (Larson) directs TWDB to conduct studies of such aquifer storage and recovery projects.

HB 831 (Huberty) clarifies the eligibility of officeholders to run for election who have been displaced by a disaster.

HB 852 (Holland) prohibits municipalities from requiring information on the value of residential dwellings for the assessment of permits and fees, except as required by the National Flood Insurance Program (NFIP).

HB 907 (Huberty) increases fines for unregistered aggregate producing operations.

HB 1052 (Larson) allows certain TWDB funds to be used in support of underground storage of floodwaters.

HB 1177 (Phelan) allows licensed Texans to carry their firearms when their property is under a mandatory evacuation.

HB 1256 (Phelan) directs the Department of State Health Services to provide direct access to first responder immunization information in the event of a disaster.

HB 1263 (Ed Thompson) authorizes Brazoria Drainage District Number 4 to order private property owners to maintain infrastructure to allow access for drainage maintenance.

HB 1306 (Frullo) provides for additional flood insurance coverage by surplus lines insurers.

HB 1307 (Hinojosa) directs TDEM to create an electronic disaster case management system.

HB 1755 (Ed Thompson) clarifies the titling and registration of assembled vehicles and former military vehicles to prohibit the use of flood-damaged electrical or mechanical components.

HB 1820 (Bailes) creates the Liberty County Drainage District.

HB 1824 (Murr) waives the permit requirement to remove sediments from the San Jacinto River and its tributaries.

HB 2305 (Morrison) establishes a work group through TDEM to improve the training and credentialing of emergency management personnel.

HB 2310 (Vo) creates an information sharing process regarding flood-damaged vehicles repaired using FEMA funds.

HB 2320 (Paul) facilitates the integration of telecommunications providers into disaster planning and recovery and requires TDEM to identify strategies for hardening utility facilities and critical infrastructure. This legislation also increases the availability, accountability, and oversight of building trade services professionals while promoting public awareness of utility payment assistance during a disaster.

HB 2325 (Metcalf) coordinates information management communications strategies among government agencies and the public during and after a disaster.

HB 2335 (Walle) directs the Health and Human Services Commission to work with county judges to establish a list of sites that can maintain accessibility to supplemental nutrition assistance program benefits after a natural disaster.

HB 2340 (Dominguez) encourages federal-state partnerships to improve information sharing and efficiency and also creates an unmanned aircraft study group to identify state laws that may be changed to improve the use of drones in disaster response.

HB 2345 (Walle) establishes the Institute for a Disaster Resilient Texas under the Texas A&M University System.

HB 2634 (Flynn) creates specifications for developing cemeteries in relation to areas used for flood control.

HB 2784 (Phelan) directs the Texas Workforce Commission to create the Texas Industry-Recognized Apprenticeship Programs Grant Program to engage the private sector in boosting the state's specialized industrial workforce to respond to the needs of Hurricane Harvey.

HB 3070 (Ken King) authorizes volunteer fire departments to submit an emergency request to the Rural VFD Assistance Program to repair or replace equipment damaged or lost in responding to a disaster.

HB 3175 (Deshotel) mandates the confidentiality of personal information used in disaster recovery fund applications.

HB 3317 (Zerwas) exempts the disaster recovery loan account, the Flood Infrastructure Fund, the Texas Infrastructure Resiliency Fund, and the disaster reinvestment and infrastructure planning revolving fund from becoming part of the General Revenue Fund.

HB 3365 (Paul) provides civil liability protections (Good Samaritan laws) to charitable organizations, emergency response agencies, and associated volunteers who assist in disaster response.

HB 3384 (Shine) authorizes the Texas Comptroller of Public Accounts to provide for a limited-scope review of appraisal districts in disaster areas.

HB 3616 (Hunter) creates a faith-based organization task force to help TDEM coordinate with faith-based organizations in disaster response and recovery.

HB 3668 (Walle) establishes a grant program for local food banks to build capacity to respond to disasters.

HB 3782 (Harless) establishes a process for the Harris County Flood Control District to remove personal property from District land or easement, for the purpose of flood infrastructure maintenance, after notification.

HB 3815 (Morrison) requires the disclosure to homebuyers of previous flood history, flood insurance coverage, and location within flood-prone areas.

HB 3913 (Huberty) creates an exemption from public information laws at the state level for personal information obtained by certain flood control districts.

HB 4726 (Dominguez) creates the Cameron County Flood Control District.

APPENDIX C. FLOOD-RELATED BILLS ORIGINATING IN THE SENATE PASSED BY THE 86TH TEXAS LEGISLATURE

SB 2 (Bettencourt) prescribes a number of changes to property taxation procedures, including those in declared disaster areas.

SB 6 (Kolkhorst) addresses a number of disaster response and recovery issues, including wet debris management, training and credentialing of emergency management personnel and political officers, a Disaster Recovery Loan Program through TDEM, and the potential creation of a single automated intake system for obtaining disaster assistance from multiple state and federal programs.

SB 7 (Creighton) creates the Flood Infrastructure Fund through TWDB to provide financial assistance for flood projects. The legislation also creates the Texas Infrastructure Resiliency Fund to serve as a matching account to leverage federal dollars in addition to supporting data collection and mitigation projects identified in future state flood plans.

SB 8 (Perry) directs TWDB to develop a comprehensive state flood plan every 5 years based on regional flood plans. The bill also requires TWDB to designate these planning regions and provide assistance to each through the development process. TSSWCB is charged with creating a repair and maintenance plan for flood control dams every 10 years (with coordination from TWDB and TCEQ).

SB 285 (Miles) directs the Governor to issue an annual hurricane preparedness proclamation before each hurricane season (June 1), to publish a report on state agencies' preparedness following this proclamation, and to ensure agency preparedness through executive order. GLO will conduct an annual public information campaign addressing available housing assistance in the event of a hurricane or flood.

SB 289 (Lucio) requires TDEM to develop a Disaster Recovery Task Force for use in long-term disaster recovery and future preparation. It also calls on local governments to adopt local housing recovery plans with guidance from the Hazard Reduction and Recovery Center within the Texas A&M University System.

SB 300 (Miles) authorizes GLO to enter into four-year indefinite quantity contracts with vendors for services in the wake of a disaster.

SB 339 (Huffman) requires the standard seller's disclosure for residential purchases to include flood insurance status, flooding history, and location in flood-prone areas.

SB 416 (Huffman) authorizes the attorney general to provide legal counsel on disaster-related issues to local governments in a disaster area.

SB 442 (Hancock) requires insurance providers to inform policyholders when their property insurance does not cover flooding and to inform of the potential need to purchase flood insurance.

SB 493 (Alvarado) permits the allocation of additional low-income housing tax credits to one portion of the City of Houston that has been declared a disaster area.

SB 494 (Huffman) allows the temporary suspension of public information law requirements for government bodies impacted by a disaster.

SB 500 (Nelson) makes supplemental appropriations, with specifications for numerous flooding and disaster programs.

SB 537 (Kolkhorst) allows the Texas Department of Transportation to purchase food and beverage for employees unable to leave their assignment area during disaster response.

SB 563 (Perry) requires agencies distributing federal funds for flood projects to submit quarterly reports to TWDB.

SB 752 (Huffman) reduces civil liability for volunteer health care professionals who provide services related to a disaster.

SB 799 (Alvarado) establishes a business advisory council to guide state and local governments in helping businesses recovery from a disaster. It also transfers administration of TDEM from the Department of Public Safety to the Texas A&M University System.

SB 812 (Lucio) clarifies that home repairs or replacements made due to Hurricane Harvey are not considered new improvements for the purpose of property taxation.

SB 981 (Kolkhorst) facilitates greater collaboration between state and local officials to administer the disaster supplemental nutrition assistance program.

SB 982 (Kolkhorst) directs TDEM to develop a plan for emergency shelter for specialty care populations in a disaster, facilitate coordination between local governments and volunteer networks, and create state-controlled volunteer mobile medical units in counties where volunteer networks are lacking. It also establishes a task force on disaster issues affecting elderly persons and persons with disabilities.

SB 986 (Kolkhorst) directs the Comptroller of Public Accounts to update the contract management guide to include standards and information related to disaster response, including that of debris management, infrastructure repair and construction, and preparation.

SB 1113 (Lucio) authorizes local health departments in a disaster area to apply for a waiver to allow unlicensed staff to apply mosquito control pesticides.

SB 1210 (Hancock) establishes a process for the disposal of flood-damaged alcoholic beverages.

SB 1312 (Lucio) directs state agencies to study vector-borne disease issues along the Texas-Mexico border and makes changes to some mosquito control activities.

SB 2168 (Watson) adjusts criteria for forgiving local match requirements for economically disadvantaged counties that have suffered repeat disasters.

SB 2212 (Taylor) authorizes three coastal drainage districts to enter into a partnership with USACE to implement coastal flood mitigation projects.

SB 2452 (Lucio) provides for the Economically Distressed Areas Program for water supply and sewer services and directs TWDB to maximize program effectiveness through bond proceeds in conjunction with other sources of financial assistance.

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Oilfield Water Infrastructure Connectivity: The Case for a 'Hydrovascular' Network in the Permian Basin

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Abstract: The current phase of oilfield water infrastructure buildout in the Permian Basin generally emphasizes each operator or midstream provider building its own water transportation and disposal systems. Accordingly, the overall market is balkanized and inefficient compared to the performance a more interconnected system could achieve. A hydrovascular grid in the Permian Basin could lower oil and gas production costs, conserve scarce freshwater by promoting greater recycling and reuse of produced water, help mitigate seismicity risks, and facilitate movement of produced water at large scale for use outside the oilfield. This paper assesses the barriers to such integration. It concludes by offering a set of practical ideas to overcome these barriers and help transform oilfield water into a resource for West Texas and Southeast New Mexico.

Keywords: hydrovascular grid, oilfield, produced water, market, infrastructure

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** Note: The opinions and ideas expressed in this piece are those of the author alone and do not represent the views or positions of the Baker Institute or Rice University.

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Terms used in paper

Acronym	Descriptive term
AOMD(s)	area(s) of market dominance
bpd	barrels per day
CAPEX	capital expenditures
E&P	exploration and production
EBITDA	earnings before interest, taxes, depletion, and amortization
LIBOR	London Inter-Bank Offered Rate
ROCE	return on capital employed
SWD(s)	saltwater disposal well(s)
TDS	total dissolved solids

INTRODUCTION

The Permian Basin now accounts for nearly 5% of global oil production. To unlock this hydrocarbon bounty, oil companies in the Permian Basin of New Mexico and Texas used about 5 million barrels per day (bpd) of water for hydrologic fracturing frack water as of Q4 2018. This approaches the average annual municipal water demand of San Antonio (Gorzell et al. 2018). On the produced water side—analogous to wastewater in cities—the Permian Basin is even larger. Average daily total water injection volumes are more than twice the volume of wastewater Houston (Texas's largest city and the United States' fourth-largest) treated on an average day in 2018 (Brown and Riggans 2018). The volume of produced water from unconventional wells alone could reach 35 million bpd within the next decade (Addison 2019). To accommodate water volume growth and help facilitate continued robust oil and gas production activity in the Permian Basin, water services providers must be able to economically manage the resulting tsunami. A more interconnected hydrovascular grid in the Permian Basin oilfield can help facilitate economically and hydrologically optimal water management solutions and turn oilfield water from a waste into a true resource for the region.

The hydrovascular grid concept

> "We would create a hydrovascular market, where we would have major arterials to convey water throughout the state. For us to develop this and to develop new water—whether it be desalination or reclaimed water or bring water from out of state—all of that needs to be looked at from a 50,000-foot view," (Schladen 2015).

The idea of large-scale, highly connected water infrastructure to link regions of plenty to regions of scarcity in Texas dates to the 2015 legislative session. House Bill 3298 called for the Texas Water Development Board to study the potential for developing a water market and conveyance network that would eventually become a hydrovascular grid spanning multiple regions statewide (2015). The bill did not become law and the issue has, legislatively speaking, lain dormant for 4 years and running (H.B. 3298 . . . 2015).

Municipal water grids are challenging to interconnect for a range of reasons, including politics and quality concerns stemming from the fact that humans drink the water being transferred across systems. The oilfield water space offers much better near-term potential for creating a regional hydrovascular grid, and the ongoing scale-up and consolidation of water midstream systems in the Permian Basin could potentially create a partial hydrovascular grid in that region within 3–5 years (Collins 2019b).

Pressing needs for larger-scale water solutions, coupled with a market ecosystem that would be driven primarily by commercial interests, creates an environment where systems that are consolidating now for market reasons could be strategically linked together to facilitate wheeling of oilfield water within the Permian Basin. Consolidation in turn can facilitate optimal utilization of disposal well and recycling capacity and, potentially, the construction of larger-scale infrastructure that allows water to be moved outside the Permian Basin to the mutual economic and hydrological benefit of multiple stakeholders.

The core hypothesis underlying the emergence of a Permian Basin hydrovascular grid is that the oilfield water market in the Delaware and Midland Basins will gradually coalesce into several large areas of market dominance (AOMDs) as

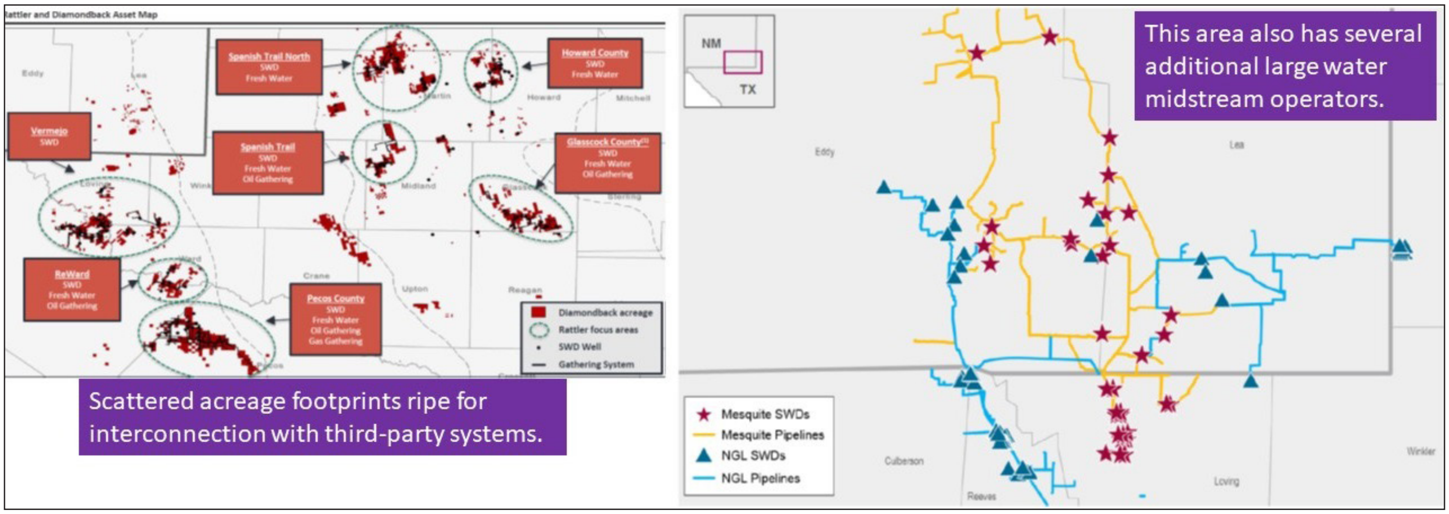

Figure 1. The case for oilfield water interconnectivity. Source: NGL Energy Partners LP 2019, Rattler Midstream 2019, Author's Analysis.

water midstream firms and their exploration and production (E&P) customers consolidate. The emergence of these broad AOMDs—akin to the watershed feeding a river system—opens the opportunity for optimized pipeline connectivity between the various oilfield watersheds that will, economics permitting, allow wheeling and movement of water in a manner that is largely impossible at present.

The areas of market dominance may also add a self-fulfilling prophecy dimension because they could offer appealing scale to large strategic buyers who possess the financial incentives, operational know how, and finances to further stitch up the Permian Basin oilfield water space. Figure 1 shows two snapshots of how prospective consolidators are beginning to emerge amidst the fragmentation that has characterized oilfield water management in the Permian Basin for much of the past several years. One possible outcome is that the largest midstreams such as Kinder Morgan or Plains All-American Pipeline could conceivably add water to their extensive existing crude, gas, and products midstream portfolios.[1]

It is also possible that the biggest existing players in the Permian Basin oilfield water space at present could bulk up even further and seek to dominate the Permian Basin moving forward. NGL Energy Partners, which has made a strategic decision to focus on the Northern Delaware Basin, appears to be substantially de-emphasizing its traditional hydrocarbon midstream businesses and bulking up instead on Permian Basin water assets. For NGL, water services accounted for 29% of firm-wide earnings before interest, taxes, depletion, and amortization (EBITDA) in Fiscal Year 2018, but this proportion rises to roughly 50% of the firm's projected Fiscal Year 2020 EBITDA (NGL Energy Partners LP 2019).

Among the "pure play" water midstream firms, WaterBridge stands out for its fast-moving and big-dollar mergers and acquisitions activity. Data for the company's publicly reported transactions suggests that in the central and southern Delaware Basin, it has spent close to $700 million on acquisitions since February 2018 (Collins 2019a). This is almost certainly a significant underestimate, since it includes neither the 2017 purchase of EnWater nor the 100,000 Series-A1 Preferred Units transferred to Concho as part of a December 2018 purchase of produced water assets and acreage dedication (WaterBridge 2017; Concho Resources Inc. 2019). Including the potential value of these two items could reasonably drive WaterBridge's Delaware Basin entry cost to date as high as $800 to $850 million.

Motivations for promoting greater connectivity between Permian Basin water systems

Before delving into the challenges—many of them substantial—that a Permian Basin hydrovascular grid would face, it is worth considering what is at stake as operators in the Permian Basin search for high-volume, economically advantaged, and stable water solutions.

A more integrated set of water handling networks can help oil and gas producers rationalize investment plans and shift water-related capital investments off their balance sheets. Investors increasingly demand capital spending discipline, while companies must offset the high natural rate of decline in horizontal wells while also trying to grow production (Matthews and Elliott 2019). In such an environment, spending $5–6 million dollars to drill, complete, and equip a shallow disposal well and as much as $10 million for a deep Devonian/Ellenburger disposal well plus additional investment in water pipelines becomes tougher to justify.

[1] See, for instance Wethe D. 21 June 2019. Dirty Water Holds Biggest Promise for Pipeline Companies, Jefferies Says. Bloomberg. Available from: https://www.bloomberg.com/news/articles/2019-06-21/dirty-water-holds-biggest-promise-for-pipelines-jefferies-says.

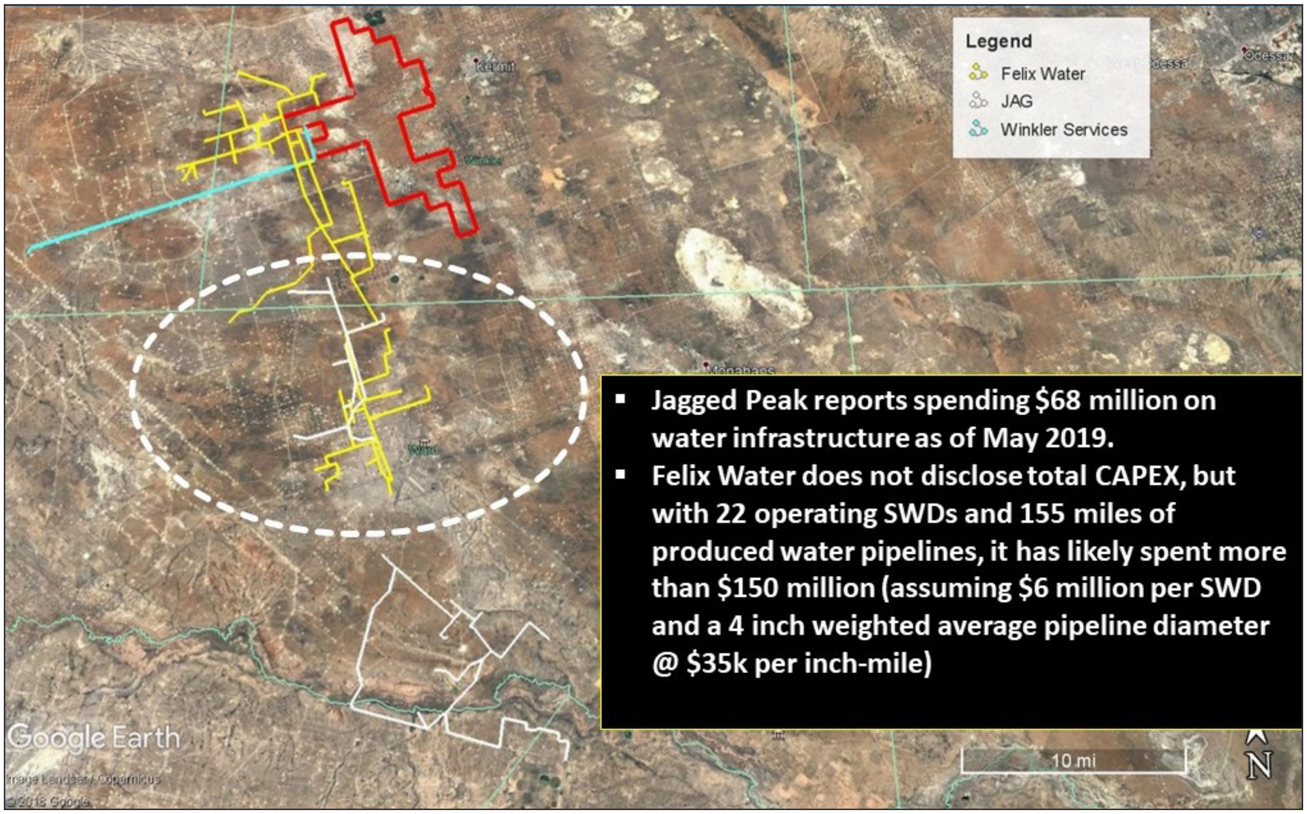

Figure 2. Jagged Peak and Felix Water Delaware Basin pipeline systems. Source: Felix Water n.d., Jagged Peak Energy 2019, Company Reports, Author's Analysis.

The case worsens when one considers proprietary water networks' generally low average utilization rates and that the funds invested in them could otherwise have been used to drill oil and gas wells. Low utilization rates affect the return on capital employed (ROCE) and help illustrate the potential balance sheet consequences of investing funds in self-operated water systems rather than drilling oil and gas wells. ROCE gives a directional sense as to how management may elect to deploy capital on projects, especially in a "live within cashflow" environment such as the one E&Ps now must operate in.

Commercial water systems may well be able to meet the 15% ROCE threshold that the most competitive Permian Basin-focused E&P companies can reap from oil and gas production investments. But most firms will likely fall short of that mark unless their system is optimally utilized and/or they operate in an area where a quasi-monopoly water services provider is charging high prices that create incentives to invest in proprietary water systems on the basis that avoided costs are effectively an economic gain that delivers a form of return on investment.

Legacy investments in proprietary water infrastructure are tempting monetization targets at present in part because recent comparable transactions suggest a higher ROCE on dollars invested in saltwater disposal wells (SWDs) and pipelines than for dollars sunk into oil and gas wellbores.

Water management is also not a core competency or management focus for most oil and gas operators, even though it is operationally critical. Broadly speaking, investors are likely to cast a jaundiced eye on additional water system investments that could have gone to oil and gas development. To that end, the more publicly traded midstream names there are with meaningful water exposure, the more pressure investors will likely exert on E&Ps to focus capital expenditures (CAPEX) on their core business and not plough money into midstream operations (for interested readers, the author can share specific details of selected oil and gas producers' water divestiture transactions and some of the likely reasoning behind them).

Treating water assets as truly commercial systems that are substantively open to third-party commercial volumes sets the stage for a more efficient marketplace. But perhaps the biggest challenge to creating a more interlinked set of Permian Basin oilfield water infrastructure comes from the need to reconcile capital providers' expectations with evolving market realities. Consider the example of Jagged Peak Energy and Felix Water, who have water systems in Ward and Winkler Counties that substantially overlap one another (Figure 2).

Each company has invested sizeable sums of capital. Jagged Peak reports spending $89 million on water infrastructure as of June 30 2019 (Jagged Peak Energy 2019). Felix Water does not disclose total CAPEX, but with 22 operating SWDs and 190 miles of produced water pipelines (Felix Water n.d.), the

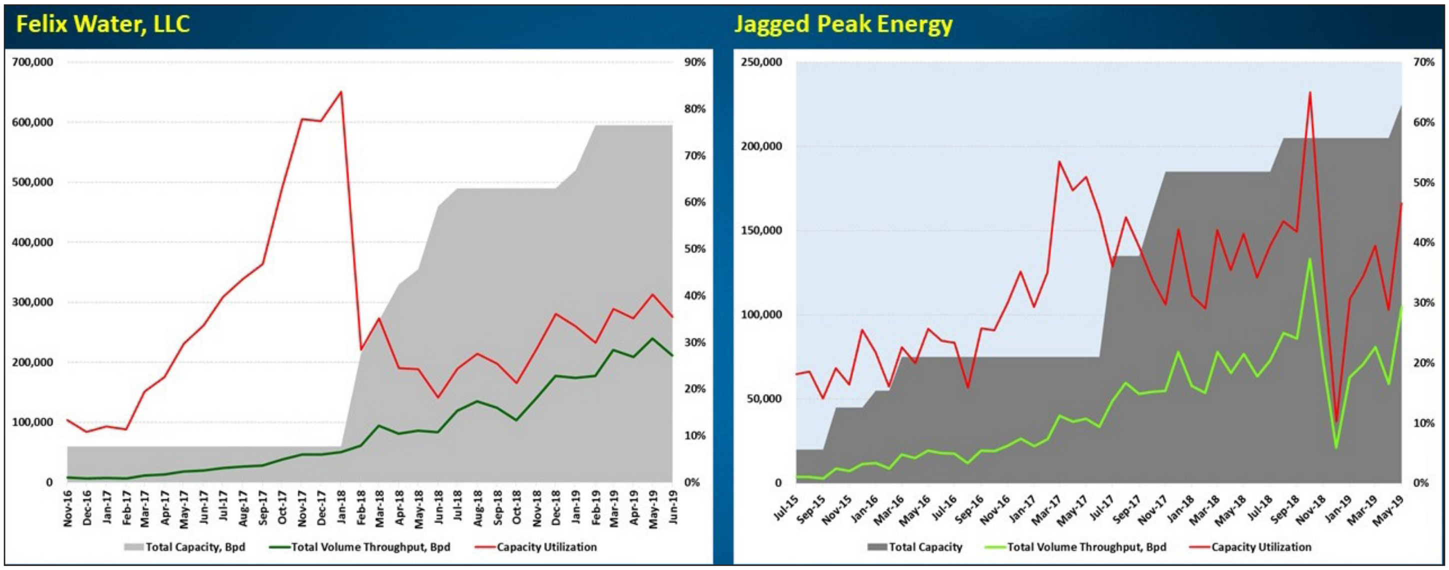

Figure 3. Capacity utilization of Jagged Peak and Felix Water systems. Volume throughput: green line, vertical axis; Capacity utilization: red line, horizontal axis. Source: Texas Railroad Commission 2019, Author's Analysis.

author estimates it has likely spent more than $150 million (assuming $6 million per SWD and a 4-inch weighted average pipeline diameter at $35,000 per inch-mile). As such, the combined cost of the two systems could exceed $250 million. Yet the actual Texas Railroad Commission data on water received by the saltwater disposal wells in each system (a proxy for overall flows) suggest that both networks are highly underutilized, with average capacity utilization rates in the neighborhood of 40% over the past 2 years (Figure 3).

Capital might have been better deployed building shared infrastructure that connects more producers, with the balance saved either deployed to build a water system with even greater geographical coverage or spun back to shareholders or used to drill oil and gas wells. It bears noting that each of the companies in this example aggressively expanded system capacity between the second quarter of 2017 and the second quarter of 2019, suggesting a temporal overlap that would have offered an ideal window for building infrastructure more collaboratively and thus optimizing capacity investments.

To frame the potential savings in terms of what the capital could have done, consider that 30-inch HDPE pipe likely costs about $1 million per mile installed (assuming $35,000 per inch-mile total installation cost), based on the author's conversations with industry experts. Thus, a Delaware SWD completed with surface facilities is, in CAPEX terms, equal to about 6 miles of large-diameter pipe and a Devonian SWD worth closer to 10 miles of large diameter pipe linking one system to another.

Optimizing CAPEX becomes especially important if the Permian Basin is transitioning into a production regime where activity remains substantial, but production of oil and gas (and by extension, water) grows more slowly. The new normal for annual output growth could be net increases on the order of 200 thousand bpd, as opposed to the heady days of 2017 and 2018 where oil production increased by 733 thousand bpd and 1 million bpd, respectively (calculated using oil production changed from January to December in 2017 and 2018; Drilling Productivity Report 2013–2019).

The output slowdown could stem from at least two core factors, and both matter for water midstream development strategies. First, some analysts suggest that the rate of increase in well productivity may be slowing.[2] Second, operators are encountering what appear to be hard physical limits on how closely wells can be spaced without adversely affecting each other's productivity.[3] This means that at a given price level, operators are likely to drill fewer wells in a given block of acreage than might have been the case previously.

Lower density development means water midstream companies may need to cover larger physical footprints to achieve a given volume and returns profile. Consider, for instance, Wolfcamp A horizontal wells with 1.5 million barrels of expected lifetime water production. Spacing of 440 feet between wells (an aggressive number) would suggest 12 wells per section

[2] For an example of the bullish view, see Rystad Says Permian Well Productivity is Just Fine. 2019 Aug 5. Journal of Petroleum Technology. Available from: https://www.spe.org/en/jpt/jpt-article-detail/?art=5802. For a bearish view, see Analytics Firm: Permian Fracturing Work Underreported by 21% in 2018. 2019 Jul 24. Journal of Petroleum Technology. Available from: https://www.spe.org/en/jpt/jpt-article-detail/?art=5763.

[3] See, for instance Concho Resources. 2019 1 Aug. Investors: SEC Filings (2019, Quarterly). Available from: https://ir.concho.com/investors/financial-reports/sec-filings/default.aspx. Copy on file with author. as well as Olson B. 2019 Jul 4. A Fracking Experiment Fails to Pump as Predicted. The Wall Street Journal. Available from: https://www.wsj.com/articles/a-fracking-experiment-fails-to-pump-as-predicted-11562232601.

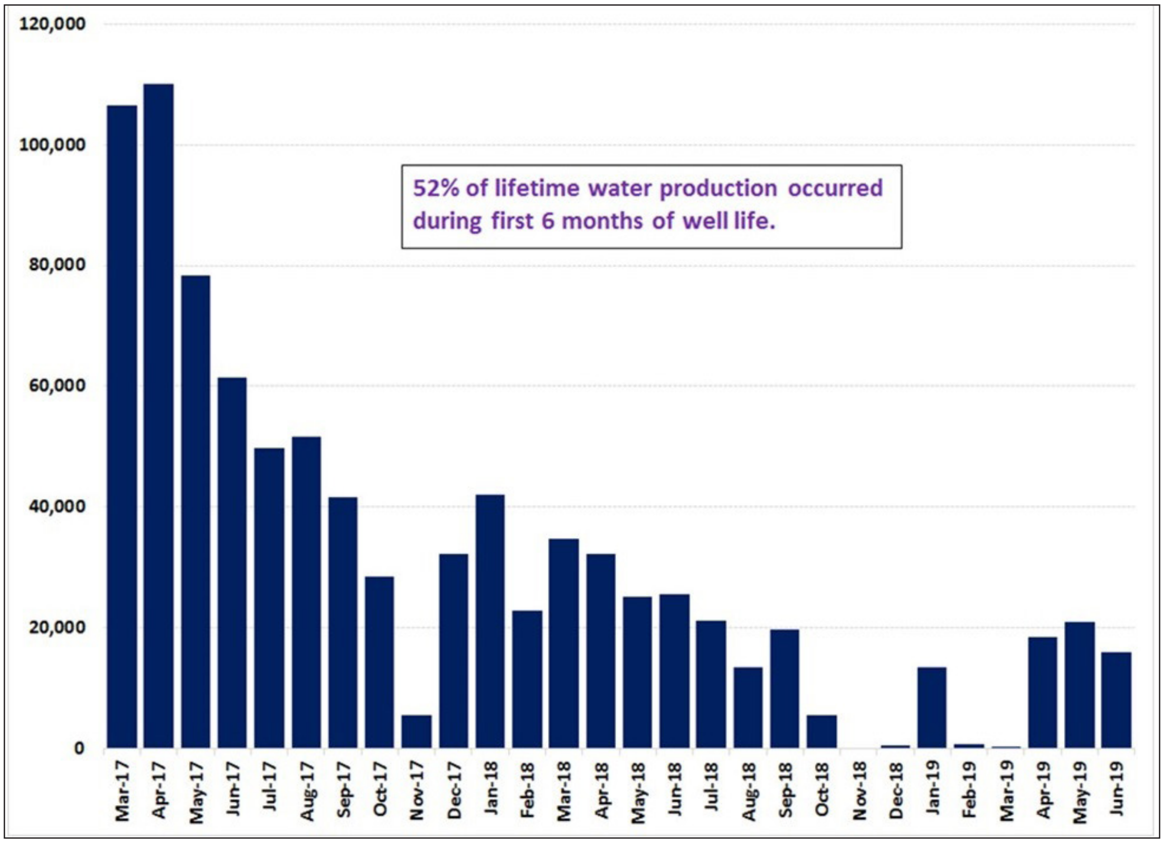

Figure 4. Permian Basin unconventional wells' water production is frontloaded just like oil and gas output is. Source: New Mexico Oil Conservation Division 2019, Author's analysis.

could be drilled in that bench, implying the opportunity for a midstream firm to gather 18 million barrels of lifetime produced water from that single 640-acre section. But conservative spacing of 1,320 feet between wells (4 wells per section per bench) now being tested by multiple Permian Basin operators would chop that cumulative water total down to 6 million barrels (Jagged Peak Energy 2019; Laredo Petroleum 2019).[4] This would force the midstream firm to potentially amass three times as much dedicated acreage to obtain the same volume of water it had expected before.

Needing more acreage to obtain a given produced water volume also exposes water midstream companies to a higher degree of geological risk, as reservoirs can vary dramatically across a tract. This also reinforces how interconnectivity between systems that allows water midstream management teams to potentially minimize their upfront capital investments and adopt a "wait and see" attitude for future capacity additions can enhance capital efficiency, profitability, and reduce investor risk. Interconnectivity can also help water midstream firms more effectively manage temporal risk—namely, the fact that oil and gas wells can be drilled, completed, and brought to sales in 2–5 months, while the time needed to obtain permits to drill disposal wells and actually install the infrastructure can be more than twice as long.

The ability to dynamically share capacity across systems can help developers rightsize systems to maximize capital efficiency. Unexpected peaks could be routed into other networked water systems, thus reducing the need to overbuild capacity on the front end and risk stranding capital if development slows or does not occur at the rate or scale originally planned. Capacity sharing also would help water management firms mitigate risk from commodity price shifts that cause drilling and completion activity to decrease, potentially leaving them with a high capital mortgage on underutilized assets. This risk is more pronounced than commonly acknowledged because the water flows from unconventional wells broadly mimic the wells' oil and gas production curves—heavily frontloaded with a material portion of total lifetime water volume coming in the first 2–3 years of well life (Figure 4).

Being able to wheel water around a larger network might also allow water midstream operators to offer more flexible contract structures to operators by reducing the dependence on any single operator as an anchor customer of the infrastructure. The degree to which this remains true in practice in a given area will depend on the ultimate market concentration that results as E&P operators continue to consolidate.

[4] See, for instance Jagged Peak Energy 2019 and Laredo Petroleum 2019.

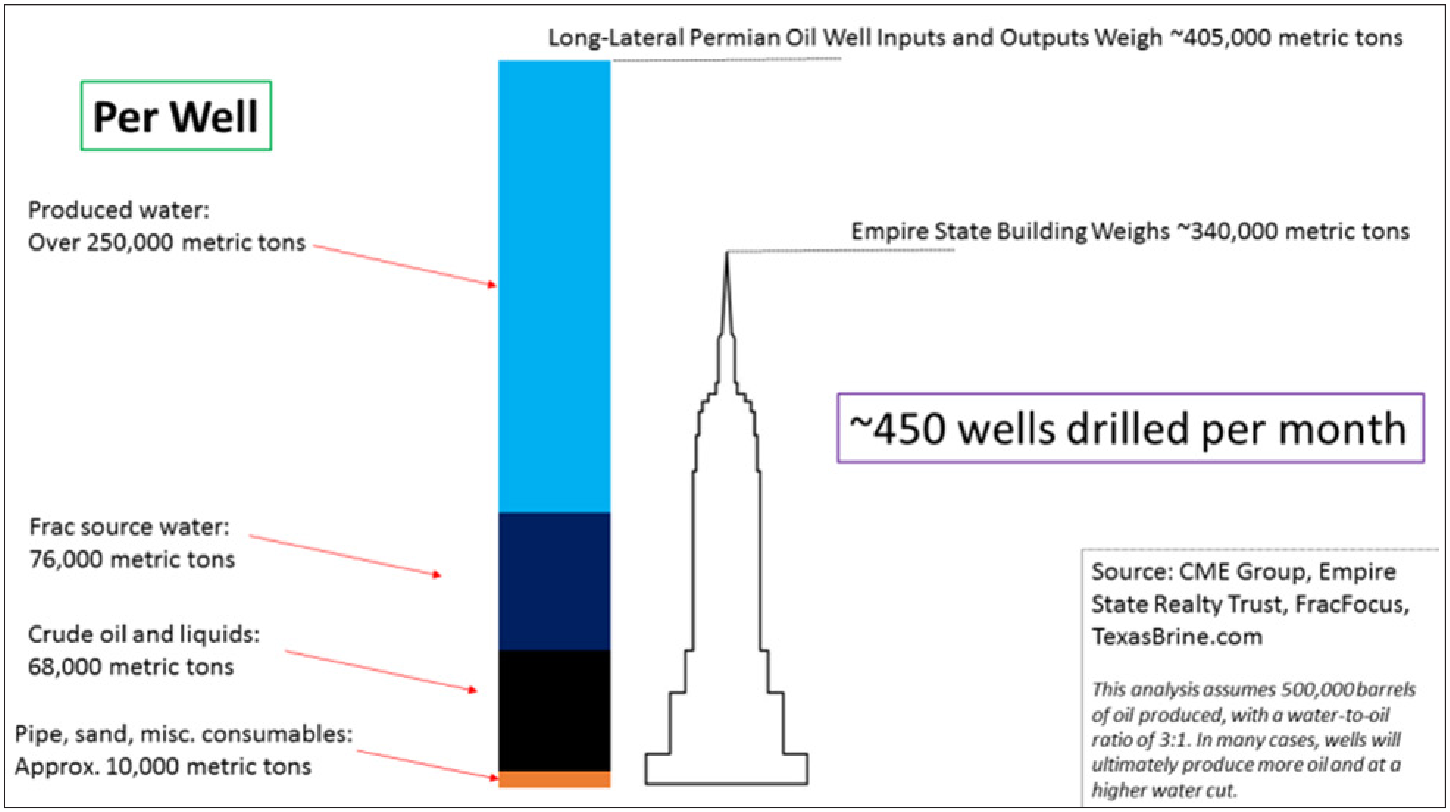

Figure 5. Mass of inputs and outputs from drilling and completion of and production from a 2-mile lateral Delaware Basin oil well. Source: FracFocus 2019, Author's Analysis.

Other benefits of greater oilfield water infrastructure connectivity

An oilfield water hydrovascular grid also yields a number of other benefits beyond capital efficiency, including enhancements to social license to operate, as well as the use of produced water in creative, nontraditional ways outside of the oilfield.

Water movement plays an outsize role in oilfield safety issues, which in turn directly influence firms' social license to operate. The author's modelling of a prototypical Delaware Basin horizontal well with a 2-mile lateral suggests that the combined lifetime mass of inputs used to drill and complete the well and the fluids produced from it exceeds 400 thousand metric tons (Figure 5). Of that total, over 325 thousand metric tons, or nearly the mass of the Empire State Building, comes from water (Collins 2018b). Note here that mass is used instead of volume because mass is what ultimately destroys roads and causes many of the water-driven social impacts currently seen across the oilfield.

Significant amounts of water still move by truck in the Permian Basin. One key end result of this is a road death rate in the core Permian Basin counties of Texas that is on par with that of Russia, one of the world's most dangerous industrialized countries to drive in (Collins 2018a). Water movement in trucks also inflicts severe road damage that outstrips local governments' ability to pay for repairs and, if left unchecked, could negate much of the benefit that planned road investments in the Permian Basin are otherwise poised to provide. Broader interconnectivity between water pipeline systems can help take more trucks off the roads.

Improved connections between oilfield water systems can also help manage seismicity issues. Seismic activity is emerging as a particular challenge in parts of the Delaware Basin, where the Texas Railroad Commission has adopted a risk-based permitting approach that can dramatically increase the time needed to get a saltwater disposal well permit and can also lead to significant cutbacks in allowable daily injection volumes. If cutbacks were imposed after a developer had sunk capital into a disposal well network, the economic impacts could be severe at the project level (Collins 2018d). Thus, being able to weave multiple water networks together with pipelines could allow water services providers in seismically active areas to optimize their investments in tough to obtain disposal wells and allow diversion of water to other disposal wells if future seismic events prompted regulatory cutbacks to injection volumes.

Greater oilfield water system connectivity can also help promote produced water recycling and the conservation of precious local freshwater resources in the Permian Basin. Consolidation

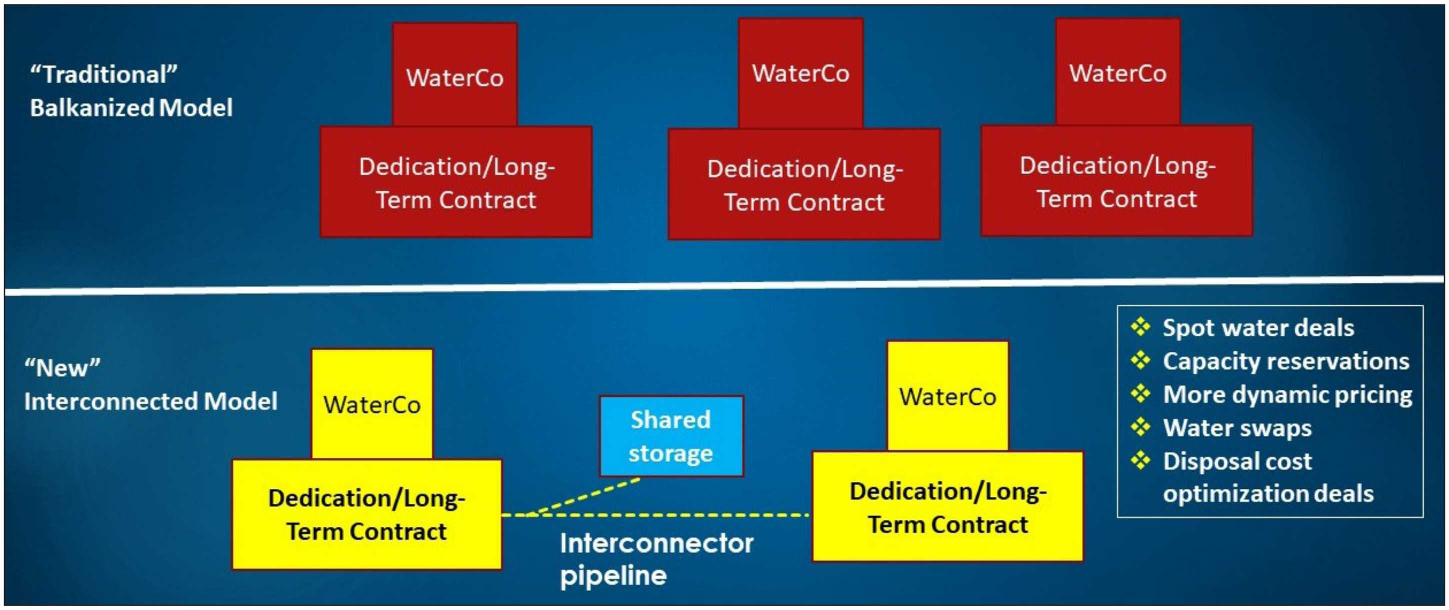

Figure 6. How greater water infrastructure connectivity can facilitate more dynamic commercial and financial structures.

of water systems and the creation of a broader hydrovascular grid will likely promote greater levels of water trading and recycling.

System interconnections can facilitate swaps and dynamic trading of water volumes that will help make the oilfield water space more like the developed commodity markets seen in oil and gas midstream or electrical power (Figure 6). Both of these sectors are very CAPEX and infrastructure-intensive, but oil and gas molecules and electrons are generally substantially more fungible than water molecules are in most of today's Permian Basin water systems.

Consider the following illustrative example: E&P Company A delivers water for disposal into Midstream Company A's system at a charge of $0.70 per barrel, while E&P Company B, which is hooked up to Midstream Company B's pipeline system, needs water 15 miles away for a frac. Midstream A is linked by a pipeline to Midstream B and is operating near the capacity of its system, while Midstream B is underutilized and has headroom to work with. Midstream A can thus either allow Midstream B to take a certain volume of water free of charge (because the reduction in SWD operating cost increases its profits) or charge Midstream B a reduced rate relative to freshwater or treated produced water prices in the area—say $0.15 per barrel—and also make an additional profit while avoiding disposal costs on the water sent out of system (Figure 7).

Assume it costs Midstream Company A $0.20 per barrel to dispose of or recycle the water in the most expensive facilities in its system because the low-cost options are full. Further assume that it costs $0.10 per barrel to pipe the raw produced water to Midstream B's system, and Midstream B will pay $0.10 per barrel for delivered raw produced water. Midstream A can thus make a net gain of $0.20 per barrel of water shipped to Midstream B rather than using the highest cost marginal disposal wells available in its own system.[5]

Such a future with pipeline-grade produced water that can be exchanged between systems with minimal to no additional treatment is already rapidly emerging and will only gain steam with further consolidation.[6]

Solutions beyond the oilfield

Consolidation may also open the door for out-of-basin water movement at a scale far larger than what is seen today. Large-scale midstream infrastructure has the potential to enable creative new uses of water beyond disposal and recycling alone.[7] This would likely require utility-scale systems with pipelines that could be 36 inches in diameter or larger. These ideas also presuppose two other developments: (1) a higher degree of interconnection between oilfield water handling footprints,

[5] $0.10 is avoided cost - pipeline shipping cost from sidestepping A's highest cost disposal assets and $0.10 of the total comes from B's actual payment for the raw produced water.

[6] The idea of pipeline grade produced water comes from the natural gas industry, where gas must meet certain quality specifications in order to be considered of pipeline quality and be sold into commercial pipeline systems. See, for instance, Foss MM. 2004. Interstate Natural Gas—Quality Specifications & Interchangeability. Sugar Land, TX: Center for Energy Economics. Available from: http://www.beg.utexas.edu/files/energyecon/global-gas-and-lng/CEE_Interstate_Natural_Gas_Quality_Specifications_and_Interchangeability.pdf.

[7] It is also important to start thinking now about repurposing part of the produced water stream, so that the practices and technologies have a better chance of being deployable at scale when oilfield recycling demand begins to slow in coming years as parts of the Delaware and Midland Basins reach maturity.

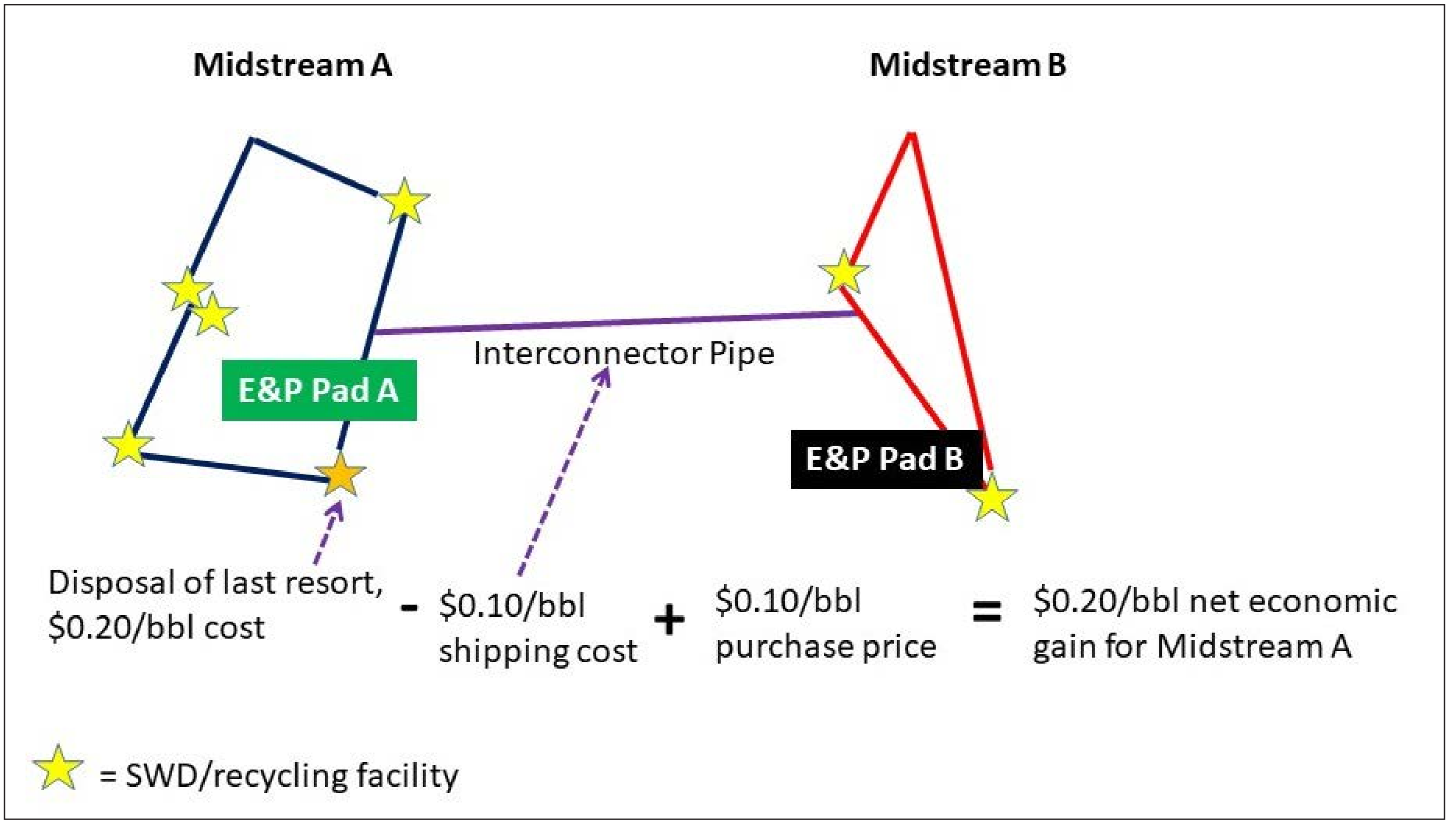

Figure 7. Simple illustration of gains through trade facilitated by interconnectivity.

which at this point in time are highly fragmented, and (2) lower-cost treatments that can provide "upgraded" produced water at scale.

Repurposing may eventually involve local agricultural use, as well as longer distance transport to cities or industrial consumers located far from the oilfield. For liability reasons, the initial agricultural uses of treated produced water are likely to focus on crops such as cotton and biofuel feedstocks (switchgrass or algae, for instance) that humans do not consume by taking into their bodies. The "non-consumption" distinction is made here to clarify that even certain non-food items such as hemp still yield outputs that humans introduce into their bodies. It is also essential to do substantially more research into the potential long-term impacts on soil of irrigating with various concentrations of produced water.

Possible agricultural uses

At least one preliminary trial shows some promise. Texas A&M University researchers and Anadarko (now owned by Oxy) conducted a pilot study near Pecos, TX in 2015 that entailed irrigating cotton plots with a blend of freshwater and treated produced water (Lewis 2015). While the study's results were not peer-reviewed, in its particular case the data showed that cotton lint yields remained stable, and the use of the blended water suggested the potential for better managing soil salinity and potentially improving soil quality (Lewis 2015). There is an urgent need for peer-reviewed scientific studies that span multiple crops and multiple growing seasons on the same land plots, and the plant science community is beginning to deliver these.

At least two recent studies have irrigated spring wheat with blended produced water from the Niobrara Formation in the Denver-Julesburg Basin of Northeastern Colorado. The first analysis irrigated wheat groups with Fort Collins, Colorado municipal tap water, a 10% produced water/90% tap water blend, a 50% produced water/50% tap water blend, and a salinity control solution that incorporated sodium chloride to match the total dissolved solids (TDS) content of the 50% produced water blend (Sedlacko et al. 2019). Wheat irrigated with both produced water blends suffered significant declines in plant size and grain yield relative even to the high salinity control solution, suggesting that chemical components of the produced water other than salinity were adversely impacting plant health (Sedlacko et al. 2019). Some members of the research group then conducted a follow-on study using the same water blends to investigate the impacts varying blends of produced water might have on spring wheat's immune response to one bacterial pathogen and one fungal pathogen (Miller et al. 2019). The research revealed that wheat irrigated with both produced water blends (10% and 50%) experienced significant immune system suppression relative to the tap water and high-salinity irrigated test groups. The researchers hypothesized that the physiological effects on the plants could be explained by both inorganic constituents such as boron and hydrocarbon-related organic compounds in the water (Miller et al. 2019).

As other scientists conduct similar analyses using waters derived from Permian Basin wells, more heavily treated produced water, and different crops, sector participants will be able to more clearly assess whether produced water indeed offers upside as an irrigation water source.

If certain waters/crops prove tolerant of irrigation with produced water, a large and ongoing body of work on saline agriculture in other parts of the world potentially offers insights for farmers in the Permian Basin who might contemplate greater use of produced water as part of their irrigation water supply. The International Center for Biosaline Agriculture (ICBA), based in the United Arab Emirates, is a global leader in developing a range of salt-tolerant crops, including quinoa, mustard, *Sesbania*, safflower, triticale, and *Salicornia* (ICBA 2018). These plant strains have generally not yet been commercialized but are sufficiently salt-tolerant that they can even be irrigated with seawater (approximately 35,000 mg/l TDS), suggesting that they could utilize blended produced water if other chemical constituents in the water do not harm them.

Salicornia, a member of the beet and spinach family also known as glasswort, already has at least one variety that grows wild along the Texas coast, and the species more broadly shows promise as a biofuel source (Sea Center Texas 2019). In January 2019, the UAE's flagship airline, Etihad Airways, used *Salicornia*-derived biojet fuel to successfully power a commercial flight on a Boeing 787 from Abu Dhabi to Amsterdam (Etihad Aviation Group 2019). These experiences suggest that there may indeed be a range of non-food crops that could eventually be commercially grown in the Permian Basin with treated produced water as one of the core irrigation water sources. They also highlight a potential point of international engagement and a set of new development opportunities for farmers and water companies in the Permian Basin.

Logistics of moving water beyond the Permian Basin

Current state of the art for out-of-basin movement are the Llano and Rattlesnake Pipeline systems operated by Goodnight Midstream (Goodnight Midstream 2019). Yet with several hundred thousand bpd of capacity and movement beyond basin boundaries of perhaps 25 miles, these pipelines are smaller scale than what may ultimately be required to send water out of the basin, particularly if oil prices remain high enough that the tens of thousands of additional wells are developed.

The next phase of beyond-basin water transportation could involve movements of 100 miles or more, with individual line capacities of 500 thousand barrels per dayor greater. As an example of what the capital investment and transportation economics for such a development could look like, consider the Vista Ridge Pipeline.[8] Vista Ridge is slated to enter service in 2020 and carry freshwater 142 miles from Burleson County to the city of San Antonio (San Antonio Water System 2019). The line will transport approximately 1 million bpd of water, making it broadly representative of the scale likely needed for many long-distance produced water transport projects to be economically viable (Garney 2019b). The author acknowledges that Vista Ridge is a freshwater project and that transporting produced water is more challenging from a physical and chemical perspective and thus can cost significantly more than would be the case for freshwater projects. Nonetheless, freshwater projects still provide useful illustrations of achievable physical scope and scale for future long-distance produced water movement projects. With respect to economic challenges, if future disposal constraints drove the costs of handling the marginal barrels of produced water near their source high enough, export projects would likely be able to overcome the higher cost burdens and still deliver economic returns.

KEY CHALLENGES TO BUILDING A PERMIAN BASIN OILFIELD HYDROVASCULAR GRID

Challenge 1: Capital providers' return expectations diverge from underlying market realities

The single toughest challenge for consolidating Permian Basin water systems will likely be the existing spreads between what many financial sponsors think their project is worth and what the market is likely to actually value the assets at. Bid-ask differentials will be exacerbated by the fact that a large part of both the Delaware and Midland Basins are now claimed under acreage dedications, many of which are now perfected to varying degree with actual built water infrastructure.

In areas without duplicative development, the spread will likely be easier to manage. But in a situation such as that described earlier in this paper, with two adjacent systems each running at 40–50% of nameplate capacity and each developer having sunk large sums of capital into their respective projects, the exercise of trying to rationalize capacity in the face of sponsors who expect a two and a half times return on capital invested may prove impossible in the near-term, absent some type of

[8] Note that the Vista Ridge project transports water purchased under a long-term, price-stable agreement from a private developer for us in a public utility system. Transactions conducted through an oilfield hydrovascular grid would be more analogous to spot and term-based merchant commodity transactions. Furthermore, in an oilfield water context, the party purchasing or selling water is likely to move the molecules to market using its own infrastructure.

financial distress situation that forces the parties to revise prior expectations (Collins 2018c).

Challenge 2: Incentivizing landowners to support a produced water market and freer movement of water across tract boundaries

Capital sponsors will not be the only vested interest that potentially has incentives to challenge consolidation. Oilfield water rents have become a vital source of income to many Permian Basin landowners, particularly those in Texas who control the surface rights (which groundwater runs with as a matter of law) but not the minerals. Geographical distinctions matter greatly because unlike Texas, where surface owners almost certainly legally own the produced water as a matter of law, New Mexico now has specifically legislated that oil and gas operators own the produced water in that state and have the right to dispose, treat, sell, or transfer such water as they please.[9]

Can Texas landowners be incentivized to participate in a hydrovascular grid?

There are strong strategic arguments for treating landowners as real stakeholders in water projects that may span multiple property boundaries. First, landowners will likely increasingly want to be paid in some way for any produced water that is clearly creating value for third parties that they are presently not sharing in. Second, additional creative solutions are likely to find their way into water development agreements between landowners and midstream service providers. For instance, if produced water from multiple surface tracts is processed or disposed of at a central facility, landowners might seek a prorated distribution of a royalty, perhaps apportioned on the basis of surface acreage size or volumes derived from specific tracts (Collins 2017b). Indeed, the available Texas case law strongly supports landowners' ownership rights toproduced water, particularly if an operator seeks to use that water off-lease.[10] The right to compensation will likely follow this affirmed ownership of private property.

Landowners are likely to take a strongly proprietary view of water as being theirs even if it is introduced into a pipeline system that may commingle water from hundreds of leases and many surface owners. Complicating matters further, landowners with surface use agreements that require operators to prioritize the use of freshwater from the tract and dispose of produced water on-tract could conceivably believe that a broader hydrovascular grid threatens their income streams.

The Midland and Delaware Basins present different situations. Midland Basin landowners tend to hold smaller tracts, while the Delaware Basin is dominated by large landowners, who in some cases control more than 50,000 acres (larger than the City of Midland's area). Smaller landowners could be offered a severance fee that makes the water property of the water infrastructure system operator, no further strings attached. Those who were not willing to participate could be bypassed by infrastructure.

Larger landowners are more complicated because bypassing someone who controls 20 or more square miles may not be economically practicable. In cases where a system is connected to leases atop several surface tracts one possibility would be to introduce an inert tracer of some type into water leaving the tract boundaries at a specified concentration. At a monetization point downstream in the water system, the relative change in the concentration of the tracer could then be used to help determine what share of the revenue the landowner whose tract the water originally came from would be entitled to (Figure 8). Disparate tracts of land could also be unitized for produced water management purposes just as is currently done for oil and gas production.

The devil will be in the economic details. It is very possible that some landowners may seek a severance fee so high it destroys the overall economics of a grid-style water project. In practice, landowners are likely to seek severance fees that reasonably approximate what they can currently get paid for water sent down disposal wells. But there is little guidance from publicly available data on potential severance fee rates, and royalty rates/fee structures negotiated in opaque private markets can vary widely. Among other factors, the royalty rates historically paid by E&P operators and water midstream firms may be too high to allow the long-distance, cross-tract transfers that become possible with an interconnected hydrovascular grid.

These rates arose in a period where the parties involved saw produced water as either a byproduct to be rid of as quickly as possible (E&Ps in the pre-recycling era) or as a tolling market where the water should be moved the minimum necessary distance and then be disposed of (water midstreams). Landowners talk to one another and anchor quickly on what are seen to be the prevailing market rates in a given area. Thus, resetting produced water disposal rates is likely to be difficult unless injection disposal becomes regulatorily impossible or at least severely restricted in key parts of the Permian Basin. If such events transpire, the volume and price effects would ripple across the Permian Basin more broadly and could shift price setting power in water developers' favor (in other words, "If I can't dispose of the volumes I thought I could via the SWD on your land, I'm no longer going to pay you $X per barrel. If you

[9] Chapter 70 NMSA 1978, Section 4 (A)(1), The Produced Water Act, which in relevant part states that "The working interest owners and operator shall have a possessory interest in the produced water, including the right to take possession of the produced water and to use, handle, dispose of, transfer, sell, convey, transport, recycle, reuse or treat the produced water and to obtain proceeds for any such uses."

[10] Robinson v. Robbins Petroleum Corp., 501 S.W.2d 865 (Tex. 1973).

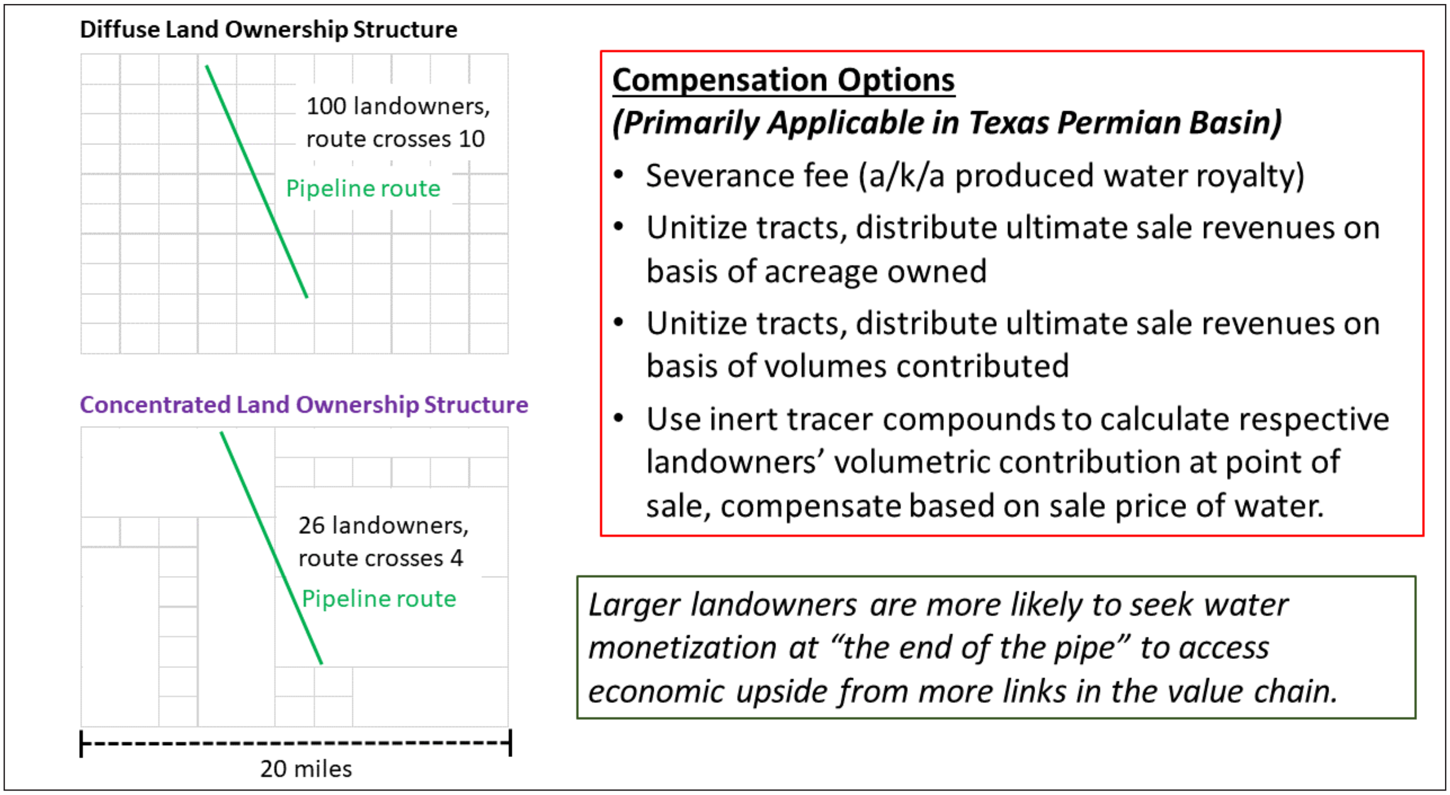

Figure 8. Incentivizing Texas landowners to buy in to a broader, more interconnected hydrovascular grid.

want the activity, the new price will have to be $0.8X or whatever is necessary to allow me, the developer, to unlock value.").

One of the few pieces of currently available produced water pricing data come from the agreement signed in January 2019 between University Lands and UL Water Midstream, LLC (composed of H2O Midstream and Layne Water Midstream). This agreement contains a royalty schedule for a range of water-related activities (Figure 9). Note that University Lands is the largest single landowner in West Texas, managing the surface and mineral interests of 2.1 million acres of land across 19 counties in West Texas (University Lands 2019).

The University Lands contract sheds some light on the rents sought by a party that is both an institutional landowner and also owns the mineral rights. However, a private, multigenerational ranch family (particularly one that does not control the mineral estate under their property) would likely find many of the royalty rates specified above to be unacceptably low.

University Land's agreement also does not address the elephant in the room for a hydrovascular grid—what, if any, rent is to be paid for moving water into a pipeline system that would take it off-tract? If UL Water Midstream wants to move produced water into other water systems, it must execute an amendment "containing mutually agreeable terms for the allocation of revenue" associated with such a water movement (Preferred Water Service Provider Agreement 2019). But no actual rates are set forth.

Challenge 3: Building the Permian Basin-produced water marketplace

If the number of discrete oilfield water networks in the Permian Basin continues to consolidate and become more tightly interlinked, the corresponding number of parties who could transact with each other also decreases. Consequently, the emerging market will likely be a more condensed version of what currently exists—a "speed dial marketplace" where most participants either already actually know each other, or if not, are an introduction and a phone call away.

The key market creation challenges will thus not be the need to bring buyers and sellers together in an "eBay" sense. Rather, the five key challenges will be: (1) building supersized oilfield water infrastructure and (2) financing water infrastructure at larger scale, and for projects that are more predicated upon sharing than is presently the case, (3) ensuring a baseline set of water quality standards, (4) pricing water transferred between systems whose underlying capital and operating cost structures could be substantially different, and (5) managing legal liabilities associated with transferring water that may be extremely saline and contain leftover completion chemicals and other contaminants.

Physical construction challenges are likely to be highly surmountable. In 2012 and 2013, a consortium of water infra-

Percent of Gross Revenues to University Lands				
	Years 1-5	Years 6-7	Year 8	Years 9-10
Gathering	5%	7%	8.5%	10%
Re-Use	0%	5%	5%	5%
Disposal	7%	10%	10%	10%
Sourcing & Delivery	20%	25%	30%	30%
Skim Oil	10%	15%	15%	15%
Other Revenue	5%	5%	5%	5%

Figure 9. University Lands comprehensive water royalty schedule. Source: Preferred Water Service Provider Agreement 2019.

structure-focused firms needed only 10 months to build a 60-mile, 48-inch diameter freshwater pipeline linking the T-Bar Ranch in Winkler County to the City of Midland, as well as emplace all of the necessary supporting infrastructure (Garney 2019a). Multiple of these same firms are currently working on the Vista Ridge Project in Central Texas, which upon entering service in 2020 will be capable of moving 1 million bpd of water into the San Antonio area.

Financing water infrastructure at a larger scale will require baseline cashflow assurances. In essence, can lenders be confident that the project will be able to service its debts? One wrinkle is that for out-of-basin projects done in conjunction with municipalities, project developers may be able to avail themselves of the municipal entities' credit ratings (if strong) and secure more advantageously priced financing as a result. Capital providers are interested in the space—witness WaterBridge's $1 billion Term Loan B announced in June 2019 (WaterBridge 2019). However, the transaction also suggests that lenders are attaching a meaningful risk premium. The WaterBridge Term Loan B priced at Libor + 575 basis points, a total interest rate of nearly 8% (WaterBridge 2019).

Debt issuances provide valuable insights into how the market currently perceives the risk profile of a water midstream firm. WaterBridge, one of the Permian Basin's water midstream titans, currently receives a long-term issue credit rating of B from S&P Global (Figure 10) (AC Investment 2019). S&P explains a B rating as meaning the "obligor currently has the capacity to meet its financial commitments on the obligation. Adverse business, financial, or economic conditions will likely impair the obligor's capacity or willingness to meet its financial commitments on the obligation" (S&P Global 2019).

In other words, the firm's financial condition is likely to remain in good shape in a stable macro environment, but if oil and gas prices decline and/or the company cannot secure stable long-term contracts to assure cashflows, such events can quickly threaten its financial health. The significant ratings disparity—and implications for cost of capital—between a large oilfield water firm like WaterBridge and a local municipality (such as the City of Midland) also help illustrate the attractiveness of public-private partnerships from the perspective of the lower-rated party who may need help financing infrastructure and other items.

Water quality issues will also likely pose challenges as produced water from different formations is commingled in water systems gathering from potentially hundreds of discrete leases. However, these operational and engineering challenges are likely to be overcome as the economic incentives for water infrastructure connectivity continue to grow. Multiple examples of "raw" produced water being sold out of gathering lines as frac fluid feedstock, as well as the recent Concho-Solaris recycled water supply deal, make the author optimistic that market participants are already well on their way to hammering out the

Rating	Characteristics	Examples
AAA	The obligor's capacity to meet its financial commitments on the obligation is extremely strong.	Microsoft
AA	An obligation rated 'AA' differs from the highest-rated obligations only to a small degree. The obligor's capacity to meet its financial commitments on the obligation is very strong.	City of Midland, Texas (AA+)
A	Somewhat more susceptible to the adverse effects of changes in circumstances and economic conditions than obligations in higher-rated categories. However, the obligor's capacity to meet its financial commitments on the obligation is still strong.	American Water
BBB	Exhibits adequate protection parameters. However, adverse economic conditions or changing circumstances are more likely to weaken the obligor's capacity to meet its financial commitments on the obligation.	Kinder Morgan
BB	Less vulnerable to nonpayment than other speculative issues. However, it faces major ongoing uncertainties or exposure to adverse business, financial, or economic conditions that could lead to the obligor's inadequate capacity to meet its financial commitments on the obligation.	
B	More vulnerable to nonpayment than obligations rated 'BB', but the obligor currently has the capacity to meet its financial commitments on the obligation. Adverse business, financial, or economic conditions will likely impair the obligor's capacity or willingness to meet its financial commitments on the obligation.	**WaterBridge Operating**
CCC	Currently vulnerable to nonpayment and is dependent upon favorable business, financial, and economic conditions for the obligor to meet its financial commitments on the obligation. In the event of adverse business, financial, or economic conditions, the obligor is not likely to have the capacity to meet its financial commitments on the obligation.	
CC	Currently highly vulnerable to nonpayment. The 'CC' rating is used when a default has not yet occurred but S&P Global Ratings expects default to be a virtual certainty, regardless of the anticipated time to default.	
C	Currently highly vulnerable to nonpayment, and the obligation is expected to have lower relative seniority or lower ultimate recovery compared with obligations that are rated higher.	
D	In default or in breach of an imputed promise. Also used upon the filing of a bankruptcy petition or the taking of similar action and where default on an obligation is a virtual certainty, for example due to automatic stay provisions. A rating on an obligation is lowered to 'D' if it is subject to a distressed exchange offer.	

Figure 10. S&P Global long-term issuer credit ratings, WaterBridge vs. other selected corporates and an oilfield municipality. Source: S&P Global 2019, City of Midland 2019.

water quality issues likely to be faced by more systematically connected water systems.[11]

How to price water as it moves across systems will be a substantial but surmountable challenge. Crude oil pipeline systems already provide an excellent working example of how to differentially assess commodity movement charges over varying distances and producer commitment levels in a networked infrastructure ecosystem (Figure 11).

Perhaps the most challenging part of the market design puzzle will be figuring out pricing and rent sharing across systems so that infrastructure owners and the original water owners (i.e. surface owners) can be sufficiently compensated to incentivize cross-system water movements. Continued low oil prices will sharpen the discussion because the final economic structure also needs to avoid overly burdening oil and gas producers with water-related operating costs. Ideally, the structures developed will ultimately help E&P companies lock in lower water services costs that can endure through multiple commodity price cycles and help ensure that the Permian Basin remains globally competitive and can fulfill its formidable long-term productive potential.

A final portion of the market puzzle is how legal liability will be treated. New Mexico law appears to provide a clear and comprehensive set of incentives for the aggregation, treatment, and movement back to market of produced water, even across tract boundaries. The Produced Water Act (House Bill 546) passed in the 2019 New Mexico Legislative Session clarifies E&P operators' de facto ownership of the water, gives them and subsequent transferors the ability to transfer produced water with clean title, prohibits private parties from charging transit fees to entities moving water across surface lands owned by the state of New Mexico, and makes agreements that mandate use of on-tract freshwater or that otherwise would restrict the use of recycled produced water void as against public policy.[12]

[11] See, for instance Cimarex's use of "raw" untreated produced water from its SWD system as feedstock for frac fluid and also Concho Resources Inc. and Solaris Water Midstream Form Joint Venture for Produced Water Management in the Northern Delaware Basin. 2019 Jul 31.Solaris Water Midstream. Available from: https://www.solarismidstream.com/news/concho-resources-inc-and-solaris-water-midstream-form-joint-venture-produced-water-management (Solaris will provide Concho with "blended reuse source water" derived from multiple operators on Solaris's gathering and disposal network).

[12] "Fluid Oil & Gas Waste Act," H.B. 546, https://nmlegis.gov/Legislation/Legislation?Chamber=H&LegType=B&LegNo=546&year=19.

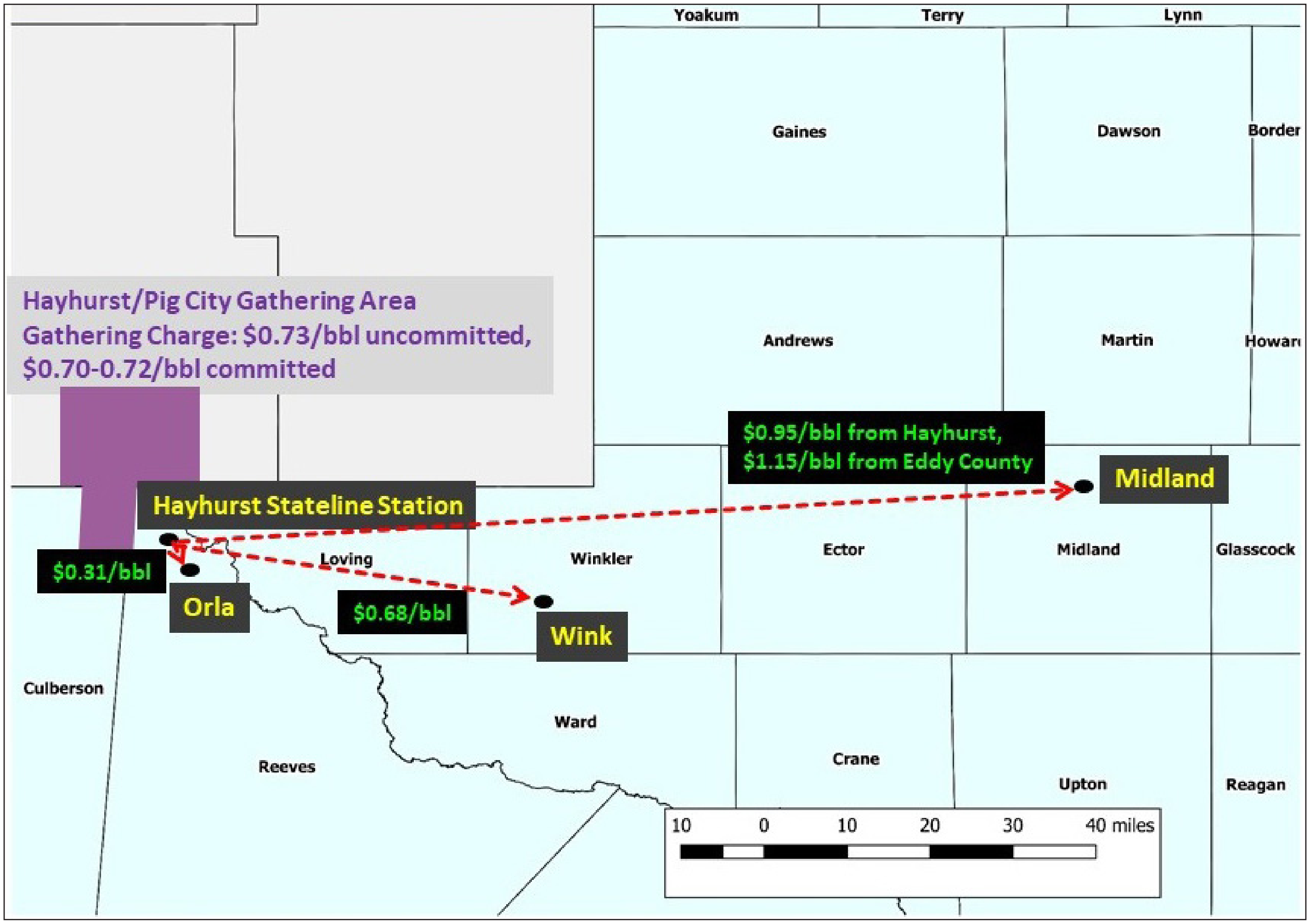

Figure 11. Commodity logistics pricing at basin-wide level (case of crude oil). Source: Federal Energy Regulatory Commission 2019, Author's Analysis.

Texas's limited body of law on produced water has evolved very differently due to the predominantly private ownership of surface lands in the state, as well as the fact that surface owners in Texas own all groundwater as a matter of law, including produced water (Collins 2017a). The author is currently working on a follow-on deep dive analysis of produced water ownership law in Texas, how it has developed, and how private property owners are likely to respond to recent legislation that allows E&P operators to attain ownership of produced water by capturing and recycling it. As such, the author will reserve further comment on Texas-specific produced water legal issues until the publication of that analysis, noting only that the legal basis exists for building a Permian Basin-scale hydrovascular system, and that any future legislation is unlikely to derail this emerging trend.

CONCLUSIONS

The emergence of a broader Permian Basin oilfield water hydrovascular grid faces several significant challenges. Nonetheless, the burgeoning volumes of produced water in the Permian Basin, pressure to optimize CAPEX in the face of commodity price uncertainty, E&Ps' need to manage water-related costs, and the ever-present prospect of drought are among the powerful incentives that will likely drive sector participants to develop creative solutions. Oilfield activity evolves fast, and the services business supporting it—water management first and foremost—evolve with equal velocity. Some of the solutions posited in this paper will come to pass, some will not, and many others we have not even thought of yet will be developed as entrepreneurs flock to the Permian Basin's uniquely large oilfield water marketplace. As consolidation ripples through the oilfield water space, a fascinating ecosystem of mutually reinforcing academic, policy, investor, and producer interests will continue evolving and spinning off opportunities.

REFERENCES

AC Investment. 2019. WaterBridge Midstream Operating LLC assigned 'B' issuer credit rating and stable outlook; debt also rated. Available from: https://www.ademcetinkaya.com/2019/05/waterbridge-midstream-operating-llc.html.

Addison B. 2019 Oct 25. Water production to increase to 35 million barrels per day. Midland Reporter-Telegram. Available from: https://www.mrt.com/business/oil/article/Water-production-to-increase-to-35-million-14563541.php.

Brown CB, Riggans B (City of Houston Office of the City Controller). 2018. Houston comprehensive annual financial report 2018. p. 240. Available from: https://www.houstontx.gov/controller/cafr.html.

City of Midland, Texas. 2019. Comprehensive Annual Financial Report (FY 2018). Available from: http://midlandtexas.gov/Archive.aspx?AMID=54.

Collins G. 2017a. Oilfield produced water ownership in Texas: balancing surface owners' rights and mineral owners' commercial objectives. Baker Institute for Public Policy. Available from: https://www.bakerinstitute.org/media/files/files/23bd889f/CES-pub-ProdWaterTX-020817.pdf.

Collins G. 2017b. Frac ranching vs. cattle ranching: exploring the economic motivations behind operator-surface owner conflicts over produced water recycling projects. Baker Institute for Public Policy. Issue Brief. Available from: https://www.bakerinstitute.org/research/frac-ranching-v-cattle-ranching/.

Collins G. 2018a. Addressing the impacts of oil & gas development on Texas roads. Baker Institute for Public Policy. Available from: https://www.bakerinstitute.org/media/files/files/04c6f77b/collins-testimony-042018.pdf.

Collins G. 2018b May 3. The lifetime water transport needs of a Permian Basin oil well can exceed the mass of the Empire State Building. Texas Water Intelligence. Available from: https://texaswaterintelligence.com/2018/05/03/the-water-transport-needs-of-a-permian-basin-oil-well-can-exceed-the-mass-of-the-empire-state-building/.

Collins G. 2018c. What does it take to create a billion dollar oilfield water midstream company? Presented at The Produced Water Society Permian Basin 2018 Symposium. Midland, TX. Available from: https://www.bakerinstitute.org/research/what-does-it-take-create-billion-dollar-oilfield-water-midstream-company/.

Collins G. 2018d Dec 10. Part 2: What injection disposal restrictions could mean for Delaware Basin E&Ps and water midstream operators. Texas Water Intelligence™. Available from: https://texaswaterintelligence.com/2018/12/10/part-2-six-ways-injection-disposal-restrictions-could-adversely-impact-delaware-basin-eps-and-water-midstream-operators/.

Collins G. 2019a. How to value oilfield water assets as big institutional money flows into the space. Presented at: Oilfield Water Connection Conference. Houston, TX. p. 24. Available from: https://www.bakerinstitute.org/research/how-value-oilfield-water-assets-big-institutional-money-flows-space/.

Collins G. 2019b. Greater oilfield water infrastructure connectivity: the case for a 'hydrovascular' network in the Permian Basin. Presented at: Produced Water Society Permian Basin 2019. Midland, TX. Available from: https://www.bakerinstitute.org/research/greater-oilfield-water-infrastructure-connectivity-case-hydrovascular-network-permian-basin/.

Concho Resources Inc. 2019. 2018 Form 10-K. Washington, D.C.: United States Securities and Exchange Commission. p. 52, 85. Available from: http://d18rn0p25nwr6d.cloudfront.net/CIK-0001358071/d61c45a0-118c-4c7a-b72d-f01310bf4169.pdf.

Drilling productivity report. Oct 2013– . Washington, D.C.: U.S. Energy Information Administration. Available from: https://www.eia.gov/petroleum/drilling/#tabs-summary-2.

Etihad Aviation Group. 2019 Jan 16. Etihad Airways flies world's first flight using fuel made in the UAE from plants grown in saltwater by Khalifa University. Available from: https://www.etihadaviationgroup.com/en-ae/home-corporate/newsroom/2019/January/Etihad-Airways0/Etihad-Airways-flies-the-worlds-first-flight-using-fuel-made-in-the-UAE-from-plants-grown-in-saltwater-by-Khalifa-University.html.

Federal Energy Regulatory Commission. 2019. eTariff Viewer. Available from: https://ferc.gov/docs-filing/etariff.asp.

Felix Water. n.d. Water disposal. [Accessed 2019 Aug 11]. Available from: https://www.felixwater.com/operations/water-disposal.

FracFocus Chemical Disclosure Registry. 2019. FracFocus Data Download. Available from: https://fracfocus.org/node/356/done?sid=19980.

Garney Construction. 2019a. T-Bar Ranch well field development & delivery project. Available from: https://www.garney.com/projects/t-bar-ranch-well-field-development-delivery-project/.

Garney Construction. 2019b. Vista Ridge Water Supply Project. [Accessed 2019 Aug 15]. Available from: https://www.garney.com/projects/vista-ridge-water-supply-project/.

Goodnight Midstream. 2019 Feb 5. Goodnight Midstream places Llano and Rattlesnake pipeline systems into service. News release. Available from: https://www.goodnightmidstream.com/uploads/2/3/6/0/23602878/2-5-2019_llano_and_rattlesnake_pipeline_systems_placed_in-service.pdf.

Gorzell B et al. (City of San Antonio Department of Finance). 2018. San Antonio comprehensive annual financial report & other reports. p. 347. Available from: https://www.sanantonio.gov/Finance/bfi/cafr.

H.B. 3298, 84th Legislature, 84th Session. (Texas 2015). Available from: https://capitol.texas.gov/BillLookup/History.aspx?LegSess=84R&Bill=HB3298.

International Center for Biosaline Agriculture. 2018. Salt-tolerant crops and halophytes. Available from: https://www.biosaline.org/content/salt-tolerant-crops-and-halophytes.

Jagged Peak Energy. 2019. Investor presentation August 2019. Available from: http://investors.jaggedpeakenergy.com/static-files/b2d377c8-3d30-486c-9a35-1638b900fecd.

Laredo Petroleum. 2019. August 2019 Corporate Presentation. Available from: www.laredopetro.com/media/223331/august-corporate-presentation.pdf.

Lewis KL, Moore J, Weathersby B. 2015. Produced water irrigation project: agricultural reuse of treated produced water. Available from: https://www.owrb.ok.gov/2060/PWWG/Resources/Lewis_Katie.pdf.

Matthews CM, Elliott R. 2019 Jun 7. Frackers scrounge for cash as Wall Street closes doors. The Wall Street Journal. Available from: https://www.wsj.com/articles/frackers-scrounge-for-cash-as-wall-street-closes-doors-11559915320.

Miller H, Trivedi P, Qiu Y, Sedlacko E, Higgins CP, Borch T. 2019. Food crop irrigation with oilfield-produced water suppresses plant immune response. Environmental Science & Technology Letters. 6(11):656-661. Available from: https://doi.org/10.1021/acs.estlett.9b00539.

New Mexico Oil Conservation Division. 2019. Well Search. Available from: https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Data/Wells.aspx.

NGL Energy Partners LP. 2019. Investor presentation June 2019. Presented at: Quarterly Investor Presentation. Tulsa, OK. Available from: http://www.nglenergypartners.com/investor-relations/presentations/.

Preferred Water Service Provider Agreement. 2019. No. 16126. Copy on file with author.

Rattler Midstream. 2019. Q2 2019 Conference Presentation. Presented at: Quarterly Investor Presentation. Midland, TX. Available from: https://www.rattlermidstream.com/events-and-presentations/events.

San Antonio Water System. 2019. Vista Ridge Pipeline. [Accessed 2019 Aug 15]. Available from: https://www.saws.org/your-water/new-water-sources/current-water-supply-projects/vista-ridge-pipeline/about-this-project/.

Schladen M. 2015 May 11. Texas lawmakers look into creation of statewide water grid, trading market. El Paso Times. Available from: https://www.elpasotimes.com/story/news/local/2015/05/11/state-likely-study-water-trading/31241709/.

Sea Center Texas. 2019. Woody glasswort. Available from: https://tpwd.texas.gov/fishing/sea-center-texas/flora-fauna-guide/salt-marshes/plant-life-on-the-salt-marsh-1/woody-glasswort.

Sedlacko EM, Jahn CE, Heuberger AL, Sindt NM, Miller HM, Borch T, Blaine AC, Cath TY, Higgins CP. 2019. Potential for beneficial reuse of oil-and-gas-derived produced water in agriculture: physiological and morphological responses in spring wheat (Triticum Aestivum). Environmental Toxicology and Chemistry. 38(8):1756-1769. Available from: https://doi.org/10.1002/etc.4449.

S&P Global. 2019. S&P Global Ratings Definitions. Available from: https://www.standardandpoors.com/en_US/web/guest/article/-/view/sourceId/504352.

Texas Railroad Commission. 2019. Skim Oil Reports (P-18). Available from: https://rrcsearch3.neubus.com/esd3-rrc/index.php?_module_=esd&_action_=keysearch&profile=28.

University Lands. 2019. About University Lands. Available from: http://www.utlands.utsystem.edu/.

WaterBridge. 2019 Jun 27. WaterBridge announces significant transactions. News release. Available from: https://www.prnewswire.com/news-releases/waterbridge-announces-significant-transactions-300876132.html.

WaterBridge. 2017 Aug 22. WaterBridge Resources acquires EnWater Solutions. News release. Available from: https://www.fivepointenergy.com/news/waterbridge-resources-acquires-enwater-solutions/.

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Runoff Inflow Volumes to the Highland Lakes in Central Texas: Temporal Trends in Volumes and Relations between Volumes and Selected Climatic Indices

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Abstract: Inflow to the Highland Lakes has substantially decreased from 1942–2013, likely due to increased evapotranspiration from the proliferation of 19 major upstream reservoirs and about 69,500 minor reservoirs and water bodies. Increased evapotranspiration from land surfaces and stream channels also probably represent major causes for inflow reduction. Eight climatic indices were evaluated with respect to correlations with inflow volumes to the lakes. A combination of the indices for the Atlantic Multidecadal Oscillation and Oceanic Niño Index (Niño 3.4 region) was found to be, up to three months in advance, a fair indicator for the wettest three-month inflow periods, and a good indicator, up to nine months in advance, of the driest three-month inflow periods. The single best index indicator of dry periods is the Pacific Decadal Oscillation—a good indicator of the driest three-month periods up to a year in advance.

Keywords: Highland Lakes, inflow, climatic indices

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Terms used in paper

Acronym/Initialism	Descriptive Name
AMO	Atlantic Multidecadal Oscillation
BEST index	Bivariate EnSo Time series
CRMWD	Colorado River Municipal Water District
ENSO	El Niño/Southern Oscillation
ft^3/s	cubic feet per second
LCRA	Lower Colorado River Authority
MEI	Multivariate ENSO Index
NAO	North Atlantic Oscillation
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NOAA	National Oceanographic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
ONI	Oceanic Niño Index
PDO	Pacific Decadal Oscillation
PNA	Pacific/North American teleconnection pattern
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
TWDB	Texas Water Development Board
TCEQ	Texas Commission on Environmental Quality
UCRA	Upper Colorado River Authority
USGS	U.S. Geological Survey

INTRODUCTION

The Highland Lakes, located on the Colorado River in Central Texas, are managed by the Lower Colorado River Authority (LCRA) and are represented by Lake Buchanan, Lake Travis, and four small pass-through reservoirs (Inks Lake, Lake Lyndon B. Johnson, Lake Marble Falls). Lake Austin, which is immediately downstream from Lake Travis, is excluded from all analyses in this report. The lakes provide drinking water to more than a million people and water to industries, businesses, agriculture, and the environment throughout the lower Colorado River Basin. However, during the period 2011–2014, inflow volumes to the lakes were minimal, resulting in their combined storage volume to be almost the lowest since the reservoirs filled in 1942. A graph presenting total storage in the Highland Lakes since 1940 is presented in Figure 1.

As of March 1, 2015, Lakes Travis and Buchanan had a combined storage of about 700,000 acre-feet, which is only 35% of their full capacity of about 2 million acre-feet. Storm runoff later in the year and in 2016 more than doubled the storage volume. However, future drought could cause the storage volume to drop below 600,000 acre-feet, or 30% of capacity. If the storage drops to that level, the LCRA Board of Directors might issue a drought worse than the Drought of Record declaration. Following a state-approved plan, LCRA might then require cities, industries, and other firm customers to reduce their water use by 20% and cut off all Highland Lakes water to interruptible customers (LCRA 2015).

Inflow volumes to the Highland Lakes have substantially reduced over time. Additionally, the effect of El Niño conditions does not provide certainty of increased inflow volumes to the Highland Lakes. The purposes of this report are to document temporal trends in inflow volumes to the Highland Lakes, identify possible causes for any trends, and analyze the relations, especially for the wettest and driest periods, between inflow volumes to the Highland Lakes and selected climatic (oceanic and atmospheric) indices.

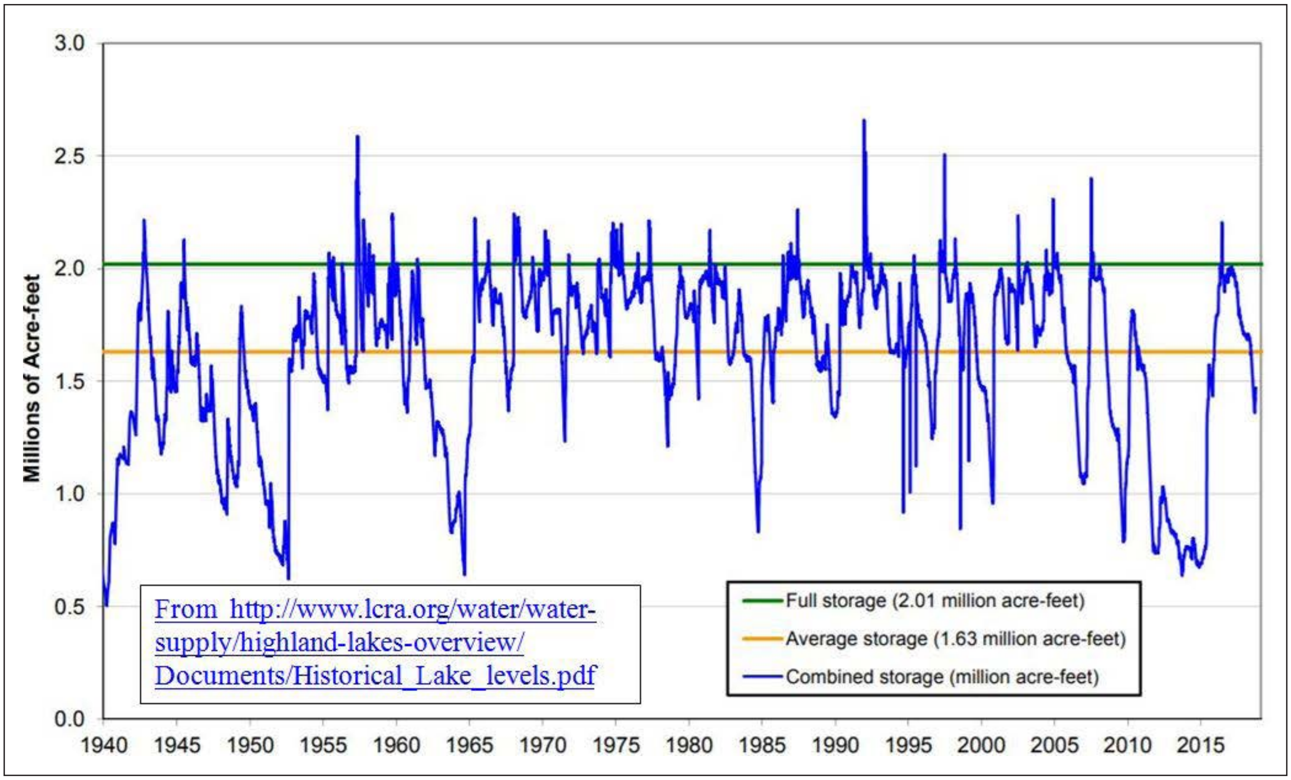

Figure 1. Total combined storage in Lakes Buchanan and Travis.

INFLOW VOLUMES TO THE HIGHLAND LAKES

The LCRA uses streamflow data from four U.S. Geological Survey (USGS) streamflow stations to calculate total stream inflow into the Highland Lakes (Figure 2, station numbers 4–7). The stations gage streamflow volumes on the four largest streams that provide direct inflow to the lakes—the Colorado River, the Llano River, Sandy Creek, and the Pedernales River. The gaged flow values are multiplied by factors equal to or exceeding 1.0 to estimate the runoff from the ungaged parts of their basins and from the ungaged basins that provide inflow to the Highland Lakes. The inflow runoff factors are presented in the section "Upstream Flow Conditions and Gauged Inflows" (LCRA 2018).

The total contributing drainage area for the four streamflow stations represents 92% of the total drainage area for the Highland Lakes; thus, inflow is estimated for only 8% of the Highland Lakes Basin. The estimated inflow values represent only a small part of the total inflow; therefore, the author considers the potential error for the total inflow values to be minimal for this analysis.

Inflow to Lake Buchanan is based solely on the Colorado River streamflow-gaging station near San Saba (Figure 2, Station 4). The contributing drainage area for the station represents about 97% of the Lake Buchanan Basin; thus, the gaged flow volumes are increased by 3% to account for total inflow to Lake Buchanan. Direct inflow to Lake Travis and the three reservoirs between Lake Buchanan and Lake Travis are based on gaged streamflow from the Llano River, Sandy Creek, and the Pedernales River (Figure 2). The drainage area for the three stations represents about 79% of the basin for Lake Travis and the associated three reservoirs.

Based on the calculations described above, monthly, seasonal (three-month period), and annual inflow volumes to the Highland Lakes were calculated for the period January 1942 through December 2013 (Figure 3) and used for analyses in this report. The LCRA presents an interactive map of the Highland Lakes Basin at http://hydromet.lcra.org/full.aspx, and the USGS has an interactive map presenting the locations and historic and current flow data for the streamflow stations at http://maps.waterdata.usgs.gov/mapper/index.html?state=tx.

The 1942–2013 mean inflow to the Highland Lakes is 1,673 cubic feet per second (ft^3/s), equivalent to 1.212 million acre-feet per year. Monthly inflow volumes to the lakes were analyzed to assess the distribution of such values. The 864 monthly values were sorted by magnitude to assess inflow volumes during the wettest and driest periods. Based on the analysis, relatively rare large regional floods produce most of the inflow to the lakes. For example, the wettest half of all months (the

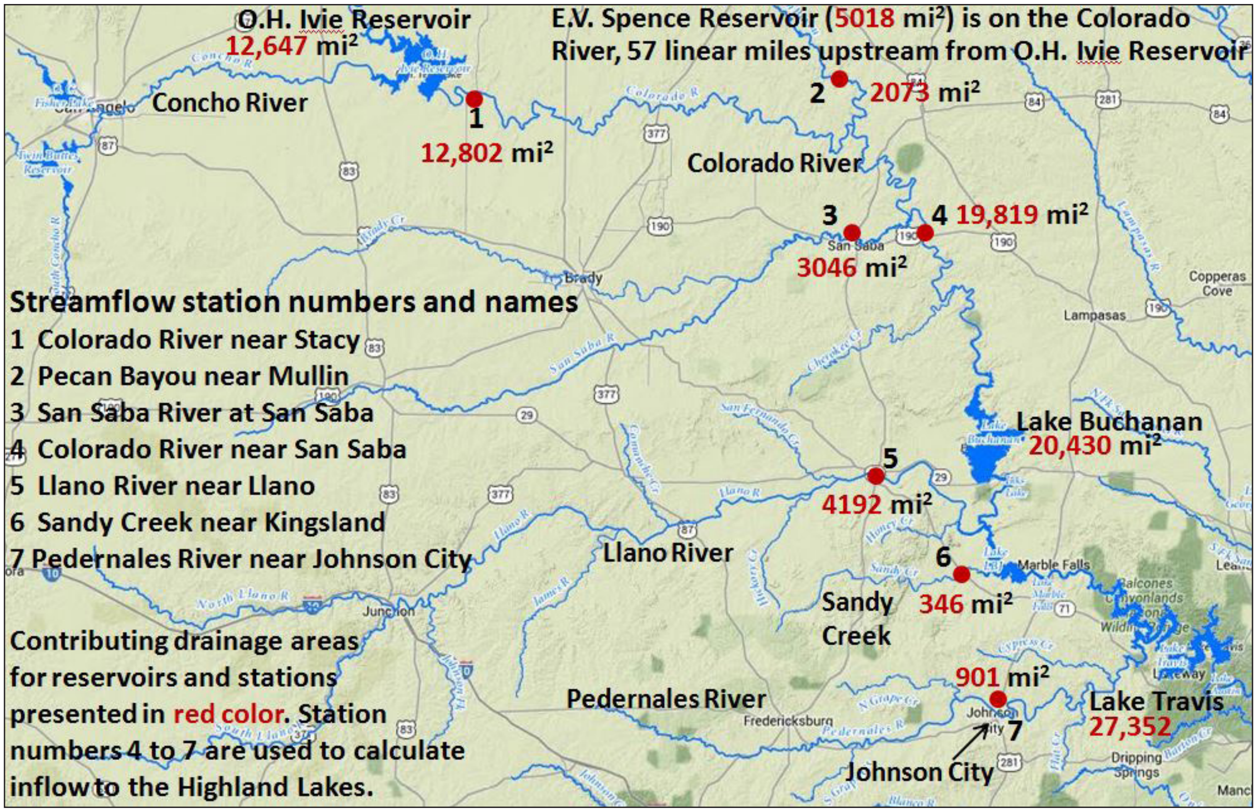

Figure 2. Locations of streams, reservoirs, and streamflow-gaging stations.

432 months with the greatest inflow volumes) produced 89% of the 1942–2013 total inflow volume to the lakes. Also, the wettest 10% of the months (87 months) produced 49% of the total inflow to the lakes. Additionally, the wettest 1% of the months (nine months) produced 13% of the total inflow volume.

Likewise, the driest months produce inflow volumes substantially lower than the mean inflow. For example, the driest half of the months (the 432 months with the lowest inflow volumes) produced only 11% of the total inflow volume to the lakes. Additionally, the 10% of the months with the lowest inflow volumes produced only 0.7% (less than 1%) of the total inflow volume.

A best-fit linear trend for the annual inflow volumes to the Highland Lakes indicates a 19% reduction in total inflow. Inflow volumes for each lake and the causes for changes in volumes are discussed below.

Inflow to Lake Buchanan

Annual inflow volumes to Lake Buchanan are presented in Figures 3 and 4. The mean inflow to Lake Buchanan is 772 ft³/s, or 559,000 acre-feet per year, which represents 46% of total inflow to the Highland Lakes for the period 1942–2013.

Prior to the completion of E.V. Spence Reservoir in 1969, inflow to Lake Buchanan represented 59% of total inflow to the Highland Lakes (Figure 3). However, since the completion of E.V. Spence Reservoir (Figure 5), inflow to Lake Buchanan represents only 39% of total inflow to the Highland Lakes and only 29% of such for 2006–2013.

Additionally, inflow to Lake Buchanan has decreased substantially over the 72-year period shown (Figure 5). A best-fit linear trend documents inflow to have decreased from about 792,000 acre-feet per year to about 323,000 acre-feet per year during the period—a 59% decrease. The portion of the Lake Buchanan Basin controlled by upstream major reservoirs has increased from 22% in 1942 to 72% since 1990 (Figure 4). The basin for O.H. Ivie Reservoir represents 62% of the Lake Buchanan Basin (Figure 2)—13 of the major reservoirs are upstream from O.H. Ivie Reservoir. An additional 10% of the Buchanan Basin is controlled by Brady Creek Reservoir and Lake Brownwood (Figure 5) on tributaries that enter the Colorado River downstream from O.H. Ivie Reservoir. Three of the smaller major reservoirs are in the drainage basin for Lake Brownwood. Information regarding these reservoirs and a map of their locations can be found on the Texas Water Development Board (TWDB) website (TWDB n.d. a).

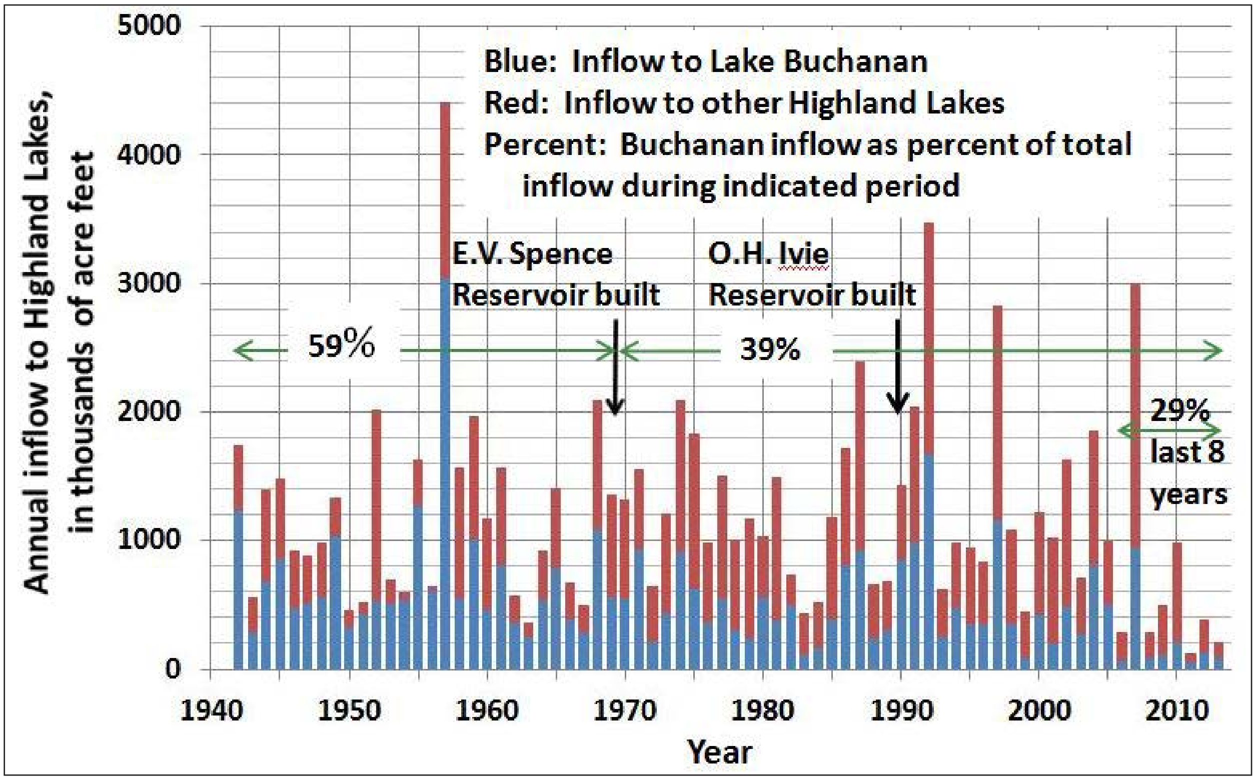

Figure 3. Annual runoff volumes to the Highland Lakes, 1942–2013.

Inflow reduction

The two largest reservoirs upstream from Lake Buchanan are E.V. Spence Reservoir and O.H. Ivie Reservoir. O.H. Ivie Reservoir was completed by the Colorado River Municipal Water District (CRMWD) in 1990 (Figure 2) and was filled to its capacity (554,000 acre-feet) by large floods in 1992. Wetter than normal years in 1996 and 1997 kept the reservoir nearly full; however, since 1998 its contents have been mostly declining.

The streamflow-gaging station on the Colorado River near Stacy, Texas is immediately downstream from O.H. Ivie Reservoir (Figure 2), and thus represents outflow from the reservoir. From 1968 to the completion of O.H. Ivie Reservoir in 1990, the streamflow volume at the gaging station (outflow from O.H. Ivie Reservoir) represented 32% of the inflow volume to Lake Buchanan (Figure 4). However, from 1990 through 2013, flow at the gaging station represented only 8% of inflow to Lake Buchanan. Additionally, since 1999, flow at the Stacy station represented only 2% of inflow to Lake Buchanan. Therefore, during the past many years, the Colorado River drainage basin downstream from O.H. Ivie Reservoir has produced the vast majority of the inflow to Lake Buchanan. However, small-discharge environmental releases are required from O.H. Ivie Reservoir (Hauck and Pandey 2015). For example, as represented by the Colorado River near Stacy gage, the monthly mean releases from O.H. Ivie Reservoir have averaged less than 1 ft³/s, or 59 acre-feet per month, only twice since completion of the reservoir.

Based on this analysis, it is likely that releases from O.H. Ivie Reservoir will not represent substantial inflow contributions to Lake Buchanan until O.H. Ivie Reservoir and possibly the other upstream reservoirs are full or nearly full. However, as of July 29, 2016, O.H. Ivie Reservoir was only 23% full and E.V. Spence Reservoir was only about 10% full (CRMWD n.d. b). These two reservoirs are at low conditions; thus, substantial releases from O.H. Ivie Reservoir likely will not occur until that area receives substantial runoff from several large regional storms.

Additionally, outflow from Brady Creek Reservoir has decreased substantially from 1940 to 2013 (Figure 5). For example, from 1940 to 1986, the mean outflow from Brady was 17.0 ft³/s, or 12,300 acre-feet per year, which represents about 2% of the mean inflow to Lake Buchanan. However, from 2001 to 2013 the mean outflow was 1.20 ft³/s—an outflow reduction of 93%. Outflow data do not exist for Lake Brownwood on Pecan Bayou, but data for a downstream streamflow gage near the mouth of the creek document the mean flow to be 175 ft³/s from 1968 to 1999 but only 129 ft³/s from 2000 to 2013—a 26% reduction.

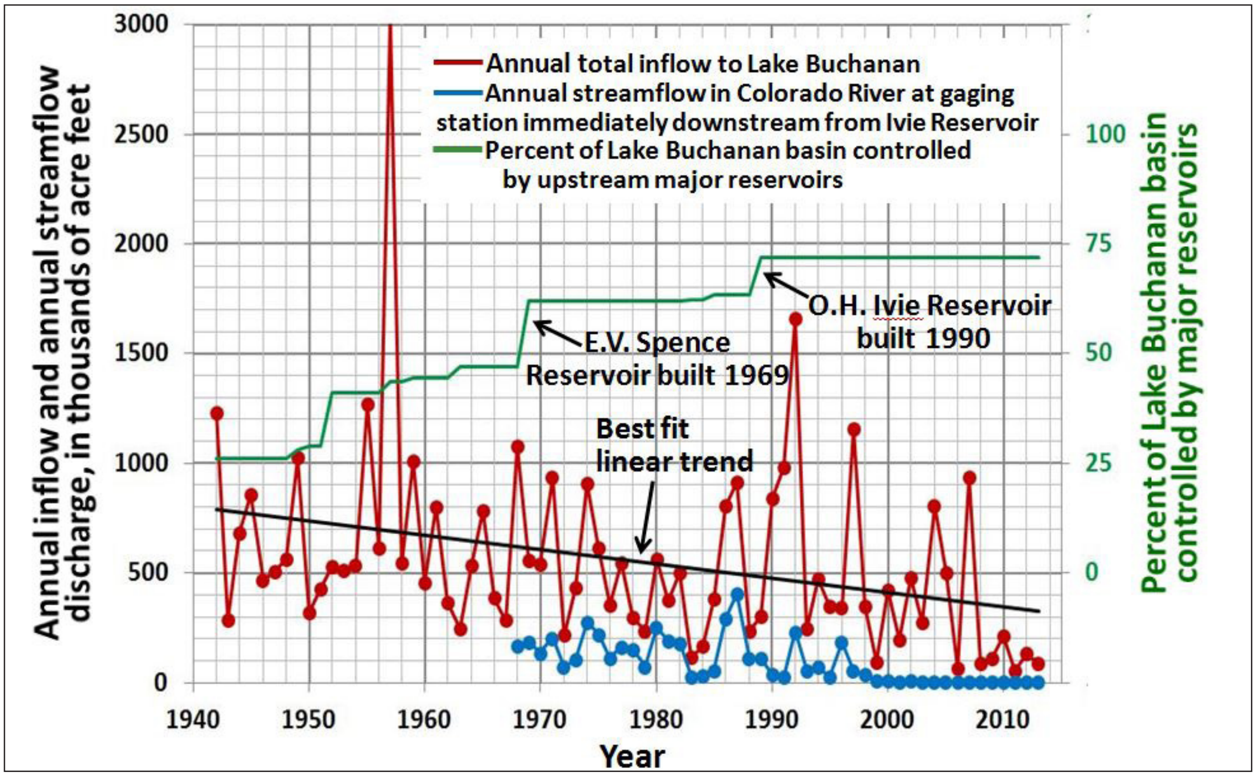

Figure 4. Temporal trends in inflow volumes to Lake Buchanan, 1942–2013.

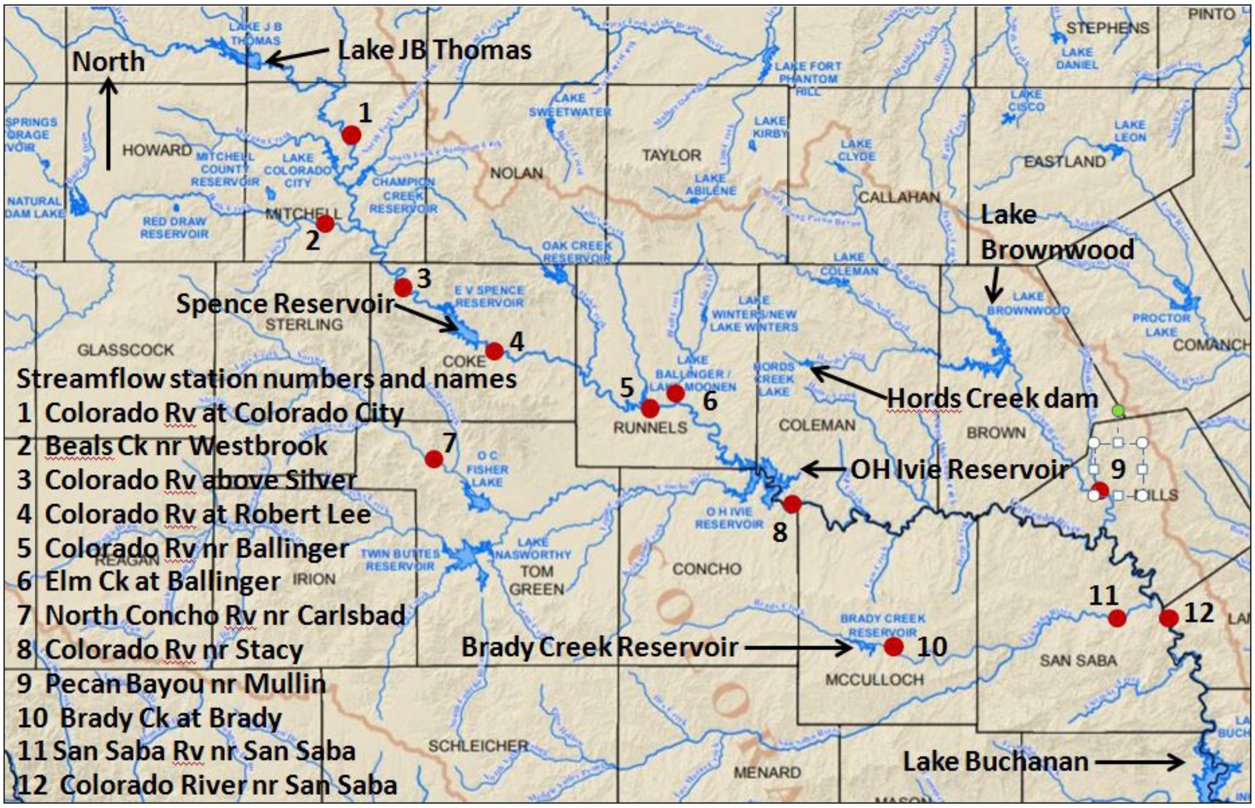

Figure 5. Locations of streamflow gages and other sites used for analyses.

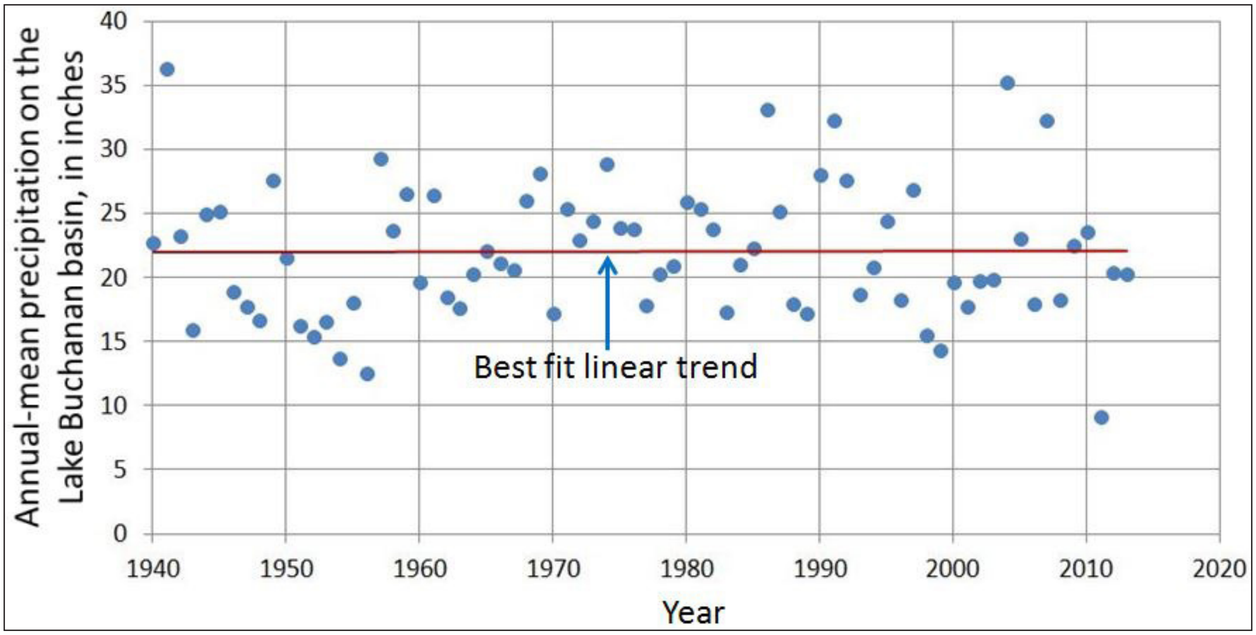

Figure 6. Annual precipitation on the Lake Buchanan Basin, 1940–2013.

Causes for inflow reduction

The purpose of this section is to identify and attempt to quantify for the Lake Buchanan drainage basin, the meteorologic and hydrologic factors that have contributed to the reduction of inflow to Lake Buchanan. Therefore, the changes in data values or significance for the factors and their impact on the reduction of inflow to Lake Buchanan from 1942 to 2013 are emphasized. The basin is believed to be free of major volumes of import or export of water and free of major deliveries of groundwater to the surface or of surface water to groundwater; thus, the factors identified below are believed to represent major water consumption within the basin. Data values for most of the factors associated with inflow reduction are estimated and have large potential error; however, the author believes the data values to be indicative of the relative magnitude of impact on the reduction of inflow values.

Precipitation and withdrawals

Temporal trends in precipitation were investigated as a potential factor affecting reduced inflow to Lake Buchanan. A graph presenting annual precipitation from 1940 through 2013 for the Lake Buchanan Basin is presented in Figure 6. The annual precipitation data are from the TWDB (TWDB n.d. c) and represent values of annual mean precipitation for the one-degree quadrangle numbers 506, 507, 606, 607, 608, and 609—the areas for those quadrangles approximate the drainage area for Lake Buchanan. A severe drought occurred in 2011, but annual precipitation values for most of the years from 2000 to 2013 have exceeded about 20 inches per year—a value within 2 inches of the long-term mean value of 22.12 inches per year (Figure 6). Additionally, the best-fit trend line indicates no meaningful temporal trend in annual precipitation for the Buchanan Basin.

However, infrequent large storms produce most of the runoff in the area. For example, for the Beals Creek, North Concho River, Elm Creek, and San Saba River streamflow-gaging stations (Figure 5), 1% of their largest daily-mean streamflow values from 1940 to 2013 contain 52%, 80%, 57%, and 31%, respectively, of the total flow volumes for the period. Therefore, daily precipitation data were analyzed for every National Weather Service rain gage in the Buchanan Basin with data from 1940 to 2013. The annual number of daily values with precipitation depths exceeding 2 inches was identified for each of the seven gages found. Based on this analysis, for each of the gages, the frequency of large storms since 2000 is comparable to the frequency of such storms prior to 2000. Therefore, changes in large-storm precipitation are not likely a major cause for reduction in inflow to Lake Buchanan.

Increases in surface water withdrawals from 1940 to 2013 were investigated as a potential source for inflow reduction to Lake Buchanan. The population for the 13 counties totally within the basin was 178,000 in 1940 and 244,000 in 2013—a 37% increase (Texas Almanac n.d.). However, other than for irrigation data beginning in 1958, surface water withdrawal data for the Buchanan Basin could not be found prior to 1974. Total reported surface water use was 112,900 acre-feet in 1974 and only 51,700 acre-feet in 2016 (TWDB n.d. b). Irrigation represented 58% of the 1974 water use but declined to only

36% of the 2016 use. Therefore, total water use, a large part of which includes irrigation, cannot be estimated based on water-use values for 1940 without substantial potential error in the value.

However, based on population data and per-capita use, it is estimated that 2016 water use was 37% greater than 1940 water use. Therefore, 1940 water use is estimated to be 37,700 acre-feet per year. All withdrawn water is assumed to be directly consumed. The permitted total withdrawal from the major reservoirs is 358,500 acre-feet per year—a value about six times greater than was reported withdrawn in 2016 and 64% of the mean-annual inflow to Lake Buchanan. Therefore, if future withdrawal values approach those for permitted values, additional reduction of inflow to Lake Buchanan would probably occur.

Temporal increases in unpermitted surface water withdrawals also are probably a major source of reduction in inflow to Lake Buchanan (2018 personal communications from David Bass, LCRA; unreferenced). However, data or information for this factor could not be found.

Reported total groundwater withdrawal for the 13 counties totally within the Buchanan Basin was 82,500 acre-feet in 1980 and 138,000 acre-feet in 2013. The pumpage increase of 55,500 acre-feet per year is substantial, but the impact on surface water availability is unknown. However, streamflow gain-loss studies conducted on the Colorado River, Beals Creek, Concho River, Elm Creek and San Saba River document large streamflow discharge gains in some channel reaches and large losses in other reaches. The gains and losses mostly represent interchange of water between stream channels and underlying aquifers. For example, a gain-loss study for the Colorado River from J.B. Thomas Reservoir to O.H. Ivie Reservoir in January 1987 documents the reach to be losing water in some parts and gaining in others, but the entire reach lost 23.6 ft^3/s (17,100 acre-feet per year) during high base-flow conditions (Slade et al. 2002). Increased groundwater pumpage probably reduces base-flow discharges in the major streams, but the majority of inflow to Lake Buchanan is flood runoff, which the author believes has had only a minimal impact from groundwater withdrawals.

Evaporation

Temporal changes in air temperature, wind speed, solar radiation, and relative humidity associated with climate change could cause an increase in evaporation rates, which would contribute to reductions of inflow to Lake Buchanan. Annual gross lake evaporation values from 1954 to 2013 for the Lake Buchanan Basin are presented in Figure 7. The data are from the TWDB (TWDB n.d. c) and represent the annual mean gross lake evaporation for one-degree quadrangle numbers 506, 507, 606, 607, 608, and 609—the areas for those quadrangles approximate the drainage area for Lake Buchanan. A best-fit linear trend for the data documents an increase of about 1.4 inches during the 60-year period. The trend was calculated to be an increase of 1.68 inches (3% increase) after adjustment for the longer period of 1942–2013. Based on the mean value for the 1940 and 2013 mean surface areas for all reservoirs in the basin, this increase represents an increase of 8,060 acre-feet per year or 1% of the mean inflow to Lake Buchanan (Table 1). To verify the finding above, a search was made for National Weather Service weather stations with long-term evaporation data within the Buchanan Basin. Two such stations were found: Hords Creek Dam in Coleman County and San Angelo Mathis Field in Tom Green County (Figure 5). Analysis of the evaporation data for the two stations substantiate a small temporal increase in evaporation comparable to that indicated above.

Additionally, total lake evaporation in the Lake Buchanan Basin has increased due to the proliferation of reservoirs in the basin (Table 1). Three databases for reservoirs in the area were used to assess evaporation and storage characteristics. In the basin area, the National Inventory of Dams (NID) identifies all 19 major reservoirs and 558 minor reservoirs, including all Natural Resources Conservation Service (NRCS) reservoirs (Table 1). This database (National Inventory of Dams n.d.) was used to determine the surface area and storage characteristics for the major reservoirs and NRCS reservoirs in Table 1. The database includes physical characteristics for each identified reservoir posing a failure risk or meeting specific criteria for minimum storage volume or minimum dam height. The Texas Commission on Environmental Quality (TCEQ) dam safety database represents dams that are routinely inspected by the agency. It includes 531 minor reservoirs in the area. This database was used to verify the reservoir characteristics from the NID database.

The National Hydrography Dataset (NHD) for water bodies in the Upper Colorado River Basin was created in about 2005 by the USGS using land use and aerial photo information. Water bodies in this database were used to develop the characteristics for "other minor reservoirs" in Table 1. The database identifies the location and exposed surface water area for all water bodies greater than about 0.25 acres in size but contains no other data or information about the water bodies. The coverage identifies 69,211 water bodies, excluding major and NRCS reservoirs; however, the majority of the water bodies are small (Kennedy Resource Company 2017). For example, surface areas are not available for 19% of the reservoirs—likely those with less than 0.25 acres of surface area. Also, an additional 70% of the water bodies have a surface area less than 1 acre. Many if not most of the water bodies probably are not reservoirs but herein are collectively referenced as "other minor reservoirs." Although data are not readily available, some of these reservoirs are within

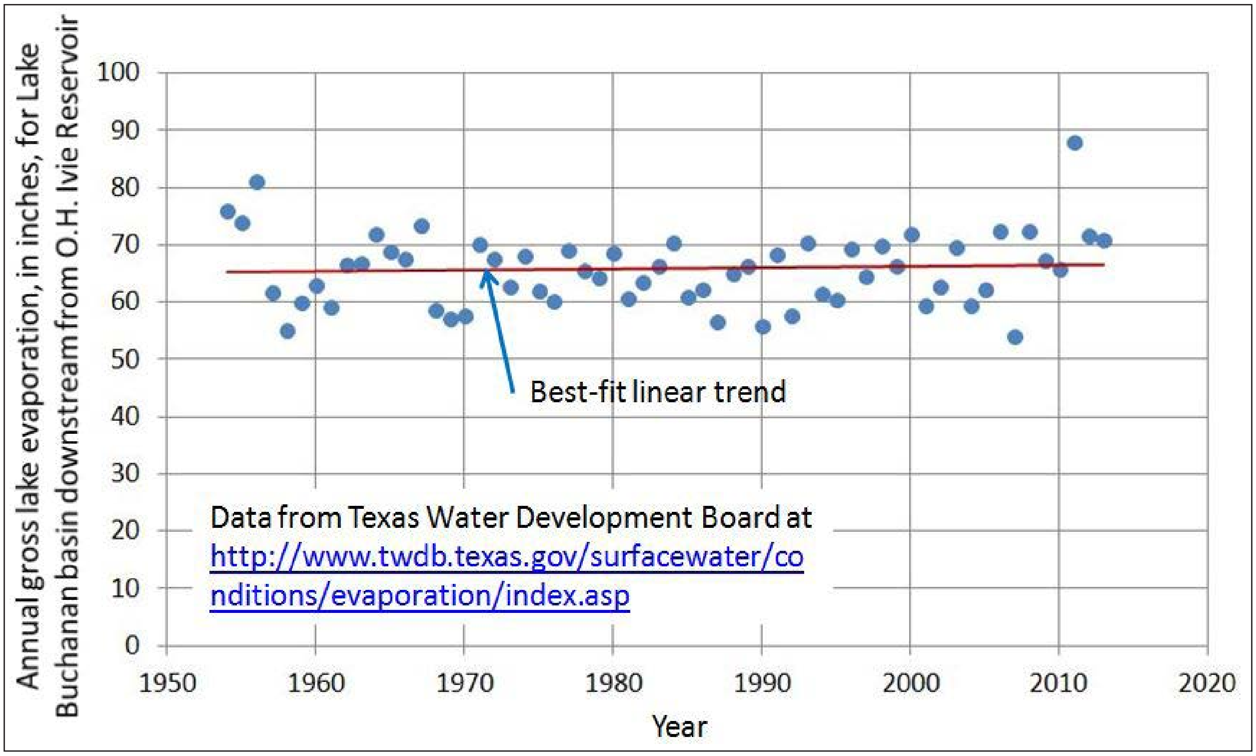

Figure 7. Annual mean gross lake evaporation for the Lake Buchanan Basin.

the non-contributing drainage area for the Colorado River, but the number of such reservoirs and their water-surface area are deemed to be minimal.

For 13 of the largest 19 major reservoirs, water elevations have been gaged since they began filling; thus, long-term mean pool areas and mean storage volumes were calculated based on the entire period of record (Table 1), from data maintained by the USGS (USGS n.d.) and the TWDB (TWDB n.d. a). The gaged reservoir data represent 96% of total conservation storage for the major reservoirs and 77% of total conservation storage for all reservoirs. Therefore, the evaporation and storage characteristics for all reservoirs and especially the major reservoirs presented in Table 1 probably contain minimal potential error. For the other major reservoirs and minor reservoirs, the average surface areas and average storage contents are estimated in Table 1.

The long-term mean storage contents for the major reservoirs without gaging data and the NRCS reservoirs are estimated to be about one-third of conservation storage (2018 personal communications from John Newman, unreferenced). Most of the reservoirs have a flat bed with sloping sides; thus, the long-term mean surface areas for these reservoirs are estimated to be one-half of the conservation pool area. Therefore, the evaporation loss for NRCS reservoirs and major reservoirs without water-elevation data are based on one-half of the value for the conservation pool area. However, the surface areas for minor reservoirs other than NRCS reservoirs are based on the NHD coverages collected in about 2005. The assumption is made that these surface-area values represent long-term mean conditions, even though, based on streamflow throughout the Colorado River Basin, 2005 was drier than long-term mean conditions. The conservation and flood storage for the 8,311 other minor reservoirs exceeding 1 acre of surface area were estimated based on mathematical relations between surface areas and storage characteristics for reservoirs in the other two reservoir databases. Additionally, the number of the other minor reservoirs existing in 1940 and their surface area and storage characteristics are based on reservoir completion dates and data from the same other two databases.

In 2013, the mean evaporation volume for all reservoirs, the major reservoirs, and the minor reservoirs represented 79%, 25%, and 54%, respectively, of the mean-annual inflow to Lake Buchanan (Table 1). The evaporation volume for reservoirs in 1940 was substantially less than that in 2013; thus, temporal increase in lake evaporation is a major cause for decreased inflow to Lake Buchanan.

Evaporation from stream channels is estimated based on data from discharge measurements made at nine streamflow gaging stations on the Colorado River and one station each on Beals Creek, the Concho River, Elm Creek, Pecan Bayou and the San Saba River (Figure 5). Based on the long-term median discharge value for each station and channel data for each dis-

Table 1. Hydrologic characteristics of reservoirs in the Lake Buchanan Basin.

Lake Buchanan began filling in 1940	Reservoir and water body types							
	All		Major[1]		NRCS[2]		Other minor[3]	
	1940	2013	1940	2013	1940	2013	1940	2013
Number of reservoirs or water bodies	17,302	69,545	2	19	0	315	17,300	69,211
Total drainage area (square miles)[4]	7,630	41,240	5,380	30,700	0	1,540	2,250	9,000
Surface area (acres)	--	--	--	--	--	--	--	--
Conservation pool	12,000	248,000	8,680	82,400	0	7,200	39,500	158,000
Long-term mean[5]	26,900	120,000	7,080	37,600	0	3,600	19,800	79,000
Net evaporation, mean annual (inches)[6]	43.88	43.88	43.88	43.88	0	43.88	43.88	43.88
Volume (thousands of acre-feet)[7]	98.3	439	25.9	137	0	13.2	72.4	289
Volume as percent of Buchanan inflow[8]	18%	79%	5%	25%	0%	2%	13%	52%
Storage, volume (thousands of acre-feet)	--	--	--	--	--	--	--	--
Conservation	253	2,500	138	2,000	0	41.8	115	459
Long-term mean[9]	152	815	114	648	0	13.9	38.3	153
Mean as percent of Buchanan inflow[8]	27%	146%	20%	116%	0	2%	7%	27%
Conservation minus long-term mean[10]	101	1,680	24	1,350	0	27.9	76.7	306
As percent of Buchanan inflow[11]	18%	301%	4%	242%	0%	5%	14%	55%
Flood	1,270	8,360	1,040	6,600	0	839	230	918

[1] Reservoirs with at least 5,000 acre-feet of conservation storage

[2] Floodwater retarding structures built by the Soil Conservation Service, now named the National Resources Conservation Service

[3] Data from aerial images as explained in text. All 1940 data for these reservoirs estimated. Conservation pool areas and storage capacities estimated only for the 8,311 reservoirs with pool areas exceeding one acre.

[4] Much of total drainage area duplicated—some reservoir basins are within the basins of other reservoirs

[5] Based on long-term gaged data for most major reservoirs and one-half of conservation pool area for other major reservoirs and NRCS reservoirs. Based on aerial photo images for other minor reservoirs

[6] For Lake Buchanan Basin—equals long-term mean annual gross lake evaporation (66.00 inches) minus long-term mean annual precipitation (22.12 inches)

[7] Product of long-term mean pool area and long-term mean annual net evaporation (43.88 inches)

[8] Based on 1942–2013 mean annual inflow to Lake Buchanan—559,000 acre-feet per year

[9] Based on long-term gaged data for most major reservoirs and one-third of conservation storage for other reservoirs

[10] Represents average conservation storage void, in thousands of acre-feet, that must be filled by runoff before full conservation storage, and typically outflow from reservoir, is attained

[11] Average conservation storage deficit expressed as percent of 1942–2013 mean annual inflow to Lake Buchanan

charge measurement, the stream width was determined for the median discharge at each gaging site (USGS n.d.). Also, based on the stream-mile distance between gages, the total area for the major stream surfaces during median flow conditions was calculated. Evaporation from minor streams is not included in this analysis, but most have small widths and intermittent flow; thus, evaporation from these streams is deemed to be minimal. The mean annual net evaporation rate of 43.88 inches (Table 1) was assumed to occur over the 6,030 acres of stream-surface area, which produces 22,000 acre-feet per year as the mean annual net evaporation from major streams—a value representing 4% of the mean annual inflow to Lake Buchanan. This analysis represents the period 1942–2013. Median stream widths, and thus the evaporation in 2013, might be slightly less than the long-term average due to temporal reduction of streamflow. However, the slight increase in evaporation rate mentioned above might offset that reduction. Therefore, it is likely that changes in stream evaporation are minimal and not a major factor of inflow reduction for Lake Buchanan.

Evaporation from wetted soil also is a major source of water loss in the basin. However, due to lack of long-term soil moisture and other data, a value for soil evaporation cannot be estimated without substantial potential error. However, it is unlikely that soil evaporation has substantially increased from 1942 to 2013; thus, this factor is not considered to be a major cause for reduction in inflow to Lake Buchanan.

Transpiration and reservoir losses to groundwater

Transpiration due to phreatophytes within reservoirs was evaluated for the major reservoirs in the Buchanan Basin. A study of transpiration from brush above the normal water level and within the O.H. Ivie Reservoir conservation pool area found that brush removal would provide a water yield averaging about 25,000 gallons per acre per year (Hauck and Pandey 2015). The assumption was made for each of the major reservoirs within the Buchanan Basin that the land area between the mean surface area and that inundated by the flood storage pool is covered with the same type and density of brush as that within O.H. Ivie Reservoir. This total area is about 92,300 acres, which, based on the yield identified above, is only 7,080 acre-feet per year—a value representing only 1.3% of the mean annual inflow to Lake Buchanan.

However, transpiration and other losses from NRCS floodwater retarding structures (Table 2) are substantial. Consumptive losses for the reservoirs, which include evaporation, transpiration, and seepage to groundwater, have been extensively studied by the USGS via calculations and analyses of inflow-outflow water budgets. Landowners are prohibited from withdrawing water from most NRCS reservoirs; thus, water-use for the reservoirs is considered to be minimal (2018 personal communications from John Newman, NRCS; unreferenced). Six NRCS reservoirs in each of two studied stream basins within the Lake Buchanan Basin were gaged for many years to measure monthly inflow and outflow volumes for the reservoirs. The volume of water by which inflow exceeds outflow represents the consumption value. Water budgets were computed for reservoirs in the Deep Creek Basin in McCulloch County and Mukewater Creek Basin in Coleman County (Figure 5). Based on data for Deep Creek, the mean consumptive loss for the reservoirs represents 30% of inflow and losses for transpiration, and groundwater seepage exceeded net evaporation by 113% (Gilbert and Sauer 1970). Losses for transpiration and groundwater seepage for the Mukewater reservoirs exceeded net evaporation by 91%; thus, the mean value for the two basins is 102%. Net evaporation losses for the NRCS and other minor reservoirs were calculated independently of these studies and reported in Table 1; thus, losses for transpiration and groundwater seepage were assumed to be 102% of net evaporation values.

However, the soils beneath the Deep Creek and Mukewater Creek reservoirs contain greater clay content than the majority of other NRCS structures in the Buchanan Basin; thus, consumption for the other NRCS reservoirs likely is greater due to increased seepage to groundwater (2018 personal communications from John Newman, NRCS; unreferenced). Therefore, the loss identified above is a minimal value. The same consumptive loss for transpiration and groundwater seepage is assumed to apply to the other minor reservoirs. Therefore, total water losses from all minor reservoirs for transpiration and seepage to groundwater was calculated to be 308,000 acre-feet per year in 2013—a value equal to 55% of the mean annual inflow to Lake Buchanan (Table 2).

The evaporation value for the minor reservoirs is about double that for the major reservoirs, but transpiration for the minor reservoirs exceeds that for the major reservoirs by many orders of magnitude (Table 2). For a comparison of transpiration losses, all the major reservoirs and all the 8,311 other minor reservoirs with surface areas exceeding 1 acre were used. Assuming a circular shape for all reservoirs, the total circumference for the conservation pool would be 175 miles for the major reservoirs and 5,885 miles for the other minor reservoirs. Additionally, assuming that phreatophytes exist around each reservoir conservation pool for a distance of 0.05 miles (about 260 feet), then there would be a phreatophyte zone of 5,700 acres around the major reservoirs and 147,000 acres around the minor reservoirs. Though the reservoirs are not perfectly circular, this exercise demonstrates the extent by which the area of phreatophyte coverage around the minor reservoirs exceeds that around the major reservoirs.

Information or data regarding losses to groundwater from major reservoirs could not be found for the area. The results for inflow-outflow water budgets performed for a dry period for Lake J.B. Thomas and Brady Creek Reservoir accounted for essentially all reservoir losses without the inclusion of reservoir losses to groundwater. Therefore, such losses likely are minimal.

However, transpiration losses are considerable in the stream channels upstream from O.H. Ivie Reservoir (Slade and Buszka 1994). Prior to 1950, salt cedar was confined to a few areas in small thickets; however, from 1950 to 1969, areal coverage increased at least 500% (Larner et. al 1974). As of 1969, salt cedar of various densities covered 1,450 acres in the Colorado River flood plain. As of 1982, salt cedar covered about 10,000 acres in the Colorado River flood plain and about 2,500 acres in the Beals Creek flood plain in the study area (Slade and Buszka 1994).

The lengths of the reaches of the Colorado River, Beals Creek, Elm Creek, and the Concho River upstream from O.H. Ivie Reservoir are 239 miles, 13 miles, 10 miles, and 33 miles, respectively. The flood plain along the Colorado River covers

Table 2. Summary of water losses in the Lake Buchanan Basin, 1942–2013.

Lake Buchanan began filling in 1942 All values in acre-feet per year	Year		Increase in data value 1942–2013	Data value increase as percent of	
	1942	2013		annual-mean inflow to Lake Buchanan	1942–2013 reduction in inflow to Lake Buchanan
All reservoirs	--	--	--	--	--
Net evaporation	98,300	439,000	341,000	61%	73%
Transpiration and other[1]	73,900	315,000	241,000	43%	51%
Major reservoirs	--	--	--	--	--
Net evaporation	25,900	137,000	111,000	20%	24%
Transpiration	111	7,080	6,970	1%	1%
Minor reservoirs	--	--	--	--	--
Net evaporation, total	72,400	302,000	230,000	41%	49%
TRNS reservoirs	0	13,200	13,200	2%	3%
Other reservoirs	72,400	289,000	217,000	39%	46%
Other losses, total[2]	73,800	308,000	234,000	42%	50%
TRNS reservoirs	0	13,500	13,500	2%	3%
Other reservoirs	73,800	295,000	221,000	40%	47%
Surface water withdrawals[3]	37,700	51,700	14,000	2%	3%
Channel transpiration[4]	18,900	189,000	170,000	30%	36%
Channel evaporation[4]	22,000	22,000	0	0%	0%

The vast majority of basin losses are from reservoirs. Basin losses exceed the reduction of inflow to Lake Buchanan because much of the water loss from the reservoirs would otherwise be lost downstream as evapotranspiration in the channel before arriving at Lake Buchanan.

Although values could not be found, increased evapotranspiration outside stream channels due to increased phreatophytes is probably a major cause for reduced inflow to Lake Buchanan.

See Table 1 for additional information and data for reservoirs.

[1] Represents transpiration losses for major reservoirs and losses for transpiration and seepage to groundwater for minor reservoirs

[2] Represents transpiration and seepage to groundwater

[3] As reported based on permits. Unpermitted withdrawals considered to be substantial.

[4] Represents major stream channels as described in this report

34,200 acres, and an additional 11,000 acres is included for the flood plain around E.V. Spence Reservoir. Flood plains for Beals Creek, Elm Creek, and the Concho River cover about 3,200 acres, 1,200 acres, and 12,000 acres, respectively. As of 1992, excluding E.V. Spence Reservoir, 50,600 acres of flood plain along the four streams were covered by salt cedar and mesquite. The transpiration rate from phreatophytes across the flood plain of the four major streams is estimated to be 29.6 inches per year on the basis of the coverage data for salt cedar and mesquite and the Blaney-Criddle formula (Rantz 1968). This transpiration loss calculates to be 125,000 acre-feet per year (Slade and Buszka 1994)—a value representing 130% of the mean annual inflow to O.H. Ivie Reservoir (CRMWD n.d. a) and 22% of the mean annual inflow to Lake Buchanan. After 1994, the CRMWD initiated control measures for phreatophytes in major stream channels, which likely have mitigated spread of the phreatophytes; thus, it is likely that the current phreatophyte coverage for the stream channels listed above is comparable to that in the 1990 decade (2018 personal communications from John Newman, NRCS; unreferenced).

Based on the estimated increase in brush described above in the years 1950–1969, 1969–1982, and 1982–1992, phreatophyte coverage is estimated to have been more than 1000% greater in 1992 than in 1950. However, some brush likely

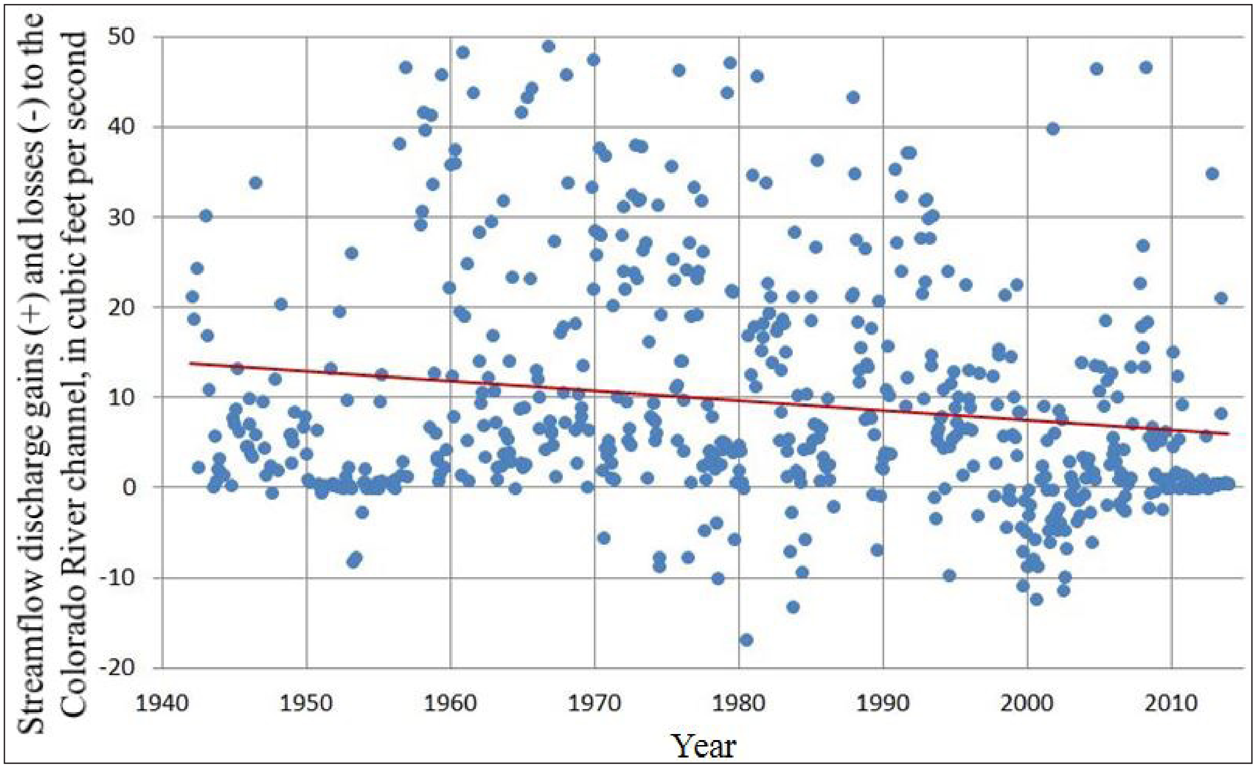

Figure 8. Channel gains and losses for the Colorado River between E.V. Spence Reservoir and O.H. Ivie Reservoir.

existed in the floodplains in 1940; thus, channel transpiration at that time is estimated to be about 10% of that in 1992 and 2013. Phreatophyte density in the 201-river mile reach of the Colorado River between O.H. Ivie Reservoir and Lake Buchanan, and the 58-mile reach of Pecan Bayou from Lake Brownwood to its mouth (Figure 5) is estimated to be about one-half of that in the channel upstream from O.H. Ivie Reservoir (2018 personal communications from David Bass, LCRA; unreferenced). Additionally, the width of the floodplain for Pecan Bayou is about one-half of that of the Colorado River; thus transpiration in these reaches is estimated to be about 49,000 acre-feet per year in 2013. Additionally, phreatophyte density in the 140-mile reach of the San Saba River is estimated to be one-quarter of that in the Colorado River upstream from O.H. Ivie Reservoir (2018 personal communications from David Bass, LCRA; unreferenced); thus, transpiration for that stream is estimated to be about 15,000 acre-feet per year. This analysis does not account for transpiration from phreatophytes in tributaries to the major streams, but total transpiration from all the major streams is 189,000 acre-feet per year—a value representing 34% of the mean inflow to Lake Buchanan. Therefore, the increase in transpiration due to spread of phreatophytes in streambeds is a major cause of reduced inflow to Lake Buchanan.

In an attempt to verify temporal increases in loss of flow in the Colorado River channel, an analysis was conducted for the 47-mile Colorado River channel from a streamflow gage immediately downstream from E.V. Spence Reservoir to a gage about one-half the distance to O.H. Ivie Reservoir (Figure 5, station numbers 4 and 5). The analysis is based on low-flow discharges because during such conditions, little if any overland flow or local runoff exists. Thus, the majority of runoff is within the channel of the Colorado River. Based on comparison of monthly mean discharge values, a best-fit linear trend indicates a decrease of 8.1 ft^3/s in channel flow from 1940 to 2013 (Figure 8). This represents, from 1940 to 2013, a channel loss increase of 5,900 acre-feet per year or 125 acre-feet per year per mile of channel. For the Colorado River channel investigated by Slade and Buszka (1994), the 1992 channel loss due to phreatophytes was about 420 acre-feet per year per mile. However, the latter analysis evaluated transpiration losses for the flood plain while the channel-flow analysis identifies losses during low-flow conditions.

Brush coverage outside streambeds is increasing in the North Concho River Basin and in much of the remainder of the Concho River Basin (2018 personal communications from Chuck Brown, UCRA; unreferenced). For a paired watershed study of two small basins within the North Concho River Basin, brush was mostly eradicated in one basin and the evapotranspiration rate was compared to that for the untreated basin. The evapotranspiration rate for the treated basin was as much as 25% lower than that for the untreated basin (Saleh et al. 2009).

Within the Buchanan Basin, brush coverage has substantially increased outside stream channels from 1942 to 2013. However, data or information that would document the extent of increased transpiration due to such could not be found. The author believes the increase in transpiration due to increased brush coverage outside stream channels would be greater than that within major channels as documented above.

Conclusion and summary

An analysis is made of temporal trends in runoff from large subbasins within the Buchanan Basin to document inflow reduction without the impact from major reservoirs. Chosen for analysis were large basins with long-term gaged streamflow values (generally 1942–2013), and no or only small major reservoirs. In order to document spatial variability, a basin was chosen in each of the northern, western, eastern, and southern parts of the Buchanan Basin. Respectively, these basins are Beals Creek, the North Concho River, Elm Creek, and the San Saba River (Figure 5). Data from 1942 to 2013 exist for each of these gages except for the Beals Creek gage, which has data from 1958 to 2013.

A substantial temporal decrease in annual runoff was found for each of the four streams. The decreases indicated by the best-fit linear trend for Beals Creek, the North Concho River, Elm Creek, and the San Saba River are 50%, 98%, 38%, and 37% respectively (Figures 9-12). Based on the linear trend for 1958–2013, the percent decrease for Beals Creek was adjusted to represent that for 1942–2013. Removing the last 10 or 12 years of flow data would cause the trends to indicate almost no temporal reduction in flow for all but the North Concho River. The four basins cover 4,952 square miles, or 24% of the Lake Buchanan Basin, and the results are believed to be representative of the remainder of the basin. The major causes for the reduction in runoff for the North Concho River are increased evapotranspiration due to the spread of brush and the proliferation of minor reservoirs (2018 personal communications from Chuck Brown, UCRA; unreferenced). These factors also are probably responsible for decreased runoff for the other three basins. For example, the number of identified other minor reservoirs in the basins for Beals Creek, the North Concho River, Elm Creek, and the San Saba River are 7,557, 849, 2,852, and 6,039 respectively (Kennedy Resource Company 2017). The vast majority of the reservoirs did not exist in 1942. However, the total surface area for the reservoirs in the North Concho River Basin is only 833 acres, which represents about 0.1% of the basin area; thus, evapotranspiration from reservoirs is probably not a major cause of runoff reduction for the basin.

In addition, an analysis of runoff was conducted for the downstream-most part of the Lake Buchanan Basin not regulated by major reservoirs—the part of the basin area downstream from O.H. Ivie Reservoir, Brady Creek Reservoir, and Lake Brownwood (Figure 5). Streamflow gages exist immediately downstream from each of the three reservoirs (Figure 5, station numbers 8-10); thus, the annual mean discharge values for these gages were subtracted from those for the Colorado River near San Saba station (Figure 5, station number 12) in order to document runoff values from the intervening basin area. Based on the common period of record, 1968–2013, the mean runoff is 341 ft^3/s (247,000 acre-feet per year) and a best-fit linear trend documents the discharge to have decreased from 414 ft^3/s to 267 ft^3/s—a 36% reduction (Figure 13). Extending this trend to the 72-year period from 1942 to 2013 produces a mean discharge of 382 ft^3/s (277,000 acre-feet per year) and a flow reduction of 230 ft^3/s or 46%. A major cause for runoff reduction is evaporation and transpiration losses from the proliferation of minor reservoirs in the area, most of which were built after 1942. Based on the USGS NHD coverage, 23,485 reservoirs with a total surface area of 14,615 acres exist in the area. Based on the net evaporation rate for the area, total evaporation losses in 2013 were about 53,400 acre-feet, and losses to groundwater and transpiration from the reservoirs were about 54,500 acre-feet. These losses collectively represent 44% of the mean runoff from the area and a large percentage of reduced runoff. The remaining reduction in flow is attributed to increases in phreatophytes within and outside stream channels and probably to increased unpermitted withdrawals from the reservoirs and streams due to population increases (2018 personal communications from Chuck Brown, UCRA; unreferenced).

When Lake Buchanan began filling in 1942, its basin, which covers 20,430 square miles, contained two major reservoirs that controlled 22% of the basin. Eight percent of the basin was controlled by Lake Brownwood. The other major reservoir, Lake Nasworthy, controlled 14% of the Lake Buchanan Basin but because of its minimal conservation storage volume of only 9,600 acre-feet, it was basically a "flow-through" reservoir. Additionally, in 1942, about half of the minor reservoirs within the NID database were in the basins for Lakes Nasworthy or Brownwood; thus, the vast majority of 92% of the Lake Buchanan Basin was unregulated by reservoirs. In 1942, evaporation from all reservoirs represented only 18% of the value for mean annual inflow to Lake Buchanan (Table 2). Reservoir transpiration and seepage to groundwater collectively represented about 13% of the mean inflow value. Also, surface water withdrawals and transpiration from major channels represented 7% and 3%, respectively, of the mean inflow value. Evaporation losses from streams were about 4% of the inflow value. However, most of the consumption values for 1942 are estimated and subject to substantial potential error. Major sources for losses also include evapotranspiration outside stream channels and unreported surface water withdrawals. However,

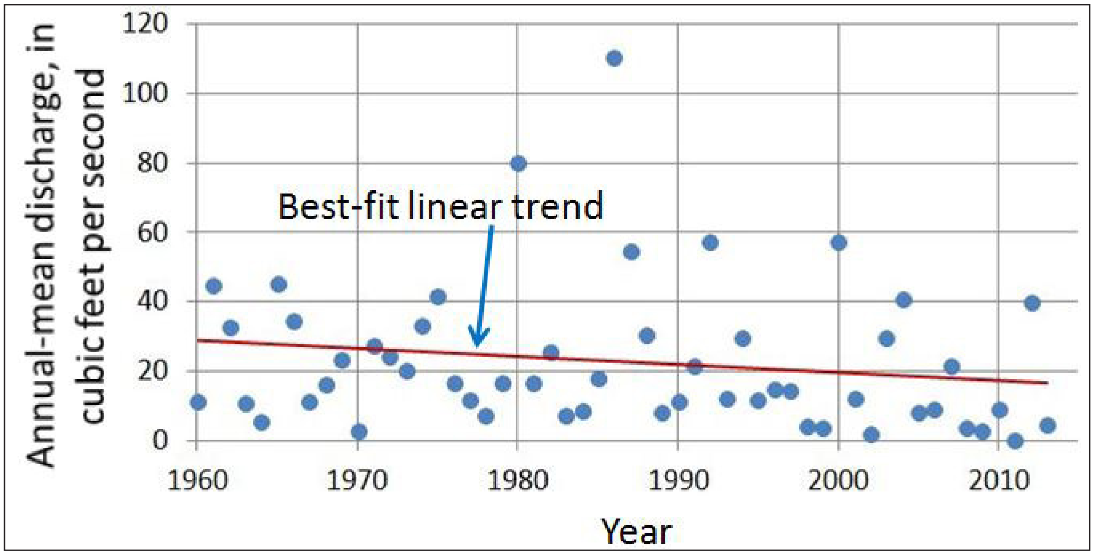

Figure 9. Annual mean discharges for Beals Creek near Westbrook, Texas.

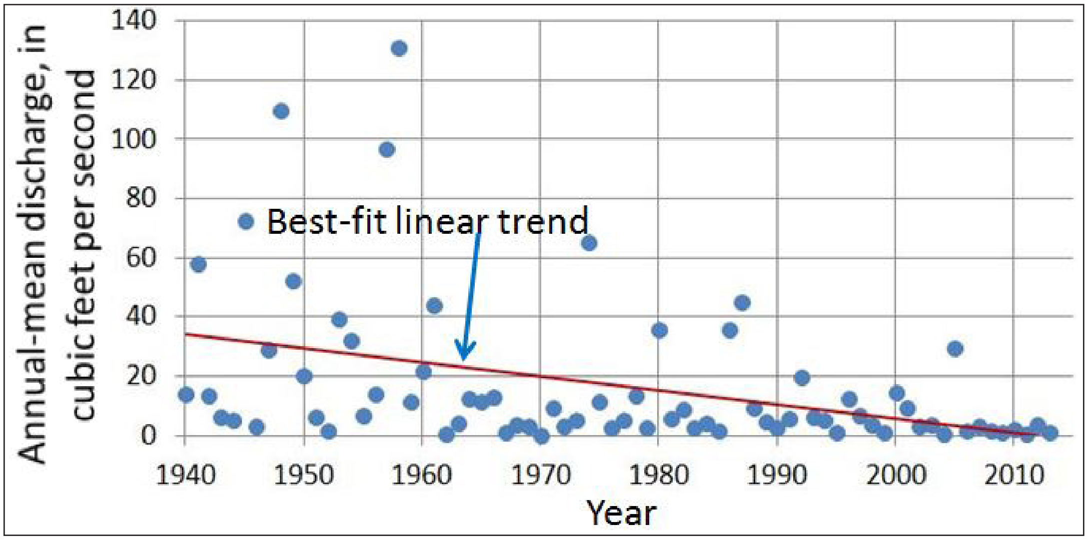

Figure 10. Annual mean discharges for the North Concho River near Carlsbad, Texas.

data values for neither could be estimated without substantial potential error. Additional information and data for basin losses are summarized in Table 2.

Finally, the average storage volume for the existing reservoirs in 1942 was less than conservation storage by only about 101,000 acre-feet—a value that represented only 18% of the mean-annual inflow to Lake Buchanan (Table 1). Therefore, only a minimal volume of runoff within the Lake Buchanan Basin was attenuated by deficits in conservation storage within reservoirs.

However, by 2013, the Buchanan Basin contained 19 major reservoirs, which control 72% (14,700 square miles) of the basin. About half of the controlled basin is within the basins of two or more major reservoirs. Also, more than 69,000 minor reservoirs were within the basin. The total drainage area for all reservoirs is 41,240 square miles; thus, on average, runoff is attenuated by 2.0 reservoirs en route to Lake Buchanan. Evaporation losses from the reservoirs represented 79% of the value for mean inflow to Lake Buchanan and was 7.5 times greater than water use in the basin. Reservoir transpiration and seepage to groundwater collectively were 56% of the mean inflow value. Additionally, surface water withdrawals and transpiration from major channels represented 9% and 34%, respectively, of the value for mean inflow to Lake Buchanan. Evaporation losses from streams was about 4% of the inflow value.

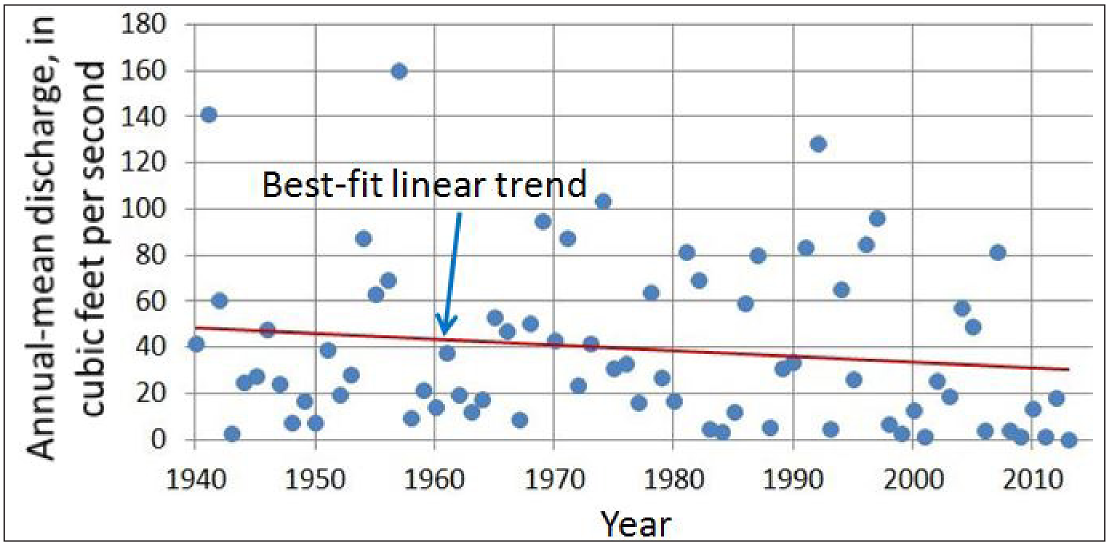

Figure 11. Annual mean discharges for Elm Creek at Ballinger, Texas.

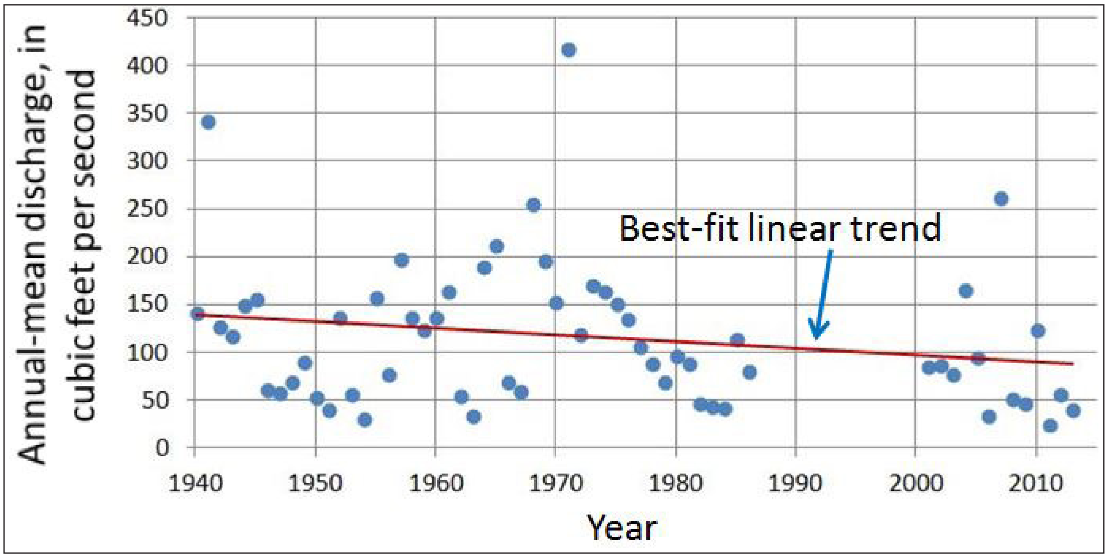

Figure 12. Annual mean discharges for the San Saba River at San Saba, Texas.

Some of the consumption data are estimated and subject to large potential error. However, the 2013 consumption values are considered to have much less potential error than the 1942 values. Major sources for losses also include evapotranspiration outside stream channels and unreported surface water withdrawals. However, data values for neither could be estimated without substantial potential error. Additional information and data for basin losses are summarized in Table 2. Finally, the average storage volume for the existing reservoirs was less than conservation storage by about 1,680,000 acre-feet—a value that represented 301% of the mean annual inflow to Lake Buchanan (Table 1); thus, the deficit in reservoir conservation storage is three times the value for the mean annual inflow to Lake Buchanan.

Also, an additional 8.4 million acre-feet of flood storage exists for the major reservoirs; however, the vast majority of this storage is attenuated but released downstream. Total flood storage for the NRCS reservoirs (Table 1) is much larger than the conservation storage for these reservoirs. However, the purpose of these structures is to attenuate flood peaks—their dams contain discharge pipes, which drain flood storage after storms. Thus, such storage has minimal if any impact on downstream runoff volumes. Additionally, only rare large storms produce sufficient runoff to produce flood storage in most of the struc-

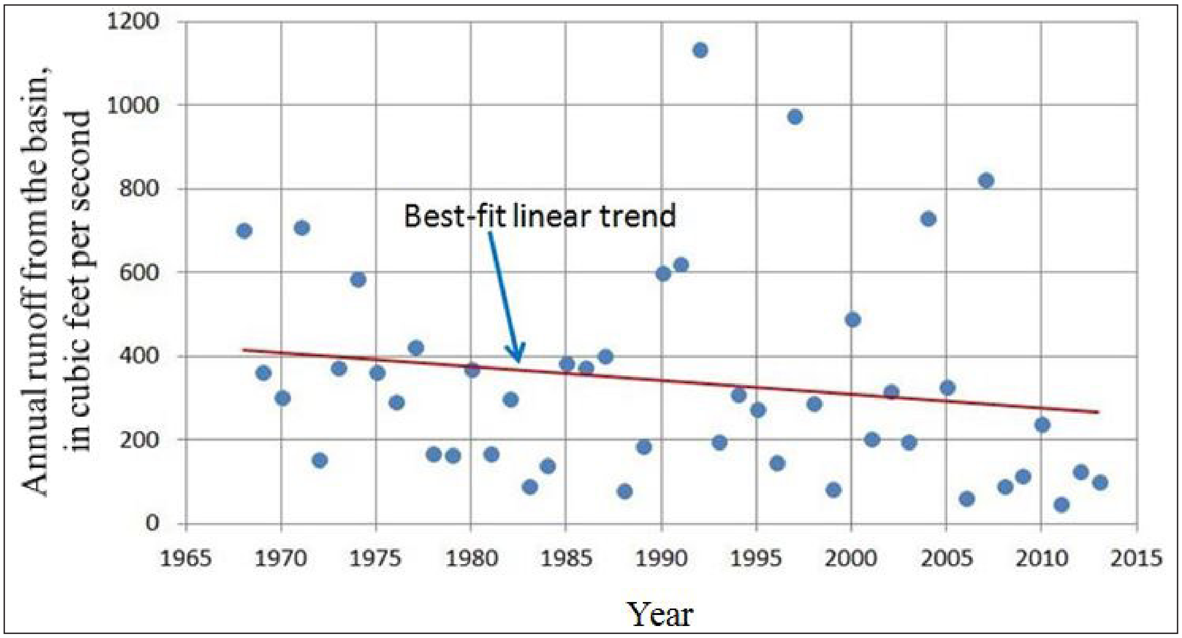

Figure 13. Runoff from the basin upstream from Lake Buchanan and downstream from O.H. Ivie, Brady Creek, and Brownwood reservoirs.

tures (2018 personal communications from John Newman, NRCS; unreferenced).

From 1942 to 2013, inflow to Lake Buchanan was reduced by 647 ft^3/s or 469,000 acre-feet per year. During the same period, increased lake evaporation represented 73% of the value for inflow reduction, and increased transpiration in major stream channels represented 36% (Table 2). The 1942–2013 increase in reservoir transpiration and seepage to groundwater was 51% collectively of the value for inflow reduction, and increased surface water withdrawal was 3%. Although information for such could not be found, increased transpiration outside stream channels due to spread of phreatophytes is believed to be a major cause for inflow reduction, as is increased unreported surface water withdrawals.

Finally, based on the linear trend for inflow to Lake Buchanan (Figure 4), the mean inflow value was 792,000 acre-feet per year in 1942 and 323,000 acre-feet per year in 2013—values that represent 3.3% and 1.3%, respectively, of the mean annual precipitation on the Buchanan Basin. Therefore, in 1942, almost 97% of precipitation was consumed in the basin and did not inflow to Lake Buchanan. Even during relatively natural conditions in the basin, before most reservoirs and the spread of phreatophytes, only a minimal amount of rainfall became runoff to Lake Buchanan. By 2013, almost 99% of precipitation was consumed. However, the value for the identified increase in basin consumption from 1942 to 2013 greatly exceeds the value for the decrease in inflow to Lake Buchanan (Table 2). This is because much, if not most, of any restored consumption would be consumed downstream and thus would not inflow to Lake Buchanan. For example, potential evapotranspiration from land and stream channels and potential channel losses to groundwater exceed actual values most of the time. For instance, any increased discharge in the Colorado River downstream from O.H. Ivie Reservoir would extend the width of the stream, which would cause increased evapotranspiration during the long travel time. Also, stream channel losses to groundwater in the Colorado River channel from J.B. Thomas to O.H. Ivie Reservoir increase with increased streamflow discharge (Slade et al. 2002), as do streamflow losses in the 9.7 mile reach of the Colorado River channel immediately upstream from Lake Buchanan (Braun and Grzyb 2015).

Additionally, stream travel time for runoff is extensive, which creates long durations for flow to be consumed. For example, based on stream velocity measurements by the USGS (USGS n.d.) at nine streamflow gages on the Colorado River in the Lake Buchanan Basin, the travel time for the 202-mile stream distance from O.H. Ivie Reservoir to Lake Buchanan is about 47 days during low-flow conditions and 7 days during high-flow conditions. The travel time for the 423-mile distance from Lake J.B. Thomas to Lake Buchanan is about 98 days during low-flow conditions and 19 days during high-flow conditions. Therefore, it is the author's opinion that much, if not most, "restored" water losses in the basin would not inflow Lake Buchanan, many miles downstream.

Inflow to Lake Travis and the other small reservoirs

Direct inflow to Lake Travis, excluding that released from Lake Buchanan, increased 42% from 1942 to 2013. Unlike the basin for Lake Buchanan, no major reservoirs exist in the basins that feed Lake Travis and the three small reservoirs between Lakes Buchanan and Travis (Figure 2). In order to assess temporal trends in inflow to Lake Travis and the other reservoirs, a double-mass graphical analysis was conducted for annual inflow volumes to the lakes and associated annual precipitation on the basin for the lakes. Figure 14 presents, for 1942 through 2013, the relation between cumulative values of annual precipitation and cumulative values for annual inflow volumes to Lake Travis and the other 3 reservoirs. The annual precipitation data are from the TWDB (TWDB n.d. b) and represent the mean values of the annual mean precipitation for one-degree quadrangle numbers 708 and 709. The areas for those quadrangles approximate the drainage area providing inflow to Lake Travis and the other reservoirs.

A best fit linear trend to the data is included in Figure 14. Based on the relations between the plotted values, a change in the slope of the plotted cumulative values is not evident. A change in the slope of the best fit line would have indicated a substantial change in inflow characteristics to the lakes. A decrease in the slope of the line would have indicated a substantial decrease in inflow volumes, which could have been caused by phenomena such as increased surface water withdrawals, increased groundwater withdrawals, or other loss of runoff due to, for example, land-use changes. The findings, however, are inconclusive due to the relatively weak statistical relations between values of annual precipitation and annual inflow. Therefore, it is unknown if a minor reduction in inflow volumes has occurred during the period of record for the data.

To evaluate the potential effect of water use on inflow volumes to Lake Travis and three associated reservoirs, values for annual surface water withdrawals and annual groundwater withdrawals were aggregated for each of the Llano and Pedernales River basins (Figure 2). These data are estimated by the TWDB (TWDB n.d. b) . The data are aggregated by county: Llano, Mason, and Kimble counties were used to represent the Llano River Basin, and Blanco and Gillespie counties represent the Pedernales River Basin. A detailed map presenting the rivers and county boundaries is available online (TWDB 2014). Surface water withdrawals occur directly from the streambeds, but it is likely that some of the withdrawal volumes are not directly consumed—part of such volumes are probably directly returned to the stream. Likewise, some of the groundwater withdrawals are likely not directly consumed, and part of such volumes could be directly returned to groundwater or streams. Additionally, at least some of the groundwater withdrawals, especially those remote from major streambeds, would likely cause minimal, if any, reduction in streamflow volumes. Furthermore, some groundwater may be produced from regional flow paths that would have little to no impact on local streamflow.

Based on the data, groundwater withdrawals for the Llano River Basin represent a mean value of about 14 ft³/s over the last several years, and surface water withdrawals represent about 13.4 ft³/s. Total withdrawals (groundwater and surface water) represent about 72% of the lowest annual mean gaged flow in the Llano River but only about 7% of the gaged long-term (1942–2013) mean flow at the gage. Therefore, based on this analysis, it is likely that withdrawals would cause substantial reduction in runoff during dry periods only. Based on data from the TCEQ, permitted total surface water withdrawals from the Llano River Basin represent about 20 ft³/s (TCEQ n.d.). However, at least some of the permitted water use is likely not being withdrawn.

For the Pedernales River Basin, groundwater withdrawals have increased substantially over the 38-year period for which data are available. For example, in 1974, groundwater withdrawals represented 6.9 ft³/s but have increased to 16.7 ft³/s by 2011. However, surface water withdrawals represent only 1.7 ft³/s over the last few years. Total withdrawals represent 260% of the lowest gaged annual mean flow in the Pedernales River but only about 9% of the gaged long-term (1942–2013) mean flow in the river. Therefore, based on this analysis, it is likely that withdrawals would cause substantial reduction in runoff during dry periods only. Based on TCEQ data, permitted total surface water withdrawals from the Pedernales River Basin represent 6.4 ft³/s (TCEQ n.d.); however, at least some of the permitted water use is likely not being withdrawn.

The substantial reduction in inflow volumes to the Highland Lakes perhaps identifies a need for increased planning and management of water use from the lakes. Therefore, a tool that provides possible advanced notification of extreme high- and low-inflow volumes could be beneficial in such management. In an attempt to identify one such tool, the relations between extreme inflow volumes to the Highland Lakes and selected climatic indices were investigated and reported below.

TELECONNECTIONS BETWEEN TEXAS STREAMFLOW AND CLIMATIC INDICES

A major source of precipitation in Texas is from the Gulf of Mexico and subtropical Atlantic moisture carried into the state by low-level southerly and southeasterly winds. Another major source is moisture from the eastern Pacific from the southwest via tropical continental air masses (Slade and Patton 2003).

Many publications report that precipitation or runoff conditions in the Texas area are related to global atmospheric pressure cycles associated with atmospheric and oceanic variations.

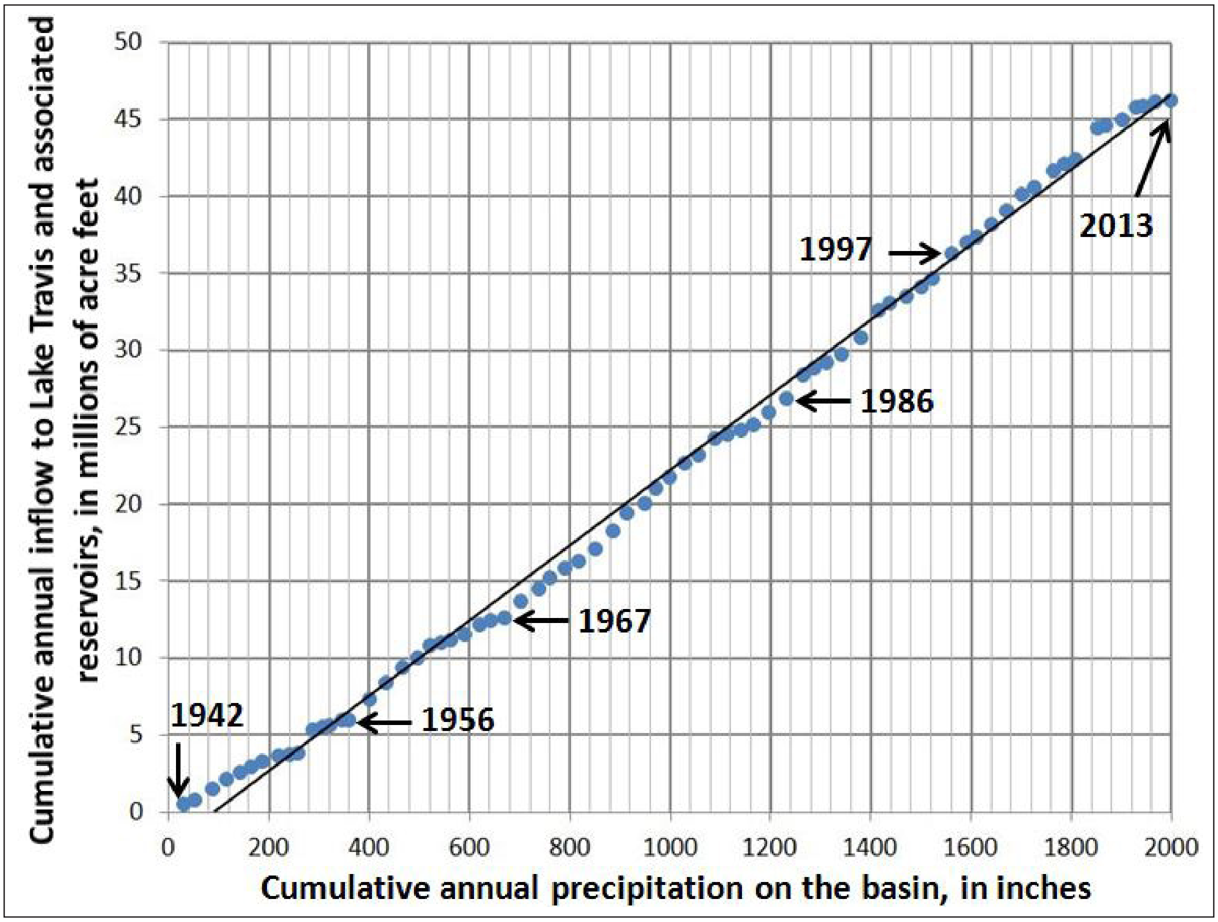

Figure 14. Relation between cumulative annual inflow to Lake Travis and associated reservoirs and cumulative annual precipitation on their basin, 1942–2013.

Such relations have been called "teleconnections," which, in general terms, are causal connections or correlations between meteorologic or other environmental phenomena that occur a long distance apart. Several of these publications (referenced below) have used limited statistical or climatic models to document such relations. The objective for many of the studies is to attempt, using individual climatic indices or combinations of climatic indices, to develop a conceptual or statistical model that could be effectively used by water managers to forecast, three to 12 months in advance, seasonal or annual hydrologic conditions (especially drought or flood conditions). However, to date (2016), none of the identified publications have developed a viable model that accurately predicts seasonal or annual hydrologic anomalies. A brief summary of studies identifying teleconnections between hydrologic forecasting for the Highland Lakes area and climatic indices is presented in the next section.

Reports relating streamflow in the Highland Lakes area to climatic indices

The analyses done by Redmond and Koch (1991) were limited to the western United States and excluded Texas. However, they found that for southeastern New Mexico, October–March precipitation increases (decreases) were strongly correlated with negative (positive) Southern Oscillation Index (SOI) values averaged for the preceding June through November period. Since southeastern New Mexico is adjacent to the headwaters of the Colorado River in Texas, these findings might also apply to the Highland Lakes area. For southeastern New Mexico, the authors also reported strong correlations between increased (decreased) October–March Pacific North American (PNA) pattern and increased (decreased) precipitation depths during the same period.

Watkins and O'Connell (2006) concluded that SOI and the indices North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) could not effectively be used with a nine- to 12-month lead time to predict seasonal or annual inflows to the Highland Lakes. However, they stated "there is potential for skillful season forecasts (with 3–6 months lead time) based on a combination of the indices," but did not provide such forecasts.

Kurtzman and Scanlon (2007) reported that for the Colorado River Basin area, October–March precipitation increased (decreased) in response to El Niño (La Niña) conditions based on the preceding June–September SOI. They also found that precipitation's decreases (increases) correlated with increased positive (negative) SOI.

Mishra et al. (2011) performed correlation analysis between seasonal streamflow extremes and climatic indices based on PDO and SOI evaluations for El Niño for many major Texas streams. They reported that the seasonal Oceanic Niño Index (ONI) sea surface temperature for the 3.4 region showed stronger connection with winter streamflow extremes (95th-and-greater percentile) for the upper part of the Colorado River Basin.

Slade and Chow (2011) reported that, with the exception of summer months (July–September), increased (decreased) precipitation in the Texas Hill Country was generally associated with El Niño (La Niña) conditions based on the ONI. They also reported, however, that for streamflow gaged at the USGS stations Pedernales River near Johnson City and Llano River at Llano, El Niño-period flow exceeded La Niña-period flow for each season except fall. During fall, La Niña flow generally exceeds El Niño flow at both stations. Hurricanes produce much of the fall rainfall, and many studies have found that La Niña periods yield more hurricanes and more intense hurricanes in the Atlantic Ocean (Slade and Chow 2011).

At least three other studies—Piechota and Dracup (1996), Rajagopalan et al. (2000), Tootle and Piechota (2006)—found no spatially coherent teleconnections between streamflow in Central Texas and climatic indices.

Wei and Watkins (2011) evaluated many potential predictors for forecasting inflows to the Highland Lakes during various seasons, including large-scale climatic indices related to the El Niño-Southern Oscillation (ENSO), PDO, NAO, and others. Results indicate that hydrologic persistence (autocorrelation of inflows) is a useful predictor of seasonal inflows to the Highland Lakes during winter and spring. In addition, the authors state that winter inflow forecasts may be improved by including either a derived Sea Surface Temperature (SST) index or the PDO index, and spring reservoir inflow forecasts may be improved by including a derived SST index and PNA. However, the authors do not present the tools for such analyses.

In a report on precipitation and water availability in the Rio Grande Basin in Texas, Khedun et al. (2012) stated that "positive PDO enhances the effect of El Niño and dampens the negative effect of La Niña, but when it is in its neutral or transition phase, La Niña tends to dominate climatic conditions and reduce water availability."

Measures of atmospheric and oceanic variations

The above reports indicate five indices (SOI, PNA, NAO, PDO, and ONI) that can be associated with runoff conditions in the study area. Although not found in the above reports, an index for the Atlantic Multidecadal Oscillation (AMO) is added below because a preliminary investigation indicated it to be related to high- and low-flow conditions in the study area. Additionally, the National Oceanographic and Atmospheric Administration (NOAA) has produced two separate indices (Bivariate EnSo Time series [BEST index] and Multivariate ENSO Index [MEI], presented below) that incorporate multiple indices, including sea surface temperature and air pressure components.

Therefore, a total of eight indices can be considered measures of atmospheric and oceanic variations for the study area. The first six indices below represent sea surface temperatures or air pressures for the Pacific Ocean, and the last two indices represent sea surface temperatures and air pressure differences for the Atlantic Ocean. A definition and description of the eight indices are presented in the Supplemental Information section, along with a reference for values of the indices. Some of the monthly indices are smoothed—typically on the basis of values for consecutive months—and some are standardized on the basis of recent climate patterns.

RELATIONS BETWEEN INFLOW VOLUMES IN THE HIGHLAND LAKES AND CLIMATIC INDICES

To assess the statistical relations between inflow volumes to the Highland Lakes and each of the eight indices described above, a database was created that includes the 1942–2013 monthly values for total inflow and each of the associated indices. The inflow values are based on streamflow discharges as described earlier in the report. Additionally, the monthly inflow and index values were aggregated by seasons so that seasonal analyses also could be performed. The seasonal values are represented by winter (January–March), spring (April–June), summer (July–September), and fall (October–December). Each seasonal inflow and index is calculated as the mean of the three monthly-mean values for each season. In addition to allowing exploration of the relations between seasonal indices and corresponding inflow, the three-month seasonal database

Table 3. Statistical summaries for selected climatic indices.

Index	Monthly indices			Seasonal (three-month) indices		
	Lag 1 autocorrelation coefficient	Mean	Standard deviation	Lag 1 autocorrelation coefficient	Mean	Standard deviation
AMO	0.93	0.01	0.21	0.86	0.01	0.20
ONI	0.05	-0.03	0.79	0.80	-0.03	0.77
PDO	0.81	-0.15	1.07	0.73	-0.15	0.99
SOI	0.08	0.19	10.20	0.69	0.19	8.76

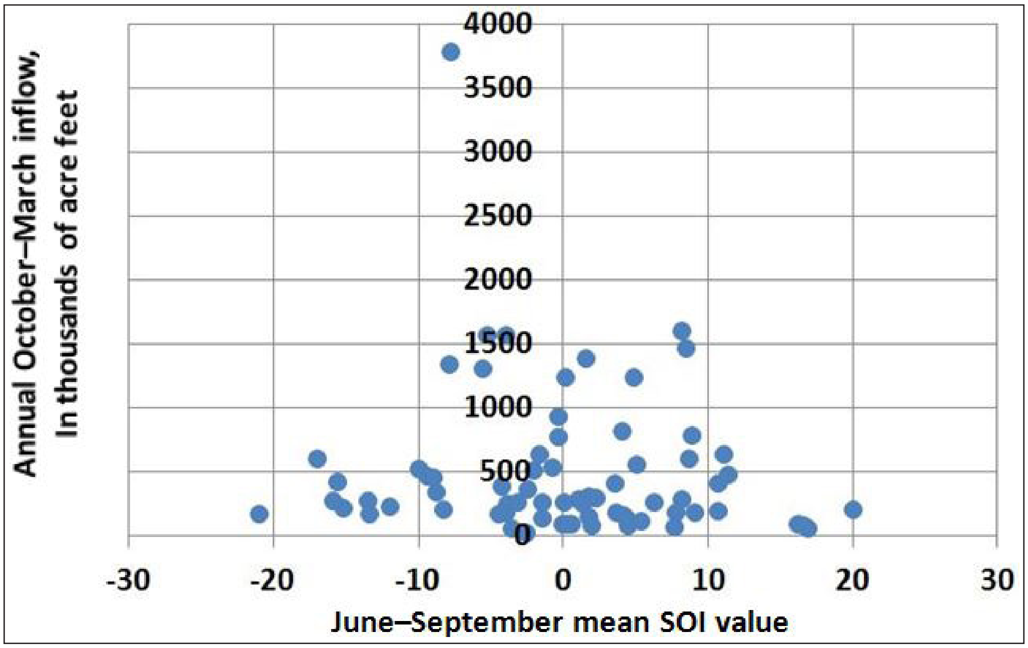

Figure 15. Relation between annual June–September mean Southern Oscillation Index and following October–March inflow volumes to the Highland Lakes, 1942–2013.

allows a longer period in which to explore the relations between indices and inflow, regardless of the season. For example, the effect from a given climatic index might be better realized as rainfall and runoff during a three-month period than during a one-month period.

The watersheds that provide inflow to the lakes are relatively large; thus, substantial runoff volumes can occur for many days after the end of each storm. For large storms near the end of a month or season, some of the flow volume could carry over and become part of the volume for the following month or season. However, the lag 1 autocorrelation coefficient for monthly mean inflow volumes is only 0.28; thus, carryover is not considered to be substantial for most months. The lag 1 autocorrelation coefficient for seasonal inflow volumes is only 0.21. Statistical summaries for selected climatic indices are presented in Table 3.

The lag 1 autocorrelation coefficients vary substantially among the climatic indices. However, as noted previously, some of the coefficients represent smoothed or standardized values—such indices would be expected to have lag 1 autocorrelation coefficients larger than those not smoothed or standardized.

The relations between values for each of the eight climatic indices and corresponding values for Highland Lakes inflow were evaluated, but only those with the best correlations are reported in the following sections.

Relations between inflow volumes for extended periods and Southern Oscillation Index

Redmond and Koch (1991) and Kurtzman and Scanlon (2007) reported that decreased (increased) SOI values from June–November or June–September, respectively, were relat-

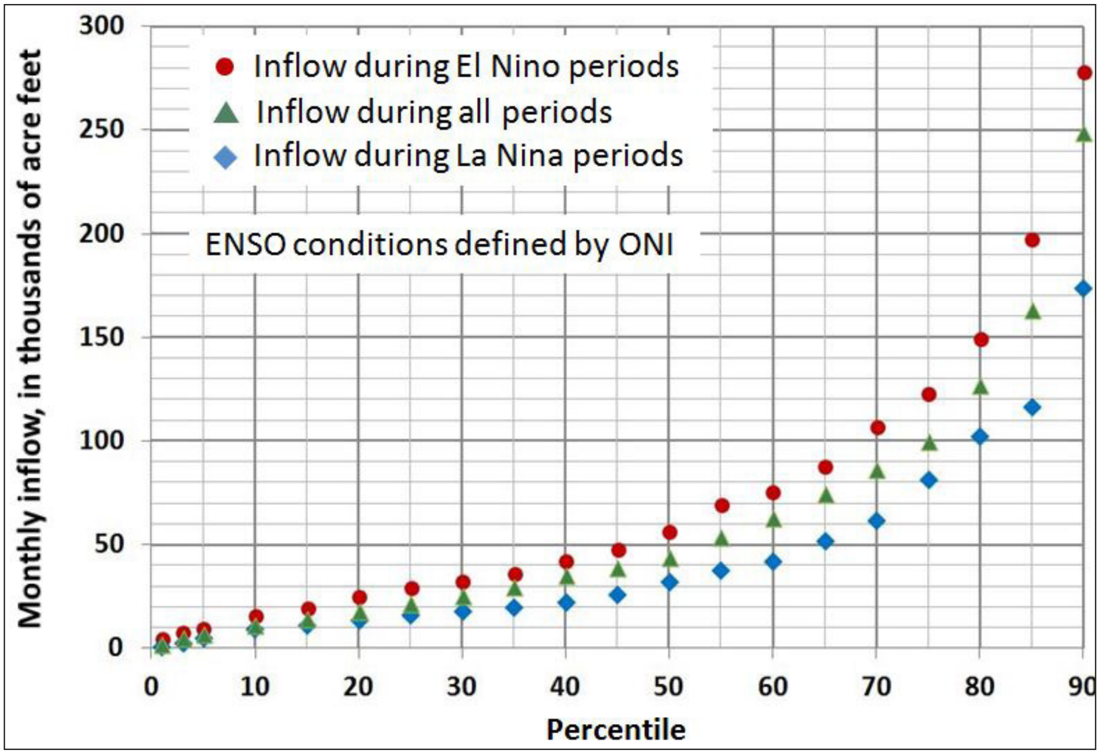

Figure 16. Percentiles for monthly total inflow volumes to the Highland Lakes for various ENSO conditions, 1950–2013.

ed to the following October–March precipitation increases (decreases). Figure 15 presents the relation between June–September mean SOI values and the following October–March (six-month period) total inflow volumes to the Highland Lakes for 1942–2013. The correlation coefficient between the two datasets is -0.10. The long-term (71-year) mean for October–March inflow associated with negative SOI values is 603,000 acre-feet, and the mean for October–March inflow associated with positive SOI values is 429,000 acre-feet. Therefore, negative SOI periods (indicative of El Niño conditions) have produced 41% more inflow than have periods with positive SOI values (indicative of La Niña conditions). For the 22 periods with the largest inflow volumes (those exceeding 500,000 acre-feet), 12 of the SOI values are negative, and 10 of the SOI values are positive. The mean period inflow for the 12 negative SOI values is 1.18 million acre-feet, and the mean period inflow for the 10 positive SOI values is 1.040 million acre-feet—a difference of only 13%. Therefore, the data suggest that negative SOI values are predictive of large inflow volumes but less predictive of the largest inflow volumes.

Additionally, this analysis indicates that positive SOI values imply dry conditions. For example, 12 of the 16 months with the lowest (25^{th} percentile) inflow values had positive SOI values.

Relations between monthly inflow volumes to monthly Oceanic Niño Index and Pacific Decadal Oscillation

Several reports indicate precipitation or runoff in the Highland Lakes area to be related to ONI. Although ONI values precede 1942, periods defining El Niño and La Niña conditions based on ONI values since 1950 are available online by the National Weather Service (NWSCPC n.d.). Based on the period 1950–2013, percentiles were calculated for monthly total inflow volumes to the Highland Lakes and for inflow volumes during El Niño conditions, La Niña conditions, and all periods. Figure 16 shows, for percentiles up to the 90^{th}, monthly inflow volumes for each of the three periods (El Niño, La Niña, and all). El Niño inflow volumes slightly exceed La Niña inflow volumes for low inflow percentiles, but the difference between El Niño and La Niña inflow volumes increases substantially as inflow percentile increases. Based on the data (the 768 months from 1950 through 2013), El Niño conditions occurred during 202 months (26% of the time) and produced 27.2 million acre-feet of inflow to the Highland Lakes (34% of total inflow). La Niña conditions occurred 216 months (28% of the time) and produced 16.2 million acre-feet of inflow (20% of total inflow). Based on these data, the mean of the monthly total inflow during El Niño conditions

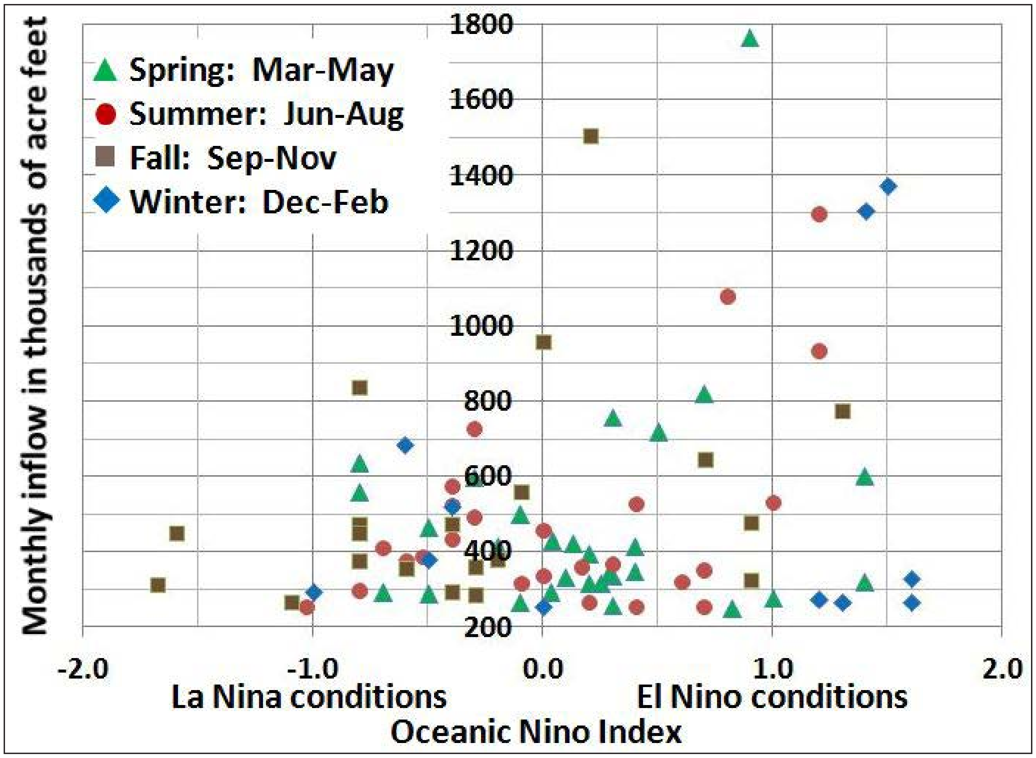

Figure 17. Relation between monthly Oceanic Niño Index and 90th-or-greater percentile monthly inflow volumes to the Highland Lakes, 1942–2013.

(134,600 acre-feet) exceeded that during La Niña conditions (75,000 acre-feet) by 79%.

The 90th percentile for the 1942–2013 and 1950–2013 monthly inflow volumes is about 250,000 acre-feet. Based on the 1942–2013 dataset for ONI values, the ONI value for each month exceeding 250,000 acre-feet of inflow (85 months) is presented in Figure 17. The correlation coefficient between the two datasets is 0.28. As shown, most of the largest monthly inflow volumes (those greater than 800,000 acre-feet) occurred during periods with positive ONI values. Eight of the 10 largest monthly inflow volumes occurred during periods with positive ONI values, one occurred during a period with a negative ONI value, and one occurred during neither condition (index equals zero). Additionally, based on the 85 values, for all but the fall season, the number of months with positive ONI values exceeded the number of months with negative ONI values. For the non-fall months, 37 months occurred during positive ONI conditions, 24 months occurred during negative ONI conditions, and four months occurred during neither condition. However, 14 of the 20 fall-season months occurred during negative ONI conditions, while only five fall-season months occurred during positive conditions; one fall-season month occurred during neither condition. The National Weather Service Climate Prediction Center forecasts ONI index values several months in advance. The site is online at http://www.cpc.ncep.noaa.gov/products/predictions/90day/tools/briefing/unger.pri.php.

As noted previously in describing the ONI, positive ONI indicate El Niño conditions, and negative ONI indicate La Niña conditions. That the majority of fall-season months occurred during negative ONI months (per Figure 17) is consistent with the finding of Slade and Chow (2011) that during the fall La Niña flows generally exceed El Niño flows at each of the two USGS stations, Pedernales River near Johnson City and Llano River at Llano. (See section "Reports relating streamflow in the Highland Lakes area to climatic indices.") Large volumes of runoff associated with hurricanes often occur during fall, and many reports have concluded that hurricanes tend to be associated with La Niña conditions.

However, the indices that best predict the driest monthly inflow volumes is the PDO. For example, the monthly PDO index is negative for 67 of the 85 driest months—those with inflow volumes less than the 10th percentile. The PDO index is, therefore, negative for 79% of the driest months even though the PDO monthly index is negative for only 54% of its 1942–2013 database. The ONI index is negative for 57 of the 85 driest months; therefore it is considered to be less predictive of the driest months than is the PDO index.

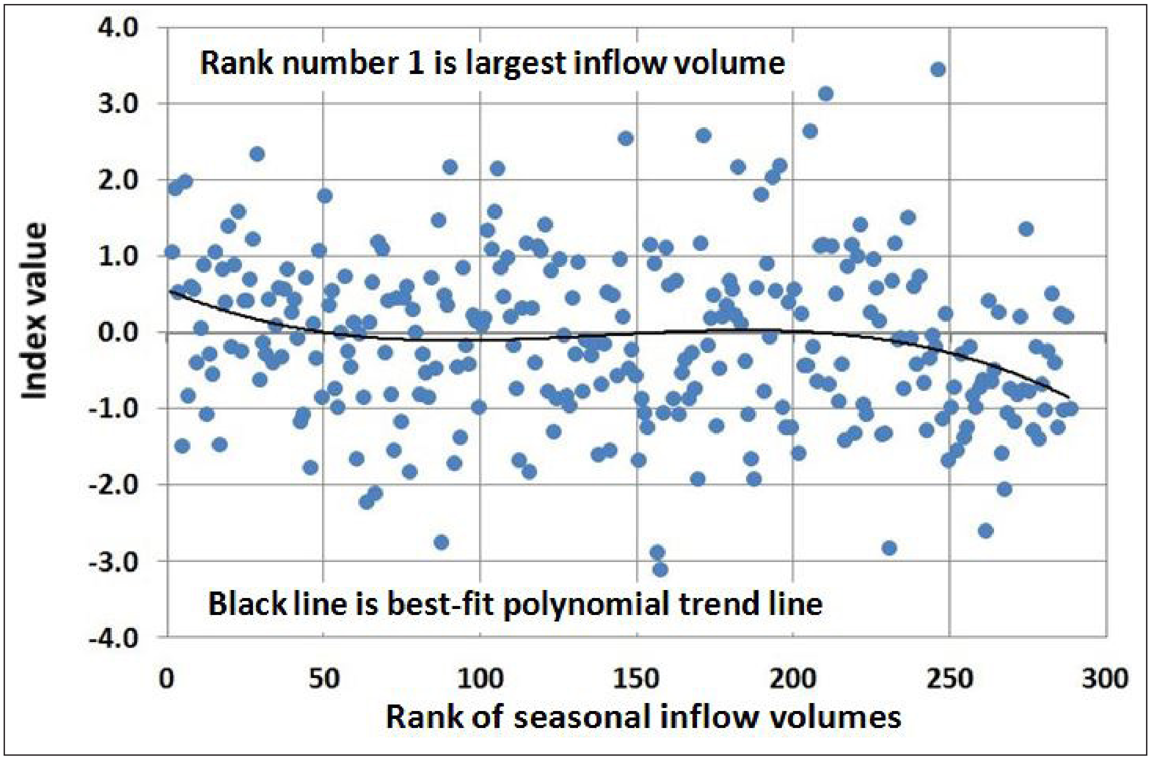

Figure 18. Relation between combination of AMO and ONI indices and ranks of seasonal inflow volumes to the Highland Lakes, 1942–2013.

Relations between seasonal inflow volumes and seasonal climatic indices

The 1942–2013 seasonal (three-month period) inflow volumes to the Highland Lakes and associated seasonal (three-month period) indices were computed and evaluated to minimize the carryover volumes from monthly storm runoff and to create a longer period for the atmospheric pressure cycles related to climatic variations and the resulting weather conditions associated with runoff to the lakes. An evaluation was made, without regard to particular seasons (i.e., winter), of the statistical relations between the three-month period inflow volumes to the Highland Lakes and each of the eight associated three-month period climatic indices.

To evaluate the indices as a prediction tool one season in advance, a second seasonal database was created for which the indices for each season were grouped with the inflow values for the following season (three-month period). Likewise, a third seasonal database was prepared for which the indices for each season were grouped with the inflow values two seasons later. A fourth database was created for which the seasonal indices were grouped with inflow values three seasons later, and finally, a fifth database was created for which the seasonal indices were grouped with seasonal inflows four seasons (one year) later.

The analysis is based on relations between inflow values for the wettest and driest seasonal inflow volumes and indices. For each of the five databases, the 288 seasonal inflow volumes for the 72 years 1942–2013 were sorted on the basis of inflow volume magnitude—the associated value for each of the indices remained grouped with each inflow value. The greatest and least 10% of the inflow volumes were then analyzed for comparisons with their associated indices. Therefore, the 29 periods with the greatest inflow volumes and the 29 periods with the least inflow volumes were analyzed. The signs (positive or negative) and values for each index relative to the associated inflow volumes were examined. Attention also was given to seeking a combination of two or more indices that might accurately predict wet and dry inflow seasons.

The two indices most closely associated with the 90th-or-greater percentile seasonal inflow volumes are the AMO and ONI. The ONI represents sea surface temperature for an equatorial region of the Pacific Ocean (Niño 3.4 region), and the AMO represents sea surface temperature for the Atlantic Ocean. Each has a weak relations with the inflow volumes. However, a combination of the two indices provides a better predictor of wet inflow seasons than either index by itself. Combining the two indices also provides the best predictor of dry inflow seasons. Thus, the AMO and ONI seasonal indices were combined to develop a single index that would be closely associated with the wet and dry inflow seasons. Combinations of most of the indices above were tested for predictability of wet and dry inflow conditions, but the combination of the AMO and ONI produced the best estimations of wet and dry inflow conditions.

Additionally, the PDO index provides a good indicator for the driest inflow seasons. The PDO represents sea surface temperatures for the northern Pacific Ocean.

Summaries of the PDO values and the combined AMO and ONI in each dataset are provided below to describe the relations with inflow volumes for each of the five seasonal databases. The correlation coefficient between seasonal values of AMO and ONI is only 0.06; thus, the values are considered to be independent indicators of inflow values.

As shown in Table 3, the seasonal (and monthly) mean for each index is near zero. Likewise, the percentiles for each index indicate that the values are almost normally distributed about the mean, and thus the skew coefficient approaches zero for each index. However, the standard deviations for the AMO and ONI indices are 0.20 and 0.77, respectively; so the ONI standard deviation is 3.85 times greater than that of the AMO. Also, negative AMO values indicate wet inflow seasons, and positive AMO values indicate dry inflow seasons. For the ONI index, positive values indicate wet periods and negative values indicate dry periods.

Therefore, to maximize the ability of the combined indices to predict wet and dry inflow seasons, the sign for each AMO value was changed, and each AMO value was multiplied by 3.85 so it would have a distribution of values similar to that of the ONI. Each revised AMO value was then added to its associated ONI value, resulting in a single combined value. Based on the combined indices, positive values indicate wet seasons and negative values indicate dry seasons.

The mean seasonal inflow for the positive-value combined indices is 373,000 acre-feet, and the mean seasonal inflow for the negative-value combined indices is 244,000 acre-feet. Therefore, the mean inflow volume for the positive indices values exceeds that for the negative indices values by 53%. A summary of the number of positive-value and negative-value combined indices associated with the wet and dry seasons is presented in Table 4. The relation between the combined indices and the ranks of seasonal inflow volumes is presented in Figure 18. The number 1 rank represents the greatest seasonal (three-month) inflow volume, and the number 288 rank represents the lowest inflow volume. A best-fit polynomial curve trend line on the graph indicates that positive values for the indices predict about the 45 wettest inflow seasons, and negative values for the indices indicate about the 70 driest inflow seasons.

Based on the results above, the combined AMO and ONI indices can be effectively used to estimate the wettest 10th percentile of seasonal inflow volumes for a current season and for only one season in advance. However, the combined AMO and ONI indices can effectively be used to estimate the driest 10th percentile of seasonal inflow volumes for as many as four seasons in advance and to estimate the driest 20th percentile of seasonal inflow volumes as many as two seasons in advance. The PDO can effectively be used to estimate the driest 10th percentile of seasonal inflow volumes for as many as four seasons (one year) in advance. The correlation coefficient between seasonal values for the combined AMO and ONI indices and values for PDO is 0.35; thus, the two indices are relatively independent. Therefore, each index could be used to estimate wet and dry seasons.

CONCLUSIONS

From 1942 to 2013, inflow volumes decreased 19% for the Highland Lakes and 59% for Lake Buchanan. The major cause for the inflow reduction to Lake Buchanan is the proliferation of 19 major reservoirs and about 69,500 minor reservoirs, which have caused, from 1942 to 2013, an increase in evaporation that represents 73% of the value for inflow reduction and an increase in transpiration and loss to groundwater that represents 51% of the value for reduced inflow. Also, the increase in stream channel transpiration due to spread of phreatophytes represents 36% of the value for inflow reduction. Although it could not be substantiated, increased evapotranspiration due to phreatophytes outside stream channels was also a probable major cause for inflow reduction. Finally, loss due to increased surface water withdrawals was probably a minor cause for inflow reduction. The sum of the losses above expressed as percentages of inflow reduction to Lake Buchanan exceed 100%. This is because most basin losses are from reservoirs—much if not most of the water loss from the reservoirs would otherwise be lost downstream as evapotranspiration in the channel before arriving at Lake Buchanan.

Based on statistical comparisons of values for climatic indices and inflow volumes, climatic indices are likely better indicators of extreme (wet or dry) inflow conditions for the Highland Lakes rather than conditions between extreme wet and dry. (Figure 18).

Climatic indices provide only fair indicators of large inflow volumes to Lake Buchanan. Larger inflow volumes are associated with the duration and extent of flooding that typically are caused by short duration timing and location of several meteorologic conditions that, for many wet periods, cannot be readily predicted by climatic indices. However, climatic indices provide better indicators of periods with low inflow volumes. Low inflow volumes are associated with drought—some climatic indices readily provide indicators of absence of moisture in the regional atmosphere and lack of sources for such moisture.

Table 4. Number of seasons with positive and negative climatic index values for various comparisons between seasonal indices and seasonal inflow volumes to Lake Buchanan.

	Temporal relation between seasonal indices and seasonal inflow volumes				
	Same season[1]	Inflow 1 season later	Inflow 2 seasons later	Inflow 3 seasons later	Inflow 4 seasons later
Combined AMO and ONI indices					
Wettest 29 seasons[2]					
number of positive values	19	19	16	15	10
number of negative values	10	10	13	14	19
Wettest 58 seasons[3]					
number of positive values	34	34	33	32	25
number of negative values	24	24	25	26	33
Driest 29 seasons[4]					
number of positive values	7	7	5	7	8
number of negative values	22	22	24	22	21
Driest 58 seasons[5]					
number of positive values	14	16	15	18	21
number of negative values	44	42	43	40	37
PDO indices					
Wettest 29 seasons					
number of positive values	19	12	13	10	8
number of negative values	10	17	16	19	21
Wettest 58 seasons					
number of positive values	36[6]	32	30	27	28
number of negative values	21	26	28	31	30
Driest 29 seasons					
number of positive values	7	7	9	7	9
number of negative values	22	22	20	22	20
Driest 58 seasons					
number of positive values	14	16	19	18	19[6]
number of negative values	44	42	39	40	38

[1] Season defined as: Winter: January–March; Spring: April–June; Summer: July–September; Fall: October–December

[2] 1942–2013 period of record is 72 years or 288 seasons. Wettest 29 seasons are 10% of all seasons with greatest inflow volumes

[3] Wettest 58 seasons are 20% of all seasons with greatest inflow volumes

[4] Driest 29 seasons are 10% of all seasons with lowest inflow volumes

[5] Driest 58 seasons are 20% of all seasons with lowest inflow volumes

[6] Index value equal zero for one season

Due to the limited ability for any single climatic indices to predict wet or dry inflow volumes to the Highland Lakes, it is suggested that several climatic indices be evaluated in order to best predict high or low inflow volumes to the Highland Lakes. Additionally, the Pacific and Atlantic each represent potential sources of moisture to the Highland Lakes; therefore, it is suggested that climatic indices representing each of these moisture sources be used as indicators of potential extreme inflow conditions for the Highland Lakes.

NOTES

The author obtained permission from all people with whom he had personal communications.

REFERENCES

Braun CL, Grzyb SD. 2015. Streamflow gains and losses in the Colorado River in northwestern Burnet and southeastern San Saba counties, Texas, 2012-14. Reston (Virginia): US Geological Survey. 41 p. Scientific Investigations Report 2015-5098. Available from: https://pubs.usgs.gov/sir/2015/5098/sir20155098.pdf.

[CRMWD] Colorado River Municipal Water District. [n.d. a]. Combined surface water. Big Spring (Texas): Colorado River Municipal Water District. Available from: https://www.crmwd.org/sources/combined-surface-water/.

[CRMWD]. Colorado River Municipal Water District. [n.d. b] Lake levels. Big Spring (Texas): Colorado River Municipal Water District. Available from: https://www.crmwd.org/lake-levels/.

Gilbert CR, Sauer SP. 1970. Hydrologic effects of floodwater-retarding structures on Garza-Little Elm Reservoir, Texas. Washington (District of Columbia): US Government Printing Office. 95 p. Water supply Paper 1984. Available from: https://pubs.usgs.gov/wsp/1984/report.pdf.

Hauck L, Pandey U. 2015. Feasibility study: computer modeling of water yield for the immediate basin of O.H. Ivie Reservoir. Temple (Texas): Texas State Soil and Water Conservation Board. 43 p. TR 1501. Available from: http://www.ucratx.org/IvieStudy_2015.pdf.

Kennedy Resource Company. 2017. Evaluation of rainfall/runoff patterns in the Upper Colorado River basin. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012011_Kennedy.pdf.

Khedun CP, Mishra AK, Bolten JD, Beaudoing HK, Kaiser RA, Giardino JR, Singh VP. 2012. Understanding changes in water availability in the Rio Grande/Río Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model, Journal of Geophysical Research. 117(D05104). Available from: https://doi.org/10.1029/2011JD016590.

Kurtzman D, Scanlon BR. 2007. El Niño–Southern Oscillation and Pacific Decadal Oscillation impacts on precipitation in the southern and central United States: evaluation of spatial distribution and predictions. Water Resources Research. 43(W10427). Available from: https://doi.org/10.1029/2007WR005863.

Larner DC, Marshall RM, Pfluger AE, Burnitt SC. 1974. Woody phreatophytes along the Colorado River from southeast Runnels County to the headwaters in Borden County, Texas. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R182/R182.pdf.

[LCRA] Lower Colorado River Authority. 2015. Water contract rules. Austin (Texas): Lower Colorado River Authority. Available from: https://www.lcra.org/water/water-supply/water-supply-contracts/Documents/Rules-LCRA-Contract-Rules-Oct2015-BdAppvd.pdf.

[LCRA] Lower Colorado River Authority. 2018. River operations report. Austin (Texas): Lower Colorado River Authority. Available from: http://hydromet.lcra.org/riverreport/report.aspx.

Mishra AK, Singh VP, Özger M. 2011. Seasonal streamflow extremes in Texas river basins: uncertainty, trends, and teleconnections. Journal of Geophysical Research. 116(D08108). Available from: https://doi.org/10.1029/2010JD014597.

National Inventory of Dams. [n.d.].Washington (District of Columbia): U.S. Army Corps of Engineers. 1965–2018. County, Texas. Austin (Texas): Texas Water Development Board. Available from: https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R182/R182.pdf.

[NWSCPC] National Weather Service Climate Prediction Center. [n.d.]. Cold & warm episodes by season. Silver Spring (Maryland): National Weather Service. Available from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

Piechota TC, Dracup JA. 1996. Drought and regional hydrologic variation in the United States: associations with the EI Niño–Southern Oscillation. Water Resources Research. 32(5):1359-1373. Available from: https://doi.org/10.1029/96WR00353.

Rajagopalan B, Cook E, Lall U, Ray BK. 2000. Spatiotemporal variability of ENSO and SST teleconnections to summer drought over the United States during the twentieth century. Journal of Climate. 13(24):4244-4255. Available from: https://doi.org/10.1175/1520-0442(2000)013<4244:SVOEAS>2.0.CO;2.

Rantz SE. 1968. A suggested method for estimating evapotranspiration by native phreatophytes. In: Department of Interior. Geological Survey Research 1968. Washington (District of Columbia): Department of Interior. 277 p. Geological Survey Professional Paper 600-D. p. D10-D12. Available from: https://pubs.usgs.gov/pp/0600d/report.pdf.

Redmond KT, Koch RW. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Research. 27(9):2381-2399. Available from: https://doi.org/10.1029/91WR00690.

Saleh A, Wu H, Brown CS, Teagarden FM, McWilliams SM, Hauck LM, Millican JS. 2009. Effect of brush control on evapotranspiration in the North Concho River watershed using the eddy covariance technique. Journal of Soil and Water Conservation. 64(5):336-349. Available from: https://doi.org/10.2489/jswc.64.5.336.

Slade RM Jr, Bentley T, Michaud D. 2002. Results of streamflow gain-loss studies in Texas, with emphasis on gains from and losses to major and minor aquifers. Austin (Texas): U.S. Geological Survey. Open-File Report 02-068. Available from: http://pubs.usgs.gov/of/2002/ofr02-068/.

Slade RM Jr, Buszka P. 1994. Characteristics of streams and aquifers and processes affecting the salinity of water in the upper Colorado River basin, Texas. Austin (Texas): U.S. Geological Survey. 81 p. Water-Resources Investigations Report 94-4036. Available from: https://pubs.usgs.gov/wri/1994/4036/report.pdf.

Slade RM Jr, Chow TE. 2011. Statistical relations of precipitation and stream runoff for El Niño and La Niña periods, Texas Hill Country. Texas Water Journal. 2(1). Available from: https://journals.tdl.org/twj/index.php/twj/article/view/3665.

Slade RM Jr, Patton J. 2003. Major and catastrophic storms and floods in Texas. Austin (Texas): U.S. Geological Survey. Open-File Report 03-193. Available from: http://pubs.usgs.gov/of/2003/ofr03-193/cd_files/USGS_Storms/index.htm.

Texas Almanac. [n.d.]. Population history of counties from 1850–2010. Denton (Texas): Texas Almanac. Available from: https://texasalmanac.com/sites/default/files/images/topics/ctypophistweb2010.pdf.

[TCEQ] Texas Commission on Environmental Quality. [n.d.]. Water rights and water use data. Austin (Texas): Texas Commission on Environmental Quality. Available from: https://www.tceq.texas.gov/permitting/water_rights/wr-permitting/wrwud.

[TWDB] Texas Water Development Board. [n.d. a]. Colorado River Basin. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/surfacewater/rivers/river_basins/colorado/index.asp.

[TWDB] Texas Water Development Board. [n.d. b]. Historical water use estimates. Austin (Texas): Texas Water Development Board. Available from: http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/index.asp.

[TWDB] Texas Water Development Board. [n.d. c]. Lake evaporation and precipitation. Austin (Texas): Texas Water Development Board. Available from: https://waterdatafortexas.org/lake-evaporation-rainfall.

[TWDB] Texas Water Development Board. 2014. Water features. Austin (Texas): Texas Water Development Board. Available from: https://s3.amazonaws.com/data.tnris.org/32f1864d-166b-4e08-b08e-72df1eadb306/assets/0376e9e8-c58c-458a-b3d8-af09362fe014-Major_Surface_Water_Features_36x36.pdf.

Tootle GA, Piechota TC. 2006. Relationships between Pacific and Atlantic Ocean sea surface temperatures and U.S. streamflow variability. Water Resources Research. 42(7):W07411. Available from: https://doi.org/10.1029/2005WR004184.

[USGS] U.S. Geological Survey. [n.d.]. National Water Information System: Mapper. Reston (Virginia): U.S. Geological Survey. Available from: https://maps.waterdata.usgs.gov/mapper/index.html?state=tx.

Watkins DW, O›Connell SM. 2006. Teleconnections and disconnections in Central Texas: a guide for water managers. In: American Society of Civil Engineers. Climate Variations, Climate Change, and Water Resources Engineering. Reston (Virginia): American Society of Civil Engineers. 198 p. p. 103-114. Available from: https://doi.org/10.1061/9780784408247.ch07.

Wei WI, Watkins DW Jr. 2011. Probabilistic streamflow forecasts based on hydrologic persistence and large-scale climate signals in central Texas. Journal of Hydroinformatics. 13(4):760-744. Available from: https://doi.org/10.2166/hydro.2010.133.

SUPPLEMENTAL INFORMATION

1. The ENSO, as documented by the ONI, probably represents the best-known teleconnection pattern related to precipitation and runoff in Texas. The calculated monthly indices from 1950 through 2013, along with the identification of El Niño and La Niña periods and the definition for such periods, are presented by NOAA online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. The values represent three-month running mean values for the equatorial region of the Pacific Ocean. Extended monthly ONI values from 1942 through 1949 were obtained from the International Research Institute for Climate and Society at Columbia University (http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.Niño/.EXTENDED/.NIÑO34/T+exch/). Positive ONI values indicate El Niño conditions and negative ONI values indicate La Niña conditions.

2. The Southern Oscillation is the atmospheric component of ENSO. This component is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the Southern Oscillation is measured by the SOI. The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia. SOI values are available at http://www.bom.gov.au/climate/current/soihtm1.shtml. Negative SOI indices indicate El Niño conditions and positive SOI indices indicate La Niña conditions.
3. NOAA describes the BEST index as the combination of the ONI and SOI components of ENSO (http://www.esrl.noaa.gov/psd/people/cathy.smith/best/). NOAA believes it is a better index than ONI or SOI alone for describing ENSO because it considers sea surface temperature and atmospheric air pressure. The monthly values for this index are online at http://www.esrl.noaa.gov/psd/people/cathy.smith/best/enso.ts.1mn.txt.
4. NOAA describes the MEI as a method to characterize the climatic conditions contributing to the onset and physiology of an ENSO event. ENSO arises from a complex interaction of several climate systems; thus, MEI is regarded by NOAA as the most comprehensive index for monitoring ENSO because it combines analysis of multiple meteorologic components. The MEI is calculated as the first principal component of six different parameters: sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and cloudiness of the southern Pacific Ocean. MEI values are at https://www.esrl.noaa.gov/psd/enso/mei/, which also contains additional information regarding this index.
5. The PDO represents monthly sea surface temperature over the northern Pacific (poleward of 20° N). Several reports, some of which are listed in the section "Reports relating streamflow in the Highland Lakes area to climatic indices," indicate that the PDO index is useful for identifying trends in precipitation and runoff. The PDO index is identified as a standardized principal-component time series. PDO index values are available at http://jisao.washington.edu/pdo/PDO.latest.
6. The PNA represents, at four locations over the Pacific Ocean and North America, anomalous air pressure, which correlates with regional temperature and precipitation anomalies across North America. This pattern influences regional weather by affecting the strength and location of the East Asian jet stream and subsequently the weather it delivers to North America. PNA index values are presented at. ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh.
7. The AMO is a mode of variability occurring in the northern Atlantic Ocean that has its principal expression in sea surface temperature. The AMO signal is usually defined from the patterns of sea surface temperature variability in the North Atlantic after any linear trend has been removed. Monthly AMO values are online at http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data.
8. The NAO represents atmospheric pressure fluctuations in the northern Atlantic Ocean. The index indicates the difference in atmospheric pressure at sea level between the Icelandic low and the Azores high. The fluctuations, which vary over time and have no particular periodicity, represent the strength and direction of westerly winds and storm tracks across the North Atlantic. NAO index values are at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table.
9. Additionally, monthly and seasonal values for many indices are presented at http://www.esrl.noaa.gov/psd/data/climateindices/list/.

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Book Review: Regulating Water Security in Unconventional Oil and Gas

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In 2018, the United States became king of oil and, until recently, oil was king. Now, though its future reign suddenly appears uncertain, oil and gas still decisively dominate the energy industry. And when the United States surpassed Saudi Arabia and Russia to become the world's largest producer of crude oil for the first time this millennium, it had hydraulic fracturing to thank. But this "fracking" process that frees previously unrecoverable oil and gas from tight formations by fracturing the rock with highly pressurized fluid uses 5 to 11 million gallons of water per well. It's also no secret that, as the human population continues to grow, having enough freshwater resources available to sustain them will become an increasing challenge. Meanwhile, many places in the U.S. (and Texas, in particular) have suffered through extreme drought, with some communities facing the possibility that their water supply could run out.

Against this backdrop comes *Regulating Water Security in Unconventional Oil and Gas*, a collection of articles authored by professionals from disciplines as diverse as agriculture, zoology, law, and economics. The book takes a multidisciplinary look at how issues related to water for unconventional oil and gas production affect water security of a nation, state, community, or sector of industry—and possible pathways toward regulations that balance economic development with the human right to water. The authors examine what other regions have been experiencing to illustrate some of the common difficulties and differing perspectives, challenges, and solutions being attempted. Authors' contributions are presented in four parts, making the dense subject matter digestible. Before delving into the details, Part I sets the stage by providing a general framework in which the authors examine the complex issues raised. Parts II, III, and IV of the book then dig deeper, using case studies to explore first how operators procure water, then issues involved in disposal of water used and produced in fracking, and finally macro-scale regulatory planning.

A consistent theme of the book is the need to look at these issues in an integrated way, recognizing the trade-offs involved in every decision related to water management for unconventional oil and gas production. Of primary concern is that, given the water-energy nexus, the two must be considered holistically. Rather than adopt a silo mentality in which institutions and sectors manage water resources independently, industry, agriculture, energy, and municipalities (to name a few) must collaborate with each other and with stakeholders who will be affected by the policies or decisions made. The book also notes a gap between decision-makers and the most current science necessary to inform regulations, law, and policy applied to water for this sector of the energy industry.

Sustainability is another key piece of this framework. Given that water is often scarce in the most significant oil and gas production zones, authors question whether unconventional oil and gas production practices are sustainable over the long term. And, even in the near term, public concern over water use, environmental contamination, and seismicity threaten the "social license to operate." Losing that social license makes public demonstration against oil and gas development more likely.

In examining water acquisition, the authors' main areas of concern are the water footprint of practices like fracking and the unpredicted effects this water usage has had on ecosystems. Throughout the book, authors reiterate the massive water footprint of each hydraulic fracturing well. Meanwhile, in the United States, the pressure to develop shale gas is only expected to increase. Unfortunately, the hottest shale plays in the world are often located where water is least secure, such as the Permian Basin in Texas, in which 87% of unconventional wells are drilled in areas of high or extremely high water stress.

As these case studies indicate, many governing systems may be incapable, or unwilling, to incorporate these impacts into regulations and permitting processes. For instance, China, having set aggressive goals for shale gas development, has been secretive about the volumes of water used and the related environmental impacts. Likewise, Ukraine sought to develop unconventional oil and gas resources as a way to reduce Russia's control over it, but environmental impacts and a Russia-backed civil war have held Ukraine back. By destabilizing potential rivals, Russia has successfully used its energy resources as an economic and political tool. In stark contrast, the United Kingdom's new charging system places a higher price on water from high risk/low resilience sources and a lower price on water from abundant sources. But in Texas, groundwater is personal property that operators can buy directly from the owner, with few regulatory obstacles, complicating governance attempts.

Indigenous groups in many of the countries studied have felt the impact of the industry's water practices and have had varying degrees of success asserting their rights. Most notably, the Standing Rock Sioux tribe's protest played a significant role in opposing the Dakota Access Pipeline in Canada and the United States, garnering popular support. And, in Canada, First Nations groups have had limited success challenging fracking when companies failed to consult and accommodate the groups, as required by procedural rules. Sadly, the Khanty people in Russia altered their millennia-old cultures, tradition, and ways of life in response to energy industry obstructing and polluting watercourses in their lands.

Dealing with wastewater produced during fracking raises unique concerns, the authors observe. Water used in the fracking process contains chemicals and proppants (sand or ceramic beads used to prop open fractures in rock to allow oil and gas to escape the formation), while produced water forced from the geologic formations being fractured is often contaminated with naturally occurring dissolved solids, heavy metals, and radioactive materials. Because treating this water is so expensive, operators most commonly inject these fluids back into the ground into non-producing formations, where geology and state regulations permit; where it does not, it may be discharged into surface waters or (least often) onto land. The EPA in 2016 noted that all these disposal methods frequently or severely degrade water. Given that injection wells and surface disposal may trigger both state and federal regulations, the regulatory process can be complex.

Induced seismicity has also been connected with wastewater injection (in the United States) and with the fracking process itself (Canada, United Kingdom, and the Netherlands), prompting additional government action. In response to studies connecting a sudden rise in earthquake activity in Oklahoma and Texas, Oklahoma has seriously limited fracking-related injections in certain areas with increased seismicity. In the United Kingdom, operations near seismic events were suspended, while the Netherlands plans to cease production from fracking entirely by 2030.

For these reasons, injection well disposal has been controversial. On a promising note, regulations, geology, and environmental concerns have prompted operators in states like Pennsylvania and Texas to ramp up treatment, reuse, and recycling of this wastewater—water otherwise permanently removed from the hydrologic cycle. Similarly, in Australia, the use of water and disposal of produced water resulting from the production of coal seam gas has been met with resistance, with Queensland adopting an adaptive management approach, New South Wales enacting a five-year moratorium from 2011 to 2016, and Victoria permanent banning the process.

The groundwater contamination potential associated with fracturing presents equally complex scientific and legal problems. Because fracturing operations occur so deeply below the groundwater-saturated strata, toxic fluids from the fractures themselves are unlikely to directly reach aquifers. This makes it difficult for a plaintiff in a civil case for contamination to prove that fracturing operations legally caused the water contamination alleged—a threshold question before the operator can be held liable. And, even if pathways could be found, often there is no baseline groundwater sample to show that the contamination did not pre-date drilling operations. It is also a challenge to prove that a particular contaminant was introduced by a specific fracking operation because trade secret law is often used to conceal what chemicals are used. Apart from fracturing fluids, however, it is possible that naturally occurring contaminants like "methane could migrate up into aquifers from the fractured shale seam through pre-existing, natural fissures in the overlying rock, or even through fissures created or enlarged by fracturing."

On a macro scale, the book highlights several key issues that—taken with those above—influence regulatory planning, including sustainability; national energy independence and conflicts between national and super-national governance; and funding regulation and enforcement. For instance, energy development applicants in South Africa must consider sustainable development principles, including "the integration of social, economic, and environmental factors into planning, implementation, and decision making so as to ensure that mineral and petroleum resources development serves present and future generations." On the other hand, Argentina pursued energy independence through fracking before establishing any policy to prevent negative environmental or social impacts. And Poland, a European Union member country, has ignored European Union directives to require that operators conduct strategic environmental assessments or environmental impact assessments to obtain license to drill well less than 5,000 meters deep. Dealing with a lack of funding and transparency, Mexico has struggled to enforce regulations on the industry, prompting civil campaigns by indigenous groups. Meanwhile, indigenous groups, local authorities, and environmental groups have had success in Brazilian courts and commonly bring civil claims opposing oil and gas operators trying to secure concessions and licenses.

The book's editors conclude by suggesting several steps and research to address these issues. They emphasize that the human right to water and sanitation recognized by some countries and international bodies like the United Nations must become "hard law" everywhere. There must be regulation on water use in unconventional oil and gas production that considers the related nature of the water-energy nexus as a crucial part of water security. Environmental regulations must not only be consistent with science but also should provide a fail-safe against environmental damage, incorporating sustainability principles and precautions to prevent the damage all together. The silo mentality should be rejected in favor of an approach to water management in which regulation is the product of collaboration between institutions, industry sectors, and communities like indigenous and environmental groups.

Regulating Water Security for Unconventional Oil and Gas articulates important lessons for managing how freshwater resources are used in the hydraulic fracturing process. Perhaps more importantly, it uses fracking as a lens through which to see how interconnected humans are to the water, energy, and environment that sustains us—and how critical it is that we manage those resources in a way that does not value one resource without considering the impact to others.

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Hydrodynamic Modeling Results Showing the Effects of the Luce Bayou Interbasin Transfer on Salinity in Lake Houston, TX

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Abstract: An overreliance on groundwater resources in the Houston (Texas) metropolitan area led to aquifer drawdowns and land subsidence, so regional water suppliers have been turning to surface water resources to meet water demand. Lake Houston, an important water supply reservoir 24 kilometers (15 miles) northeast of downtown Houston, requires new water supply sources to continue to meet water supply demands for the next several decades. The upcoming Luce Bayou Interbasin Transfer Project will divert up to 500 million gallons per day of Trinity River water into Lake Houston. Trinity River water has significantly different water quality than the Lake Houston tributaries. To evaluate the project's potential effect on water quality, the U.S. Geological Survey used an enhanced version of a previously released Lake Houston hydrodynamic model. With a focus on salinity and water-surface elevations, the model combined data from 2009 to 2017 with simulated flow from the Luce Bayou Interbasin Transfer to evaluate potential outcomes from three hypothetical flow scenarios. Overall, these scenarios found that the Luce Bayou Interbasin Transfer would cause salinities to moderately rise over most of the modeled time (2009–2017), although salinities were buffered under 2011 drought conditions. Large inflow events equalized salinities under baseline conditions as well as the enhanced flow scenarios.

Keywords: salinity, hydrodynamic model, water levels, specific conductance

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Terms used in paper

Acronym/Initialism	Descriptive Name
ac-ft	acre-feet
CRPS	Capers Ridge Pump Station
CWA	Coastal Water Authority
DWO	Drinking Water Operations
EFDC	Environmental Fluid Dynamics Code
ft	feet
HGSD	Harris-Galveston Subsidence District
km	kilometers
km^2	square kilometers
LBIT	Luce Bayou Interbasin Transfer
LBITP	Luce Bayou Interbasin Transfer Project
MAE	mean absolute error
MGD	million gallons per day
mi	miles
mi^2	square miles
μS/cm	microsiemens per centimeter
NRCS	Natural Resources Conservation Service
NEWPP	Northeast Water Purification Plant
NRMSE	normalized root mean square error
NSI	Nash Sutcliffe index of efficiency
NWIS	National Water Information System
ppt	parts per thousand
USGS	U.S. Geological Survey
WHCRWA	West Harris County Regional Water Authority

INTRODUCTION

Houston, Texas will likely soon become the third largest city in the United States (Eltagouri 2016). The city and surrounding metropolitan area have experienced exponential population growth over the past 70 years. This growth is projected to continue, with the Houston metropolitan area expecting roughly 9.2 million people by 2030 (WHCRWA 2019). With this population growth, significant pressure has been placed on regional water resources. In 2017 alone, Houston's Drinking Water Operations distributed an average of 449 million gallons per day (MGD; COH DWO n.d.).

Historically, Houston's water supply demands were largely met by groundwater resources. However, an overreliance on groundwater resources eventually led to the drawdown of regional aquifers (Gabrysch 1982). The Chicot and Evangeline aquifers, two primary drinking water sources for the region, had drawdowns of several hundred feet by the mid-1970s (Gabrysch 1982). In the long run, these drawdowns also led to widespread land subsidence, often as much as 3–4.5 meters (m; 10–15 feet [ft]) across much of the Houston metropolitan area (Bawden et al. 2012; Kasmarek and Johnson 2013). Because this land subsidence was caused by the permanent compaction of fine-grained aquifer sediments after large-scale groundwater withdrawals, it was recognized that the overreliance on groundwater resources would need to be reversed.

To reduce groundwater usage, regional water suppliers have been gradually switching to surface water resources in compliance with the mandates set by the Harris-Galveston Subsidence District (HGSD 2020). For the City of Houston (hereinafter referred to as Houston), about 71% of Houston's water supply comes from surface-water resources (Rendon and Lee 2015), as of 2015. As part of its network of surface-water resources, Houston has partial or complete rights to three reservoirs with the following daily water supply capacities: Lake Houston (150 MGD; 460 acre-feet [ac-ft]), Lake Conroe (60 MGD; 184 ac-ft), and Lake Livingston (806 MGD; 2,473 ac-ft; COH DWO 2006). Lake Houston alone supplies 10% to 15% of the total surface-water supply for Houston, according to a published regional water supply map (COH DWO 2006).

Going forward, a critical component for increasing Houston's drinking water supply is the expansion of the Northeast Water Purification Plant (NEWPP). NEWPP diverts water from Lake Houston, with average daily withdrawal rates of 54 MGD (166 ac-ft) from the 2009 to 2017 period for Lake Houston, based on the daily withdrawal rates included as part of the model archive (Smith 2019). With the plant expansion set to be completed by 2024, the plant will pull up to an additional 320 MGD (982 ac-ft) from Lake Houston. To meet this extra demand, the City of Houston and the Coastal Water Authority (CWA) have been implementing the Luce Bayou Interbasin Transfer Project (LBITP), a regional water supply project to transfer raw water from the Trinity River to Lake Houston (CWA n.d.). This project, estimated to be completed in 2020, will divert up to 500 MGD (1,534 ac-ft) of surface water into Lake Houston from the Trinity River.

A growing concern with the LBITP is the potential changes in water quality to Lake Houston. Currently, Lake Houston receives water from seven major tributaries that compose the San Jacinto River Basin (Sneck-Fahrer et al. 2005). The Trinity River, in contrast, has different water-quality characteristics than the current tributaries flowing into Lake Houston (Liscum et al. 1999; Liscum and East 2000). For example, the Trinity River generally has higher specific conductance than the Lake Houston tributaries (Liscum et al. 1999; Liscum and East 2000). This is a concern for municipal and industrial end users that treat raw Lake Houston water via ion exchange plants, as specific conductance is directly correlated with dissolved ionic species. With higher amounts of dissolved ionic species, more effort is required to remove dissolved ions for water treatment processes (EWT Water Technology 2018). Therefore, large increases in specific conductance can serve as a proxy for estimating changes in water treatment efforts, as the chemical consumption and effluent discharge for processing raw water is directly proportional to the dissolved solids within the raw water.

Beyond potential effects on dissolved ion concentrations, Lake Houston is an important recreational resource for the Houston area. During normal to wet periods, large withdrawals for NEWPP and two regional canals close to the Lake Houston dam do not substantially affect water levels in the lake or affect its recreational use. However, the extended drought in 2011 caused Lake Houston to drop by up to 1.8 m (5.9 ft) and severely reduced the reservoir's recreational capacity (Brashier 2011). Looking forward, if Lake Houston were to have increased NEWPP withdrawals and a drought similar to 2011's, the decreases in water levels could become even more problematic with the additional withdrawals (Combs 2012). As a regional example, a 2012 study commissioned to understand the economic effects of low lake levels on Lake Conroe (Texas) found that low 2011 water levels resulted in decreased revenues from recreational activities and declines in property values (Rogers et al. 2012).

As the city continues to grow and deal with considerable events ranging from large droughts to catastrophic flooding, such as Hurricane Harvey in 2017, resource planners will need to evaluate how similar events might affect Lake Houston in combination with the new surface-water additions via the LBITP and additional surface-water withdrawals from NEWPP. One method for evaluating how the Luce Bayou Interbasin Transfer (LBIT) inflows and NEWPP withdrawals might affect both the dissolved ion concentrations and water levels of Lake Houston, and under what conditions these effects could be the strongest, is to utilize a hydrodynamic model that can simulate Lake Houston conditions. Hydrodynamic models have been successfully applied in the past to simulate the dynamic hydrology and chemistry of large water bodies such as Lake Houston (Jin et al. 2007; Dynamic Solutions 2013). In 2015, the U.S. Geological Survey developed such a tool, a three-dimensional circulation, temperature, and salinity transport model for Lake Houston (Rendon and Lee 2015) using the Environmental Fluid Dynamics Code (EFDC) modeling package (Hamrick 1992; Hamrick 1996). As this model also simulates salinity, the salinity can be related back to specific conductance and therefore can be used as an evaluation tool for changes in dissolved ion concentrations.

However, the original EFDC hydrodynamic model developed for Lake Houston (Rendon and Lee 2015) did not account for the proposed LBIT flows or the additional NEWPP withdrawals. Furthermore, the existing Lake Houston EFDC model was originally calibrated and verified for only a 2-year period: 2009–2010. To improve the original model's scope, the USGS, in cooperation with the ExxonMobil Corporation, expanded the model's capabilities to evaluate both the LBITP flows and NEWPP withdrawals on Lake Houston across a wide range of hydrological and climatological conditions. These hypothetical scenarios were designed to investigate the potential effects of the LBITP on both water levels and salinity ranges under historical conditions as a proxy for future conditions. As of 2020, the ExxonMobil Baytown Complex is one of the largest industrial end users of raw Lake Houston water and therefore has a vested interest in the future water quality of Lake Houston. The expanded model looked across almost a decade of hydrological and climatological conditions, simulating water-surface elevations, water temperature, and salinities from 2009 to 2017. This expanded period contained both an extended drought (2011) and several large flooding events (2016 and 2017).

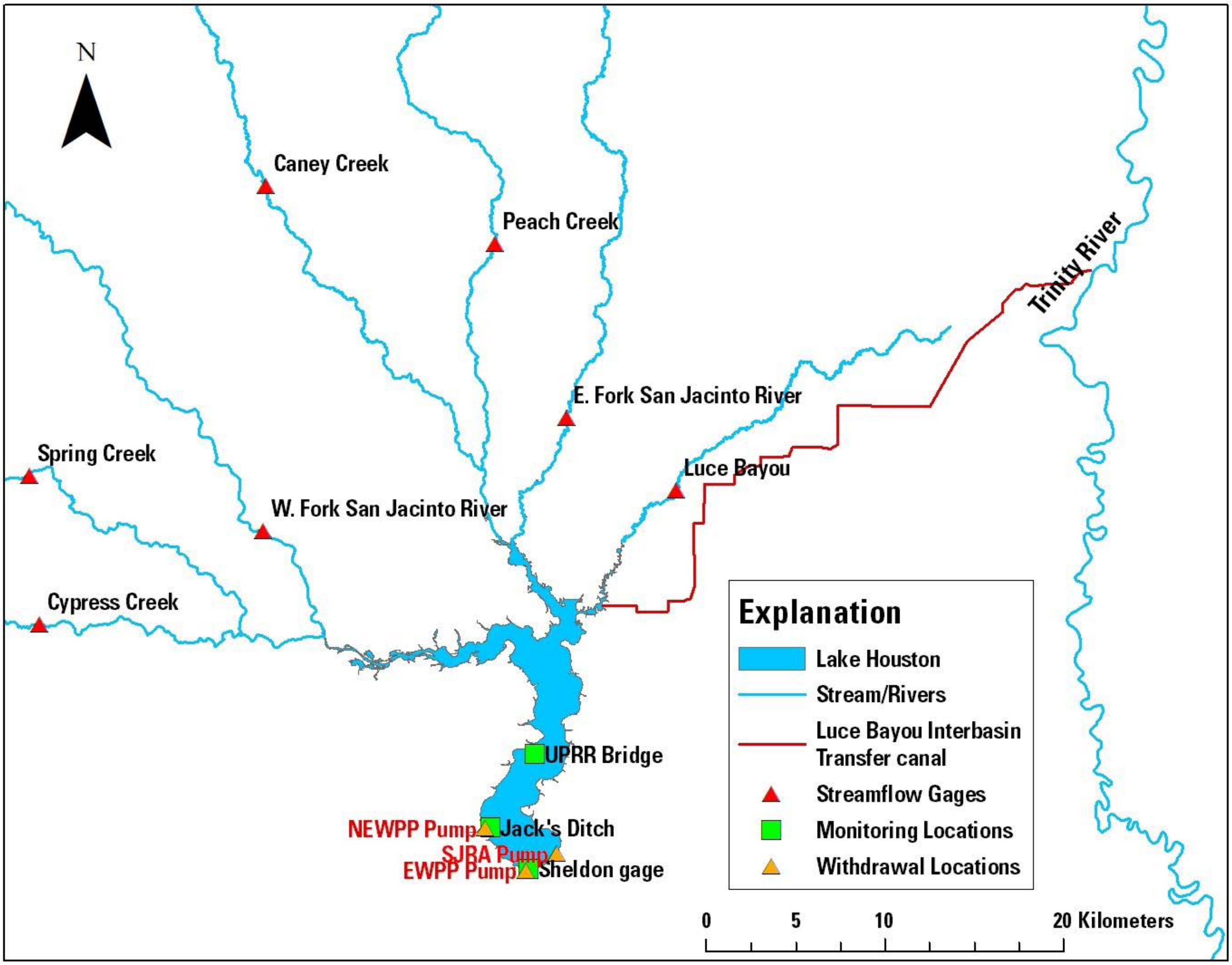

Figure 1. Map of Lake Houston, streams and rivers, streamgages, monitoring locations, withdrawal locations, and the Luce Bayou Interbasin Transfer Canal.

Luce Bayou Interbasin Transfer

Lake Houston has a storage capacity of approximately 47,800 million gallons (146,700 ac-ft; Rendon and Lee 2015). Once the LBITP is fully operational, the LBITP would equal approximately 1.0% of the daily total Lake Houston capacity at 500 MGD (1,534 ac-ft). The LBITP will also allow NEWPP to meet its required mandate to convert to primarily surface-water sources. The CWA will start actively transferring water sometime in 2020 (CWA 2019) at the Capers Ridge Pump Station (CRPS) located on the Trinity River (Figure 1). The CRPS pumps water into a series of large pipelines that convey the water for approximately 4.8 kilometers (km; 3 miles [mi]) before outflowing into a sedimentation basin at the start of a 37.8-km (23.5 mi) earthen canal (AECOM 2011). Trinity River water will be introduced via the northeast corner of Lake Houston near Luce Bayou and allowed to mix with lake water.

Currently, the maximum flow for the LBITP once in operation is 12.6 cubic meters per second (445 cubic feet per second), or 240 MGD (737 ac-ft), based on the installation of four pumps at CRPS (Miller and Marks 2018). Eventually, the LBIT is expected to sustain flows of 240 MGD or more after the first couple of years of operation. Although the additional pumps are not set up to pump 500 MGD (1,534 ac-ft), the structures are in place to add capacity up to the permitted limit of 500 MGD.

Table 1. Gaged watershed area, watershed subdivision (eastern or western), and applied scaling factor for estimating the inflows from all tributaries to Lake Houston, near Houston, Texas during model runs from 2009 to 2017. [U.S. Geological Survey, USGS; km², square kilometers; mi², square miles]

USGS station number	USGS station name	Short name in Figure 1	Eastern or western watershed	Watershed area (km²[mi²])	Scaling factor (K)
08069000	Cypress Creek near Westfield, Texas	Cypress Creek	Western	727.8 (281.0)	1.15
08068500	Spring Creek near Spring, Texas	Spring Creek	Western	1051 (405.7)	1.11
08068090	West Fork San Jacinto River above Lake Houston near Porter, Texas	W. Fork San Jacinto River	Western	2527 (975.5)	1.05
08070500	Caney Creek near Splendora, Texas	Caney Creek	Eastern	272.7 (105.3)	2.12
08071000	Peach Creek at Splendora, Texas	Peach Creek	Eastern	306.4 (118.3)	1.37
08070200	East Fork San Jacinto River near New Caney, Texas	E. Fork San Jacinto River	Eastern	1004 (387.7)	1.07
08071280	Luce Bayou above Lake Houston near Huffman, Texas	Luce Bayou	Eastern	396.8 (153.2)	1.14

STUDY SITE

Lake Houston (Figure 1) is a man-made reservoir about 24 km (15 mi) northeast of downtown Houston, Texas. The Lake Houston Dam, constructed between 1951 and 1953, impounds the West and East Forks of the San Jacinto River and serves as the primary municipal water supply for Houston, Texas (TWDB n.d.). Lake Houston also serves as a major water resource for industrial, commercial, and agricultural irrigation customers, as well as other regional municipalities. Seven major tributaries flow into Lake Houston that drain the San Jacinto River basin upstream from Lake Houston. Generally, these tributaries are grouped into one of two major subbasins: a western and eastern subbasin, comprising the West and East Forks of the San Jacinto River, respectively (Sneck-Fahrer et al. 2005). The western subbasin tributaries include Cypress Creek, Spring Creek, and West Fork San Jacinto River (Table 1). The eastern subbasin tributaries include Caney Creek, Peach Creek, East Fork San Jacinto River, and Luce Bayou (Table 1).

The regional climate for the Lake Houston watershed is classified as humid subtropical, with a mean precipitation of 1.28 m (4.2 ft) per year between 2008 and 2017, based on the Global Summary of the Year from 2008 to 2018 for George Bush Intercontinental Airport (https://gis.ncdc.noaa.gov/maps/ncei/cdo/annual). Due to periodic thunderstorms, sustained rainfall, and occasional hurricanes, the area is prone to flooding. Climate in the region has also been known to experience sustained drought periods, which can have a profound effect on lake level.

The lake has a capacity of about 181.0 million cubic meters (6.391 billion cubic feet; 146,700 ac-ft) and a surface area of 49.5 square kilometers (km²; 19.1 square miles [mi²]; Rendon and Lee 2015). Mean depth at capacity of Lake Houston is about 3.7 m (12 ft) and the maximum depth is about 15.2 m (50 ft; Liscum and East 2000). Lake Houston drainage basin is approximately 7,213 km² (2,785 mi²). The USGS is continuously collecting data at two locations in Lake Houston: Lake Houston south of Union Pacific Bridge near Houston, Texas (USGS 295826095082200; hereafter referred to as UPRR Bridge) and Lake Houston at the mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401 or USGS 295554095093402; hereafter referred to as Jack's Ditch; Buessink and Burnich 2009). Both locations continuously collected the following data on an hourly basis using a multi-probe sonde on a multi-depth monitoring buoy for at least part of the 2009–2017 period: dissolved oxygen, turbidity, specific conductance, water temperature, and pH. Data for these locations are available using the USGS station numbers (USGS 2020).

METHODS

A previously developed three-dimensional hydrodynamic model of Lake Houston was used as the starting version for the enhanced Lake Houston model. The original Lake Houston model was used to simulate three-dimensional circulation, water temperature, salinity, and residence time (Rendon and Lee 2015). Both the original and enhanced models were developed with EFDC, a grid-based surface-water modeling package developed for estuarine and coastal applications (Hamrick 1992; Hamrick 1996). EFDC solves the vertically hydrostatic equations for turbulent flow for a variable-density fluid (including salinity and temperature dependencies). EFDC is a widely used modeling framework that has been applied in a variety of surface-water studies (Ji 2017), including several reservoirs throughout the southern United States (Ji et al. 2004; Elçi et al. 2007; Dynamic Solutions 2013).

The EFDC model structure used in this study required bathymetric data, bottom friction coefficients, tributary inflow loca-

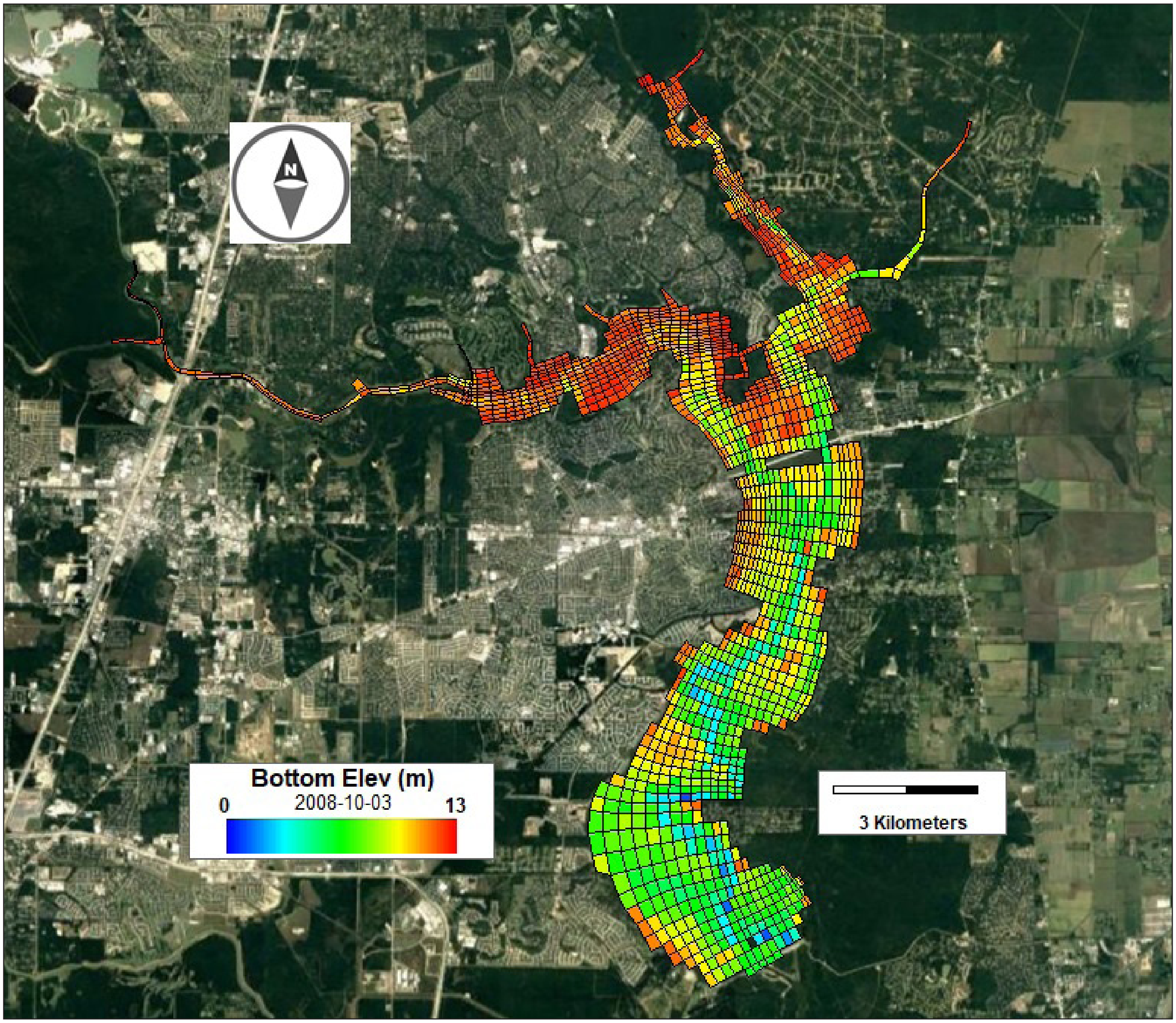

Figure 2. Model domain for the Lake Houston EFDC model, showing the two-dimensional layout of grid cells with the color scale denoting the bottom elevation of the grid cell (in meters).

tions, withdrawal locations (i.e., water intake pumping stations, canal diversions), and any hydraulic structures in the model domain (i.e., the dimensions of the dam impounding Lake Houston). Except for adding the LBIT to the model domain, the original Lake Houston EFDC model structure (Rendon and Lee 2015) was preserved for the updated model (Figure 2). For all aspects of running the EFDC model, EFDC_Explorer version 8.4 (compiled 2018-07-23) was selected, a graphical user interface pre- and post-processor for EFDC models (Craig 2017). EFDC_Explorer was used to enter the required input data into the EFDC model, control model parameters, manipulate run-time configurations, initiate model runs, and perform post-run statistical comparisons.

The enhanced model was recalibrated for the period 2009–2011 and validated for the period 2012–2017 (Smith 2019). Several continuous flow and water-quality monitoring datasets were used to calculate the initial and boundary conditions for the Lake Houston model and to provide calibration data. Data characterizing Lake Houston hydrologic conditions and its contributing areas were compiled for this effort, including inflow from all seven tributaries to Lake Houston and water-surface elevation from Lake Houston near Sheldon, Texas (USGS 08072000; hereafter referred to as Sheldon gage).

Other compiled data included specific conductance and water temperature from a subset of the gaged inflow locations, in addition to specific conductance and water temperature from the two Lake Houston monitoring stations.

Streamflow data collection and water-surface elevations

Streamflow was continuously measured for the seven major tributaries to Lake Houston. Finalized continuous streamflow records used in the enhanced Lake Houston EFDC model development are available from the USGS National Water Information System (NWIS) database using the station numbers provided in Table 1 (USGS 2020) for seven streamgage locations upstream from Lake Houston (Figure 1; Table 1). As part of the continuous streamflow record development, instantaneous discharge and stage measurements were periodically performed at these streamgage locations to verify and modify the stage-discharge relation (Rantz 1982; Mueller et al. 2013). Measured water-surface elevations for calibrating and verifying the EFDC simulations were from Sheldon gage; data are available using USGS station number 08072000 (USGS 2020).

Watershed areas for the seven major tributary locations were delineated in ArcGIS (ESRI 2018) using watershed boundary datasets available from the USGS and U.S. Department of Agriculture, Natural Resources Conservation Service (USGS and USDA NRCS 2013). A percentage of each watershed was considered to have ungaged inflow, as it was determined to not contribute to the flow measured by the USGS streamgage. To consider this flow into the model domain, a variation of the rational method described by Chow et al. (1988) and applied by Rendon and Lee (2015) for the original Lake Houston EFDC model was used. A scaling factor (K) was calculated separately for each watershed that related the ungaged watershed area to the gaged watershed area in order to estimate the total contributed flow from each major tributary (Equation 1):

$$K = 1 + \frac{A_{utw}}{A_{gtw}} + \frac{A_{ul}}{A_{gl}} \tag{1}$$

where

A_{utw} is the ungaged tributary watershed area, in square kilometers;

A_{gtw} is the gaged tributary watershed area, in square kilometers;

A_{ul} is the ungaged lake watershed area, in square kilometers; and,

A_{gl} is the gaged lake watershed area, in square kilometers.

Additionally, Lake Houston inflows also were attributed to other ungaged locations outside of the seven major tributaries, accounting for approximately 3.3% of total area. This additional inflow was also accounted for in the EFDC model (Smith 2019).

Withdrawals from Lake Houston

Three major withdrawals were accounted for in both versions of the Lake Houston EFDC model (Figure 1). Close to Jack's Ditch (Figure 1), pump 1 withdraws water for one of Houston's three primary water treatment facilities. Daily withdrawals typically range from 20 to 80 MGD, with a mean daily withdrawal rate of 54 MGD over the 2009–2017 period. On the west side of the Lake Houston dam, pump 2 withdraws water for the canal that conveys water to the south and west of Lake Houston. Daily withdrawals typically range from 17 to 120 MGD (52 to 368 ac-ft), with a mean daily withdrawal rate of 42 MGD (129 ac-ft) over the 2009–2017 period, based on the full withdrawal rates included as part of the model archive (Smith 2019). Along the east side of the Lake Houston dam, pump 3 withdraws water for the canal that conveys water to the south and east of Lake Houston. Daily withdrawals typically range from 11 to 94 MGD (34 to 288 ac-ft), with a mean daily withdrawal rate of 48 MGD (147 ac-ft) over the 2009–2017 period, based on the full withdrawal rates included as part of the model archive (Smith 2019).

Water temperature and specific conductance

Continuous daily water temperature was available (2009–2017; USGS 2020) for two of the seven major tributaries: Spring Creek near Spring, Texas (USGS 08068500) and East Fork San Jacinto River near New Caney, Texas (USGS 08070200). Each input tributary required a temperature assignment in the model, so Spring Creek measurements were applied to the western watersheds and East Fork San Jacinto River measurements were applied to the eastern watersheds (Table 1). Within Lake Houston, continuous water temperature was measured hourly at two locations (Figure 1): UPRR Bridge and Jack's Ditch (USGS 2020).

Each of the seven tributaries required a salinity estimate for the inflows. As mentioned earlier, direct measurements of salinity were not available, so available specific conductance (in microsiemens per centimeter, or µS/cm) records were converted to salinity (in parts per thousand, or ppt). Continuous specific conductance records were available (USGS 2020) for all or part of the 2009–2017 period for four of the seven major tributaries (Table 1): Spring Creek near Spring, Texas (USGS 08068500), East Fork San Jacinto River near New Caney, Texas (USGS 08070200), Cypress Creek near Westfield, Texas (USGS 08069000), and West Fork San Jacinto River near Humble, Texas (USGS 08069500).

Except for the East Fork San Jacinto River, the salinity record for the other six tributaries were either derived from a mathematical relation or a combination of a relation to discharge and direct measurements (Table 2). Using the same methods as

Table 2. Watershed names for each tributary into the Lake Houston EFDC model, the Equation 2 constants and coefficients of determination (R^2), the U.S. Geological Survey streamgage station name for the streamflow/salinity relation, and the assignment methods for salinity inputs into the enhanced Lake Houston EFDC model. [U.S. Geological Survey, USGS; ---, not applicable]

Watershed name	Constants and R^2 (a and b constant from eq. 1, R^2 in parentheses)	USGS station name for streamflow/salinity relation	Assignment of tributary salinity input
West Fork San Jacinto River	0.3928, 0.343 (0.74)	West Fork San Jacinto River near Humble, Texas (USGS 08069500)	West Fork relation: 10/03/2008–5/18/2010, 01/30/2011–10/30/2013; West Fork, direct measurements: 5/18/2010–12/31/2010, 10/30/2013–12/31/2017
Spring Creek	0.2506, 0.385 (0.86)	Spring Creek near Spring, Texas (USGS 08068500)	Spring Creek relation
Cypress Creek	0.3623, 0.444 (0.61)	Cypress Creek near Westfield, Texas (USGS 08069000)	Cypress Creek relation
East Fork San Jacinto River	0.085, 0.25 (0.40)	East Fork San Jacinto River near New Caney, Texas (USGS 08060200)	East Fork San Jacinto, direct measurements
Caney Creek	---	---	East Fork San Jacinto River relation
Peach Creek	---	---	East Fork San Jacinto River relation
Luce Bayou	---	---	East Fork San Jacinto River relation

Rendon and Lee (2015), the following mathematical relation between streamflow and salinity was used (Equation 2):

$$S = a \, x Q^{-b} \qquad (2)$$

where

S is salinity, in parts per thousand;
a, b are curve-fitting coefficients; and,
Q is instantaneous streamflow for the individual watershed, in cubic meters per second.

Table 2 shows the curve-fitting coefficients, if a streamflow to salinity relation was done for the individual watershed; in parentheses, coefficient of determination (R^2) values (Helsel and Hirsch 2002) for the streamflow-salinity relation are shown. Table 2 also shows how each individual watershed's salinity record was assigned throughout the entire calibration and verification record. Because these were indirect relations, it should be noted that the methodology used to estimate salinity may not fully characterize each inflow. Table 2 highlights the uncertainty, particularly for the eastern subbasin watersheds; overall, the East Fork San Jacinto River relation was the best surrogate available for assigning salinity for these tributaries.

As with the streamflow data, the continuous water temperature and specific conductance data are available from the USGS NWIS database (USGS 2020). Calibration datasets for specific conductance, converted to salinity, were available for the same period and frequency as water temperatures at UPRR Bridge and Jack's Ditch. Salinity (in ppt) was transformed from specific conductance (in µS/cm) through a general equation and rating table (Wagner et al. 2006).

The expected salinity changes for Lake Houston due to the new LBIT flow are one of the primary goals for the new modeling scenarios. However, there was no continuous record available for either salinity or specific conductance for the Trinity River water near the CRPS. Because the EFDC model required an input salinity record (converted from specific conductance) for the LBIT, it was necessary to evaluate the best surrogate available for the LBIT. For purposes of modeling LBIT for the modeling periods from 2009 to 2017, the continuous specific conductance record from the CWA canal at Thompson Road near Baytown, Texas (USGS 08067074; USGS 2020; not shown) was used. This record represents Trinity River water that has been diverted into a CWA canal approximately 35 km downstream from Capers Ridge. Based on comparisons of data from USGS synoptic sampling locations for the Trinity River south of Lake Livingston to the CWA canal record, it was found that the synoptic data had the same general trends and ranges of specific conductance where it and the CWA canal record overlapped. Therefore, the CWA canal continuous record was deemed an appropriate surrogate for LBIT. However, prior to August 2012, the long-term average specific conductance for all the available CWA canal data of 357 µS/cm (converted to salinity; 0.164 ppt) was used because the continuous CWA canal record did not exist.

Table 3. Model parameterization differences between the original Lake Houston EFDC model (Rendon and Lee 2015) and the enhanced model.

Parameter	Description	Rendon and Lee (2015)	Enhanced model	Variation range	Variation comment
FSWRATF	Minimum fraction adsorbed in the top layer	0.30	0.45	0.2–0.6	Sensitive
WQKEB	Background light extinction, (m^{-1})	1.6	2.3	1.2–2.5	Sensitive
IGRIDV	Selection of grid type: standard sigma versus sigma-zed layering	Standard sigma vertical grid	Sigma-zed vertical layering grid	N/A	Sensitive
SGZmin	Minimum number of sigma-zed layers	N/A	3	3–5	Insensitive
DTSSDHDT	Dynamic time stepping rate of depth change	0	0.15	0–0.3	Model run stabilization
NUPSTEP	Minimum number of iterations for each time step	2	4	2–6	Model run stabilization
DTMAX	Maximum time step for dynamic stepping (in seconds)	50	100	25–125	Model run stabilization
ABO	Vertical molecular diffusivity	1 E-09	1 E-06	1 E-05– 1 E-09	Insensitive

Meteorological data

Hourly values for selected meteorological data from 2009 through 2017 (dry bulb temperature [air temperature], relative humidity, air pressure, precipitation, cloud cover, wind speed, and wind direction) were measured at two different locations. For 2009 through March 2010, hourly data from the National Weather Service meteorological station at George Bush Intercontinental Airport was used (https://www.ncdc.noaa.gov/cdo-web/). Starting after April 8, 2010, the USGS weather station located at the Sheldon gage, near the southern end of Lake Houston, was used, and the data used is available as part of the model archive (Smith 2019). Evaporation was calculated internally in the EFDC model, based on the aerodynamic method of calculating evaporation from an open body of water (Chow et al. 1988).

Model parameterization

Most of the EFDC parameters that control the grid, bottom roughness, hydraulic boundary conditions, model run timing, and heat exchange were the same between the original Lake Houston EFDC model (Rendon and Lee 2015) and the new enhanced EFDC model. A few key differences related to time-step control, grid type, light extinction conditions, and the surface heat exchange submodel did exist between the two versions, as shown in Table 3. These parameters were varied by trial and error through a series of calibration model runs to improve the overall fit of the model.

The selection of the water balance evapotranspiration model (EFDC Original) was left the same, but the underlying surface heat exchange submodel parameterization was adjusted. Two parameters within the surface heat exchange model, FSWRAFT and WQKEB (Table 3), were found to be sensitive, particularly for the water-surface elevation calibration. Also, changing the selected grid type (IGRIDV) from standard sigma vertical layering to sigma-zed vertical layering made for a better water-surface elevation fit (Craig 2017). Finally, a series of parameters that control the model run timing (DTSSDHDT, NUPSTEP, DTMAX), and one parameter that affects the hydrodynamics (ABO), were adjusted to help with model run stabilization but were relatively insensitive for improving the model calibration.

The hydraulic structure data, as stored in the free surface elevation control file, was adjusted to account for new rating curve measurements available since the 2015 model publication. In particular, the adjusted rating curve accounted for the high flows observed during the 2016 and 2017 flooding events. The overall hydraulic structure setup, such as the length of the model cells that encompass the Lake Houston Dam, was unaltered from the original model.

RESULTS

Calibration and verification of the enhanced model

The enhanced Lake Houston EFDC model was modified and calibrated by using input boundary conditions from 2009 through 2011. The model was then verified by using 2012 through 2017 input boundary conditions as a secondary performance test. Model results at three locations in the model grid of Lake Houston (at various depths) were compared to measured data collected from the three data collection sites on the lake (Figure 1). The three types of data used to verify model

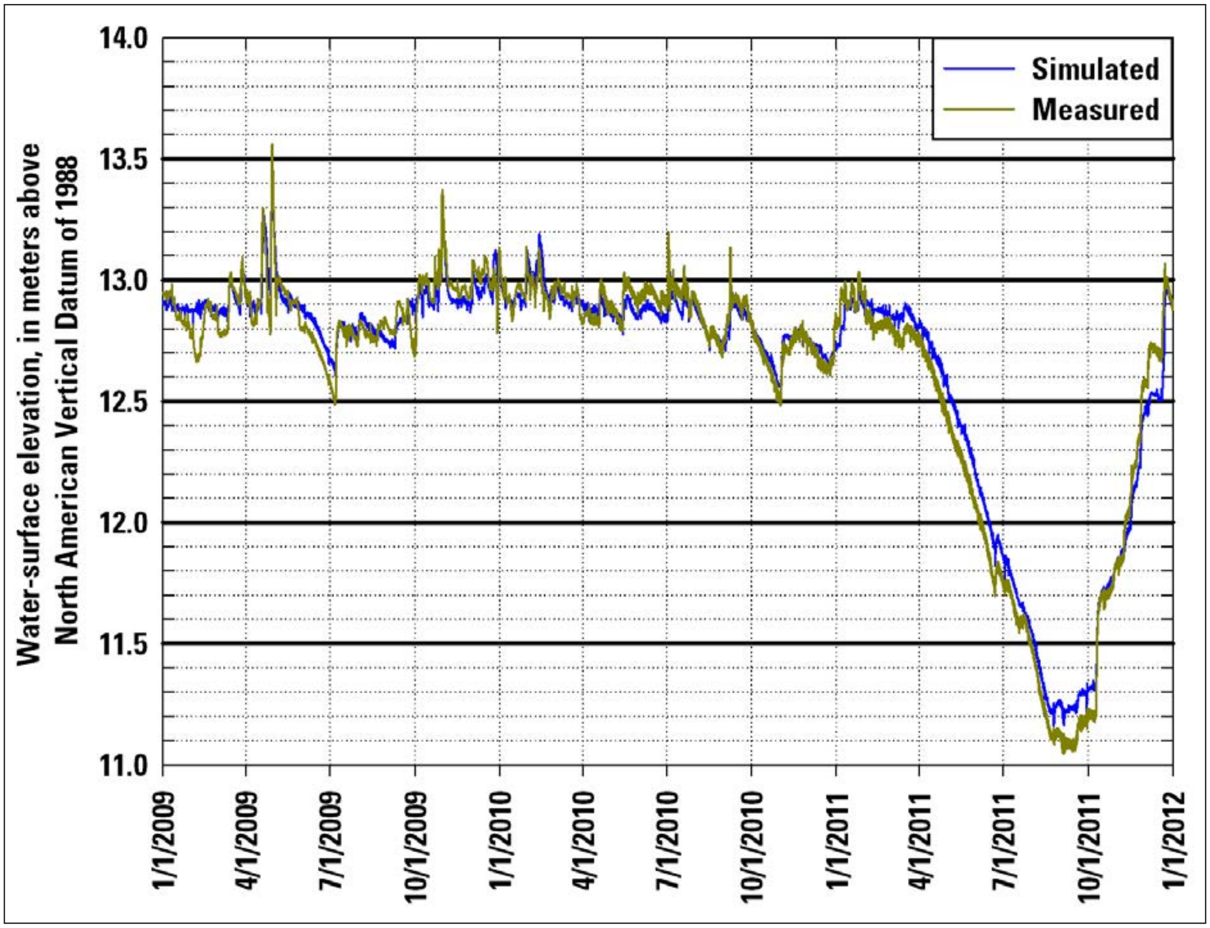

Figure 3. Simulated and measured water-surface elevations, in meters above the North American Vertical Datum of 1988 (NAV88), for Lake Houston, 2009–2011.

performance were water-surface elevations, salinity (computed from measured specific conductance), and water temperature. Water-surface elevations were compared at the Sheldon gage. Salinity and water temperature were compared at the two lake locations: UPRR Bridge and Jack's Ditch. For both UPRR Bridge and Jack's Ditch, continuous records were available at four different depths: 0.3 m (1.0 ft), 1.8 m (5.9 ft), 3.7 m (12.1 ft), and 4.9 m (16.1 ft). Not all the datasets were complete, particularly for the UPRR Bridge. Only the continuous record for the 0.3-m (1.0-ft) depth continued after June 2010 for the UPRR Bridge; on the other hand, most of the Jack's Ditch records for all four depths were nearly complete (2009–2017). Overall, adequate datasets existed for comparison during both the calibration and verification periods.

Three statistics were used to evaluate performance of the Lake Houston EFDC model: mean absolute error (MAE), normalized root mean square error (NRMSE), and the Nash-Sutcliffe index of efficiency (NSI; Nash and Sutcliffe 1970). The MAE is a goodness-of-fit statistic calculated as the mean of the absolute differences between the simulated (model) value and the measured value (Legates and McGabe 1999). The NRMSE is a slightly different metric, calculated as the root of the mean of the squares of the difference between the simulated and measured values, then divided by the range of measured values to remove the units of measure (dimensionless). The last goodness-of-fit statistic, the NSI has been classically used to evaluate hydrological model performance (Legates and McCabe 1999). The NSI ranges from minus infinity to positive 1.0: Any value above 0.0 indicates that the model is a better predictor of the measured data than the mean of the measured data, with 1.0 indicating a perfect match. NSI values below 0.0 indicate the model is worse than the mean of the measured data. For the exact NSI formula, also termed the coefficient of efficiency, consult Nash and Sutcliffe (1970) or Legates and McCabe (1999).

The first step in the calibration process for this revised Lake Houston model was the water balance. Before the water temperature and salinity calibrations could proceed, the differences between the simulated and measured water-surface elevations were resolved. The final calibrated model was able to replicate most of the large inflow events as well as accurately simulate the large drought event in 2011. A comparison between the

Table 4. Performance evaluation statistics for the enhanced 2019 Lake Houston EFDC model. Summary for the following evaluation criteria: simulated water-surface elevation relative to measured water-surface elevation, simulated salinity relative to salinity computed from specific conductance, and simulated water temperature relative to measured water temperature. Criteria represent the range of values for the individual depths (0.3 m [1.0 ft], 1.8 m [5.9 ft], 3.7 m [12.1 ft], 4.9 m [16.1 ft]) at U.S. Geological Survey reservoir stations Lake Houston south of Union Pacific Railroad Bridge near Houston, Texas (USGS 295826095082200) and Lake Houston at the mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401; USGS 2020). [m, meters; ft, feet; ppt, parts per thousand; °C, degrees Celsius; MAE, mean absolute error; NRMSE, normalized root mean square error; NSI, Nash Sutcliffe index of efficiency]

Year(s)	Evaluation Criteria		
	MAE	NRMSE	NSI
Water-surface elevation			
2009–2011	0.06 m (0.20 ft)	0.03	0.98
2012–2017	0.05 m (0.16 ft)	0.02	0.85
Salinity			
2009–2011	0.007–0.009 ppt	0.05–0.09	0.84–0.97
2012–2017	0.007–0.009 ppt	0.05–0.06	0.80–0.94
Water temperature			
2009–2011	0.66–0.86 °C	0.03–0.04	0.98
2012–2017	0.75–0.92 °C	0.03–0.04	0.97–0.98

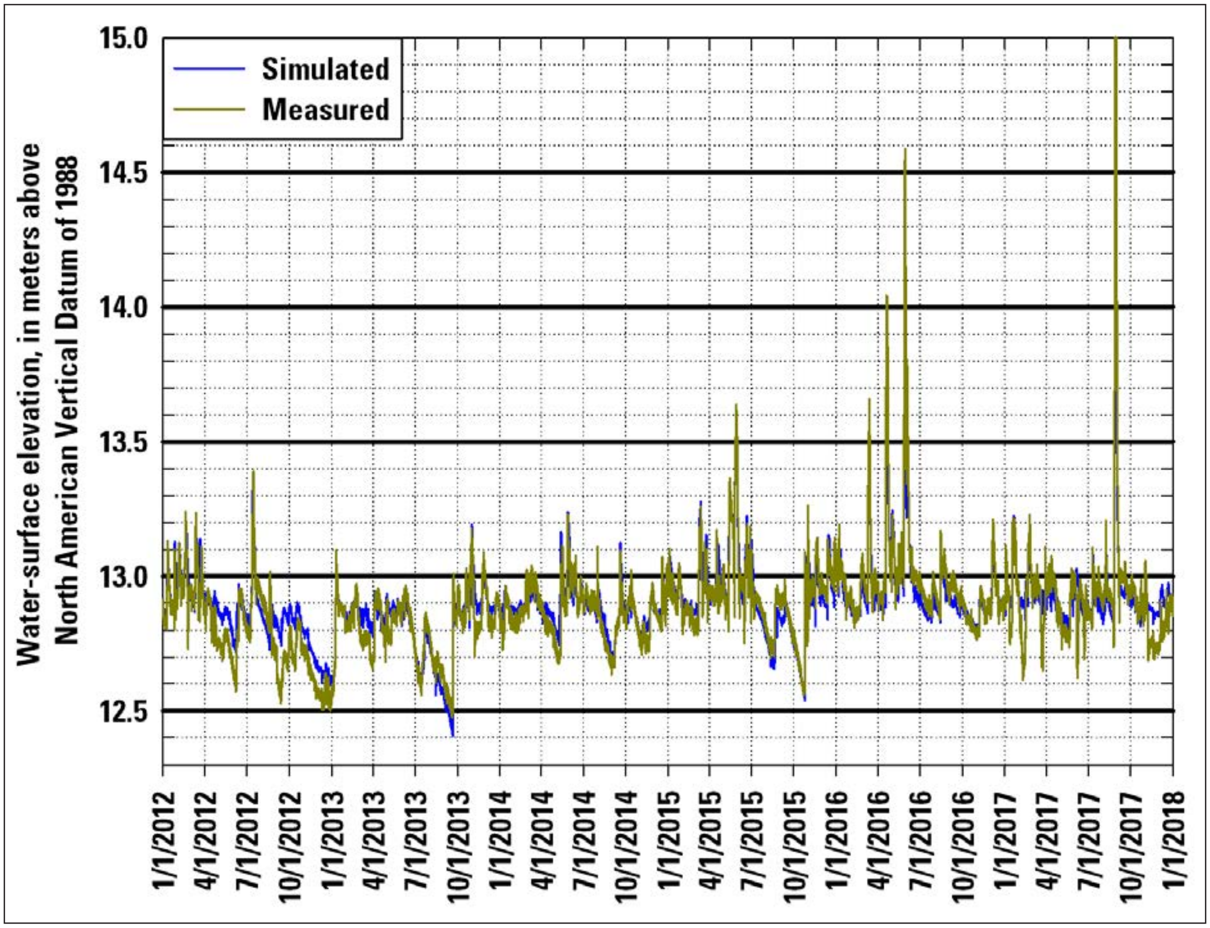

Figure 4. Simulated and measured water-surface elevations, in meters above the North American Vertical Datum of 1988 (NAV88), for Lake Houston, 2012–2017.

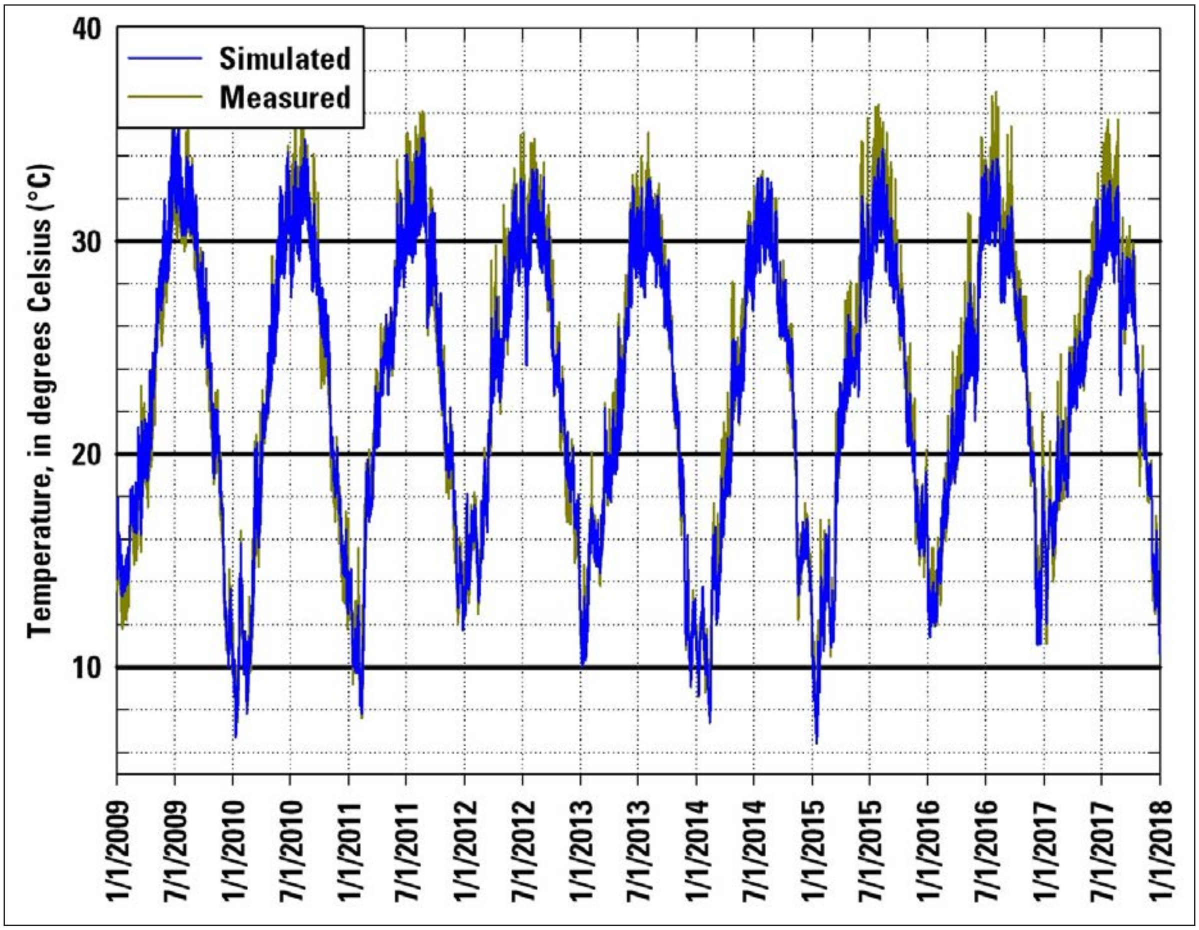

Figure 5. Simulated and measured temperature, in degrees Celsius, at 0.3-meter (1-foot) depth for Lake Houston south of Union Pacific Railroad Bridge near Houston, Texas (USGS 295826095082200), 2009–2017.

simulated and measured water-surface elevations for Lake Houston is shown in Figure 3. Overall, the enhanced Lake Houston EFDC model had an improved model fit to the measured water-surface elevation data for the three goodness-of-fit statistics selected over the original model (Rendon and Lee 2015). Table 4 shows the primary statistics for the calibration from 2009 to 2011 and the verified period from 2012 to 2017 (Figure 4). The MAE and NRMSE values were generally one-half of the original model for water-surface elevation, with an NSI of 0.98 for the calibration (2009–2011) and 0.85 for the verification period (2012–2017). For comparison, the original model had an NSI of 0.54 for the selected calibration year (2009) and 0.75 for the validation year (2010).

Water temperature for the enhanced model had NSI values above 0.9, similar to Rendon and Lee (2015) NSI values. The simulated temperatures effectively tracked the measured data across all four depths. MAE values for the enhanced model were generally between 0.6 and 0.9 °C (0.54 to 1.62 °F) for all depths. Overall, the model matched the measured data very closely for water temperature, as shown in Figure 5 at 0.3-m (1-ft) depth for the UPRR Bridge.

Figure 6 shows the simulated and measured salinity (converted from specific conductance) for the 2009–2017 period at 0.3-m (1-ft) depth for the UPRR Bridge. As with temperature, all four depths generally showed the same pattern with only slight variations with depth for salinity. Salinity had MAE values ranging from 0.007 to 0.009 ppt for the calibration, NRMSE values ranging from 0.04 to 0.09, and NSI values ranging from 0.83 to 0.97. For the verification period (2012–2017), salinity had MAE values ranging from 0.007 to 0.009 ppt for the calibration, NRMSE values ranging from 0.05 to 0.06, and NSI values ranging from 0.80 to 0.94. Overall, the simulated salinity values were able to adequately replicate most of the large inflow events and most importantly, simulate the high salinity values during the 2011 drought. Also, the NSI values exceeded the original model calibration and validation, which ranged from 0.66 to 0.86 (Rendon and Lee 2015).

Long-term LBIT simulations

A series of three model scenarios were run to better understand the long-term water-surface elevation and salinity effects

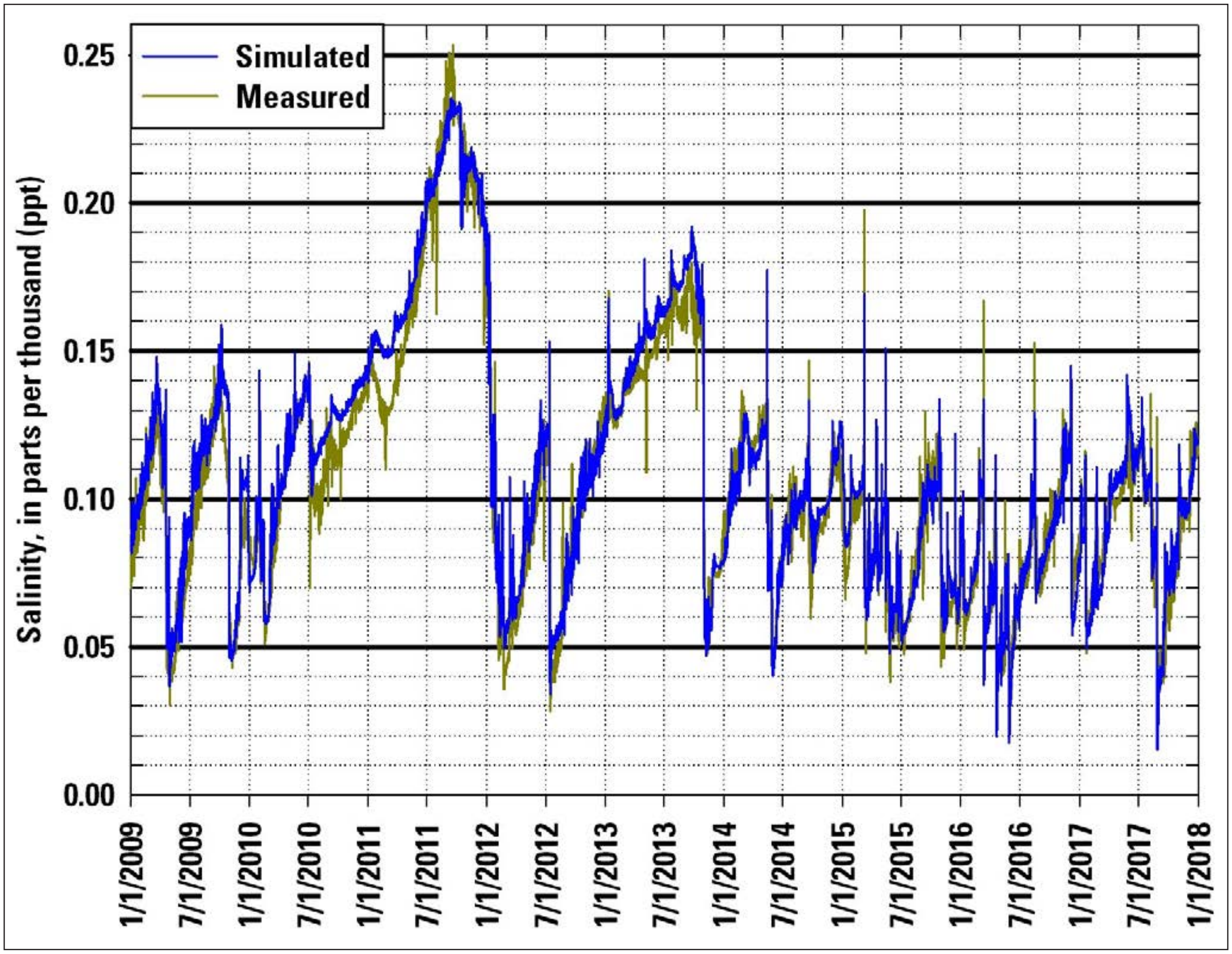

Figure 6. Simulated and measured salinity, in parts per thousand (ppt), at 0.3-meter (1-foot) depth for Lake Houston south of Union Pacific Railroad Bridge near Houston, Texas (USGS 295826095082200), 2009–2017.

of sustained pumping of Trinity River water through the LBIT to Lake Houston. All three LBIT scenarios spanned the entire period from 2009 to 2017. Running the model for the entire period was done to evaluate how the proposed sustained pumping under the LBIT would have affected Lake Houston under the hydrological and climatological conditions for the period of record. In all three simulations, it was assumed an additional 320 MGD (982 ac-ft) were withdrawn from Lake Houston to simulate withdrawals for the NEWPP plant expansion, as this is the estimated additional withdrawal once NEWPP is at full capacity.

The time from 2009 to 2017 spanned an extreme range of climatological and hydrological variability. The years 2009 and 2010 were average in terms of meteorological patterns, based on the Global Summary of the Year from 2000 to 2018 for George Bush Intercontinental Airport (https://gis.ncdc.noaa.gov/maps/ncei/cdo/annual). In 2011, most of Texas, including Lake Houston and all its tributary watersheds, experienced one of the driest years in modern Texas history (Winters 2013). After the 2011 drought ended, the meteorological patterns for the Lake Houston region have either been normal to extremely wet except for another dry period in 2013. For the years 2015, 2016, and 2017, there was at least one extreme precipitation event each year, culminating in Hurricane Harvey at the end of August 2017.

The first two scenarios included a sustained diversion of LBIT flow: Scenario 1 included 240 MGD (737 ac-ft) for the entire period and Scenario 2 included 320 MGD (982 ac-ft) for the entire period. Scenario 1 results in a net deficit of 80 MGD (246 ac-ft) being added to Lake Houston, as LBIT flow is 240 MGD versus 320 MGD for the additional NEWPP withdrawal. For Scenario 2, LBIT flow and NEWPP diversions are balanced at 320 MGD each. The final scenario, Scenario 2A, was set up like Scenario 2 except during the long drought period of late 2010 through 2011, an extra 80 MGD

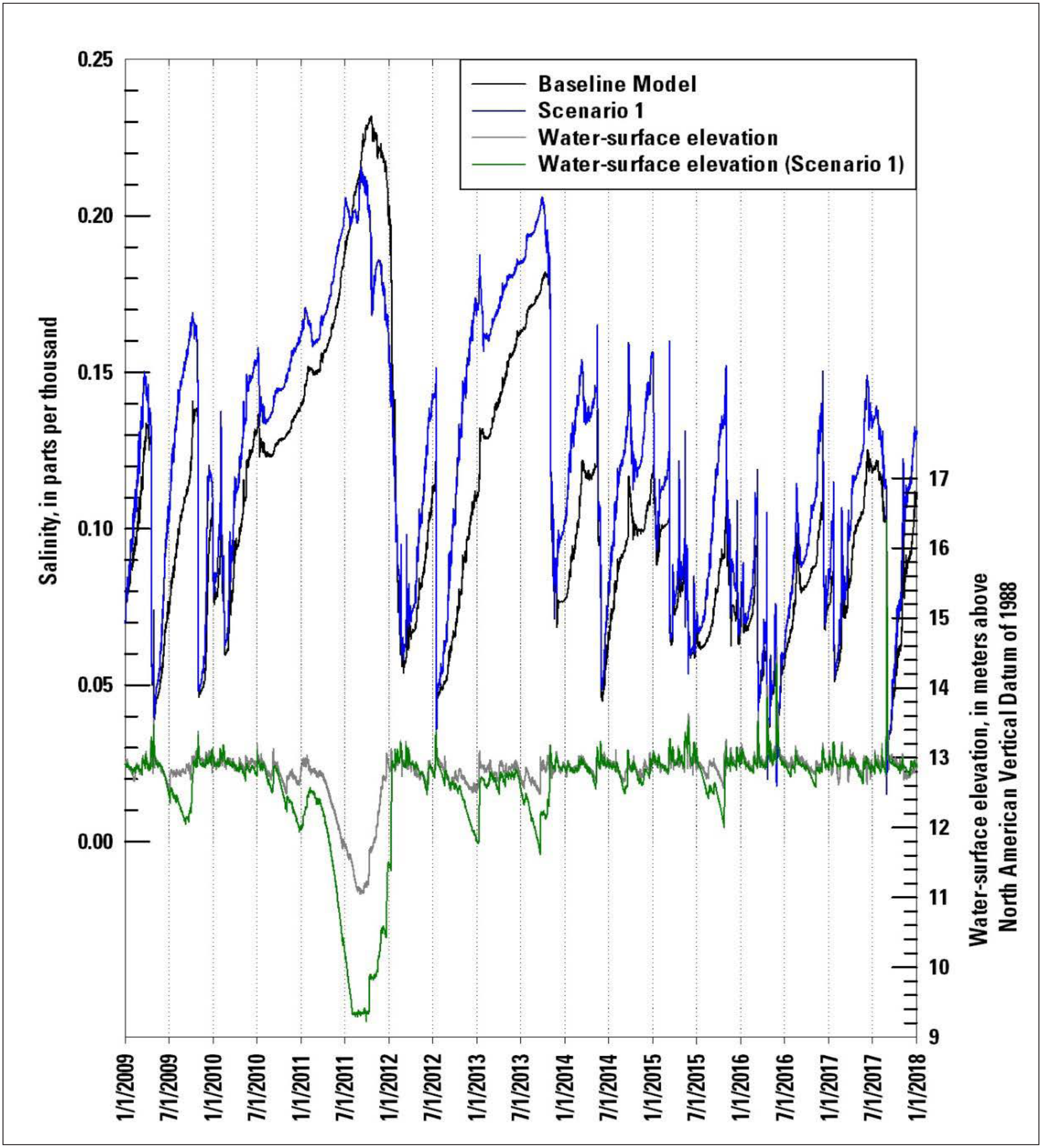

Figure 7. Scenario 1 simulated salinity (in parts per thousand) for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth, 2009–2017. Also shown is the baseline (calibrated and verified) model simulated salinity at the same location, measured Lake Houston water-surface elevation, and the simulated Lake Houston water-surface elevation for Scenario 1.

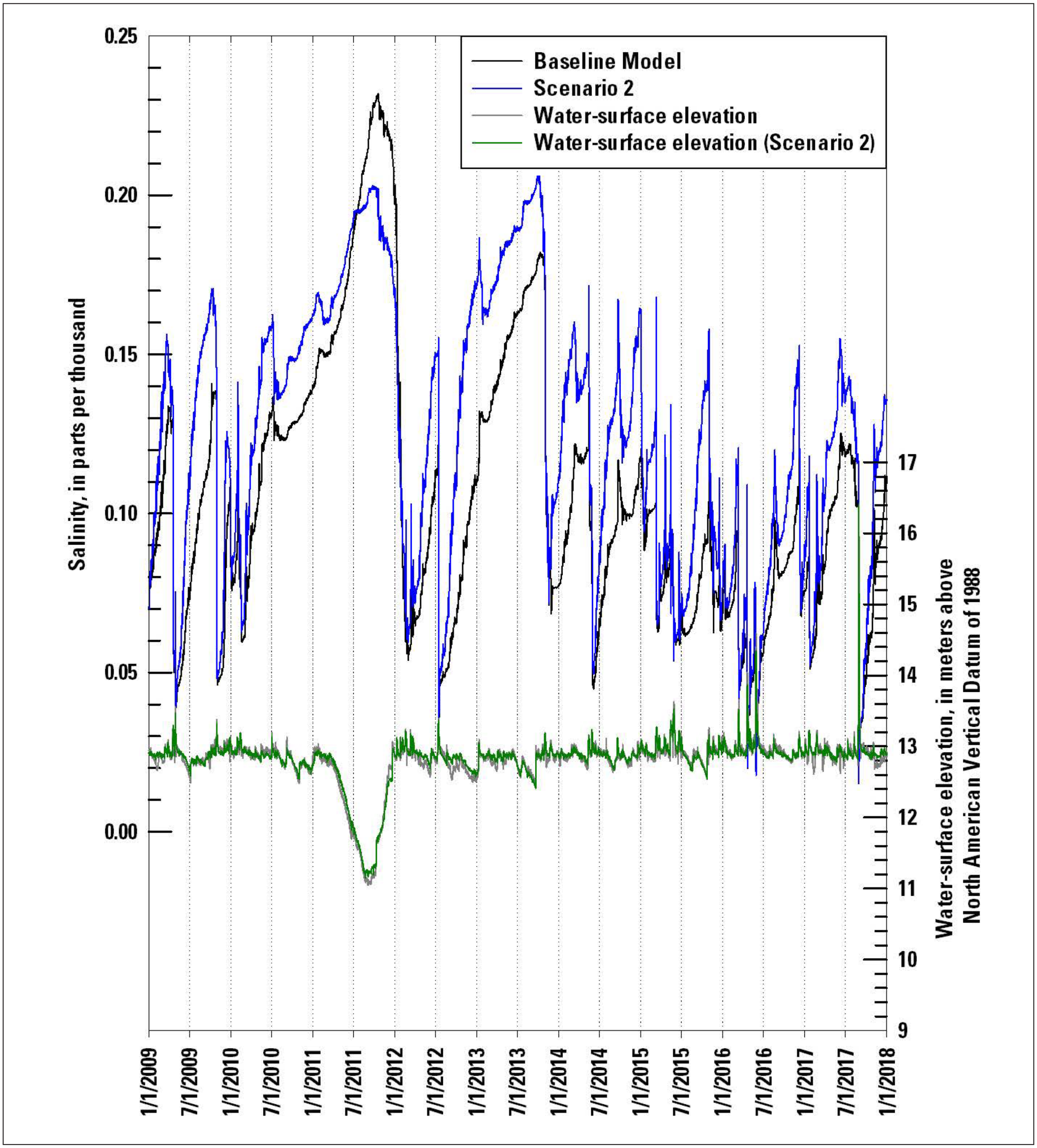

Figure 8. Scenario 2 simulated salinity (in parts per thousand) for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth, 2009–2017. Also shown is the baseline (calibrated and verified) model simulated salinity at the same location, measured Lake Houston water-surface elevation, and the simulated Lake Houston water-surface elevation for Scenario 2.

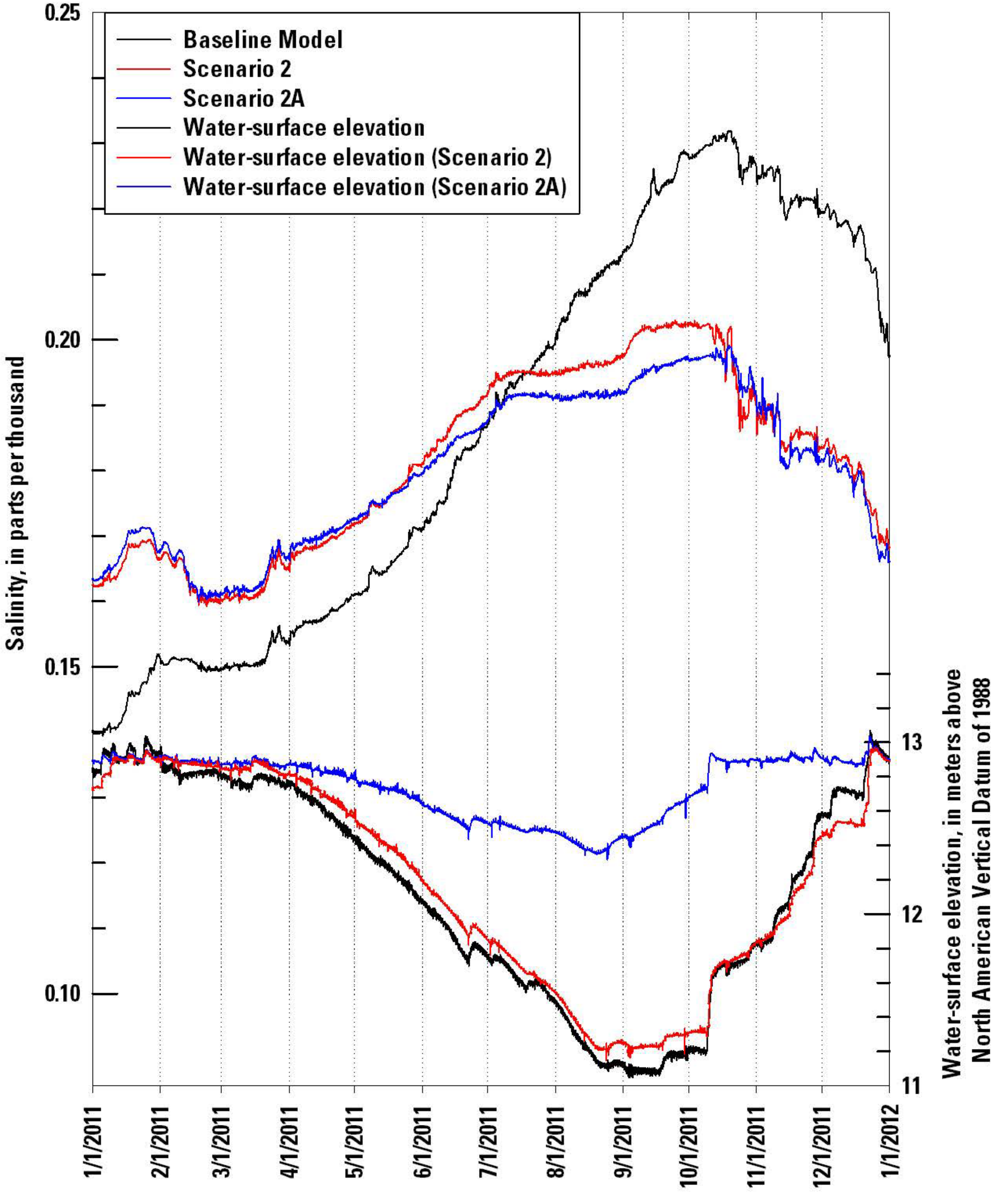

Figure 9. Scenarios 2 and 2A simulated salinity (in parts per thousand) for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth, 2011. Also shown is the baseline (calibrated and verified) model simulated salinity at the same location, measured Lake Houston water-surface elevation, and the simulated Lake Houston water-surface elevation for Scenarios 2 and 2A.

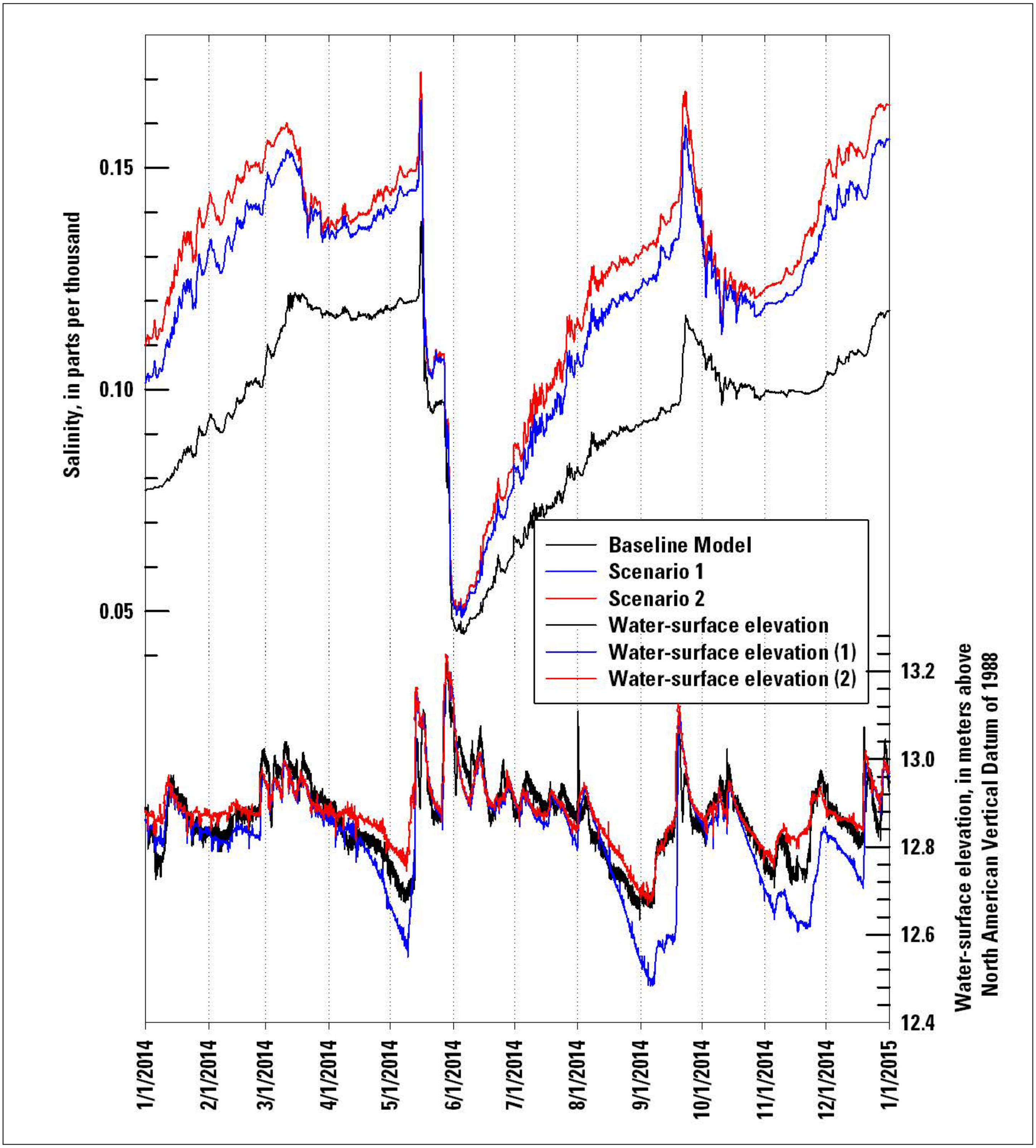

Figure 10. Scenarios 1 and 2 simulated salinity (in parts per thousand) for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth, 2014. Also shown is the baseline (calibrated and verified) model simulated salinity at the same location, measured Lake Houston water-surface elevation, and the simulated Lake Houston water-surface elevation for Scenarios 1 and 2.

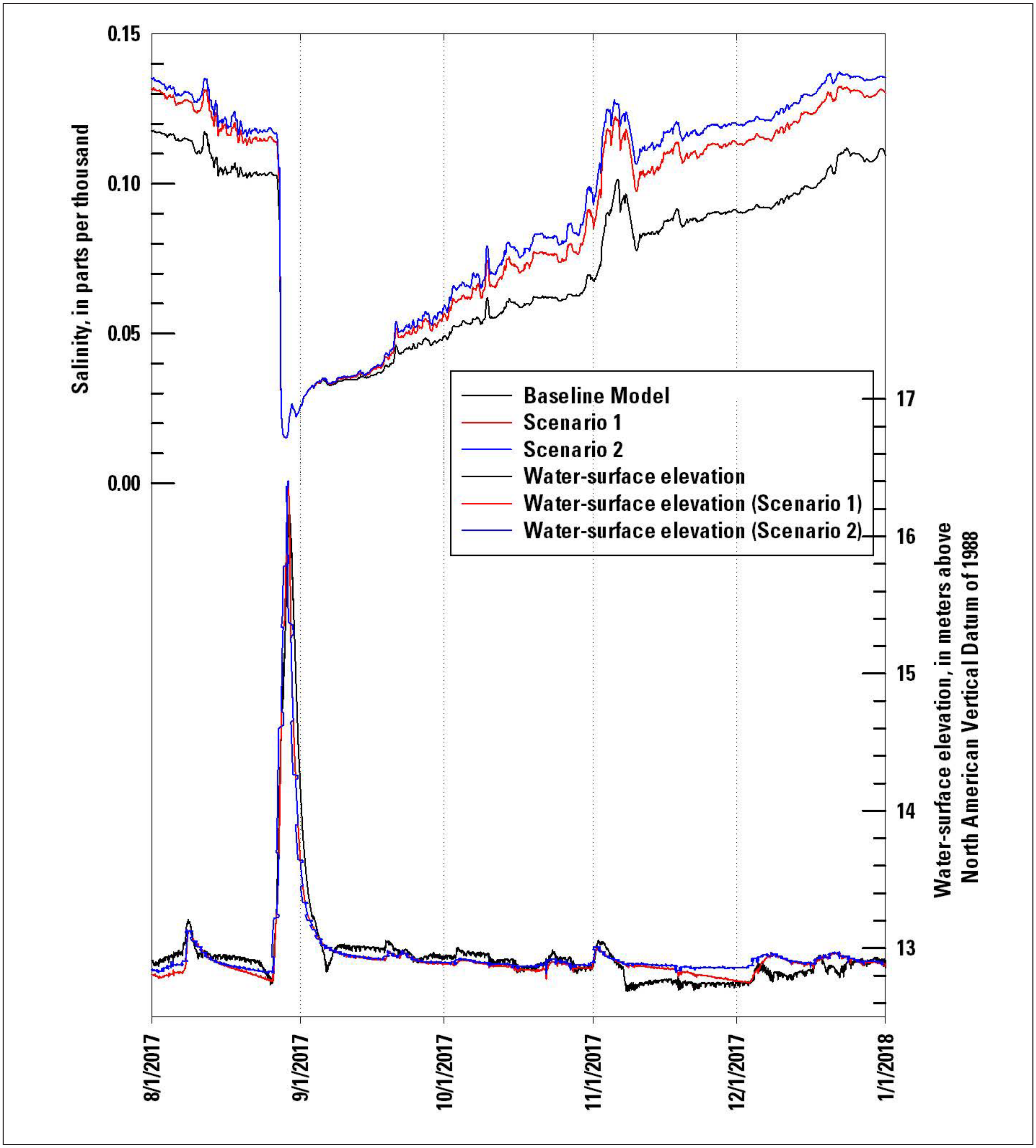

Figure 11. Scenarios 1 and 2 simulated salinity (in parts per thousand) for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth, 2017. Also shown is the baseline (calibrated and verified) model simulated salinity at the same location, measured Lake Houston water-surface elevation, and the simulated Lake Houston water-surface elevation for Scenarios 1 and 2.

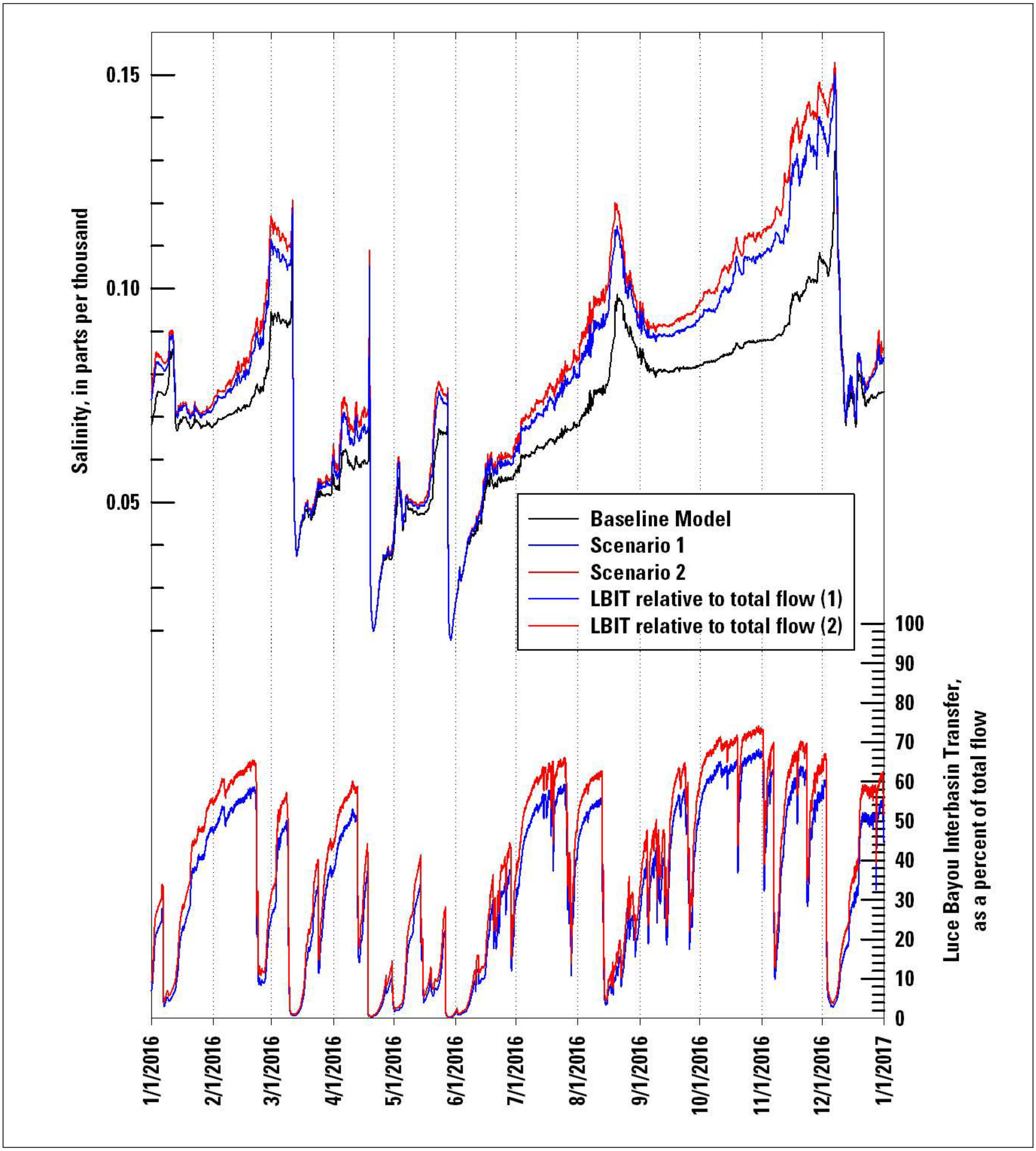

Figure 12. Luce Bayou Interbasin Transfer flow, as a percent of the cumulative flow from the Luce Bayou Interbasin Transfer and the seven tributaries, 2016. Also shown is the baseline (calibrated) model simulated salinity for Lake Houston at mouth of Jack's Ditch near Houston, Texas (USGS 295554095093401) at 1.8-meters (5.9-feet) depth for 2016, and the simulated salinities for Scenarios 1 and 2.

of LBIT flow was diverted from the Trinity River for a total of 400 MGD (1,228 ac-ft).

Scenario 1 was run from October 3, 2008, through December 31, 2017 (Figure 7). Model conditions remained identical to the baseline model (calibrated/verified model), except for a sustained LBIT flow of 240 MGD and NEWPP withdrawal of 320 MGD from January 1, 2009, through December 31, 2017. Prior to January 1, 2009, the model was run for the last 3 months of 2008 as a model warm-up period to avoid a start-up bias. The most striking difference for Scenario 1 from the baseline model was the larger drop in the water-surface elevation, particularly during the drought year of 2011. Smaller drops occurred again in 2012, 2013, and 2015. These drops were the net effect of an increase of 80 MGD in withdrawals over the LBIT flow. The effect on salinity was not the same for each of these 4 years with water deficits compared to the baseline model. In 2011, the water deficit caused water-surface elevations to drop approximately 2 m (6.6 ft) more than the baseline model, but the salinity for Scenario 1 rose less than the baseline model. For the other years with water deficits, the salinity was generally higher for Scenario 1 than the baseline model.

Scenario 2 had the same model conditions as Scenario 1, except the LBIT flow was set to 320 MGD rather than 240 MGD (Figure 8). Scenario 2 showed similar trends to Scenario 1, except the peak salinity in 2011 was more buffered by LBIT flow for Scenario 2. For the subsequent years with water deficits (2012, 2013, and 2015) in Scenario 2, the high salinity values for those years were slightly more pronounced for Scenario 2 than Scenario 1 although these differences were subtle. Peak salinity values for Scenario 2 were approximately 0.01 ppt higher than Scenario 1—for example, the salinity peaks in 2014 were 0.17 ppt in Scenario 2 as opposed to 0.16 ppt in Scenario 1. Water-surface elevations in Scenario 2 were almost the same as the baseline model, as the water deficits caused by the increased NEWPP withdrawals were canceled out by increased LBIT flow.

Scenario 2A had the same model conditions as Scenario 2, except the LBIT flow was set to 400 MGD rather than 320 MGD (Figure 9) during the prolonged 2011 drought; LBIT flow was 400 MGD from November 1, 2010, through December 31, 2011. This scenario was designed to simulate the conditions of sustained 320 MGD LBIT flow with an extra 80 MGD of supplemental LBIT flow during the severe drought when reservoir levels dropped by almost 2 m (6.6 ft). This scenario also assumes that LBIT flow could be used during a drought, because it is likely the Trinity River would also be under similar drought conditions. With the additional 80 MGD for all of 2011, the water-surface elevations only dropped by 0.5 m (1.6 ft) as opposed to the 2 m (6.6 ft) for both the baseline model and Scenario 2. Salinity for Scenario 2A is similar to Scenario 2, where the salinity is buffered by almost 0.04 ppt.

DISCUSSION

These long-term scenarios were intended to help understand the long-term effects of sustained pumping of Trinity River water through the LBIT to Lake Houston. Because the Trinity River has elevated specific conductance compared to the Lake Houston tributaries, these scenarios were designed to help understand the relative increases or decreases in specific conductance that could occur because of the LBIT. Using salinity as a proxy for elevated specific conductance and total dissolved solids, elevated salinity requires additional water treatment efforts and thereby would result in an increase in water treatment costs (EWT Water Technology 2018). Alternatively, if salinity does not increase or goes down during certain periods, the risk to elevated water treatment costs goes down. It is important to note that salinity is not completely analogous to specific conductance or total dissolved solids (Atekwana et al. 2004; Fondreist 2014). Nonetheless, salinity was the best surrogate parameter available for analysis as a sub-module within the Lake Houston EFDC model.

Overall, hydrological and climatological forcing had the largest effect on salinity in Lake Houston. Although Lake Houston salinities for the LBIT scenarios were higher than the baseline for most of the modeled time (2009–2017), the highest salinities were attributed to climatological forcing (i.e., warm, dry periods) rather than introducing LBIT flow. For example, the highest salinity levels during the entire 2009–2017 period were the salinity values in 2011 (Figure 6; Figure 9). Long periods of evapotranspiration concentrated the dissolved constituents within Lake Houston. As the water-surface elevation dropped without freshwater replenishing Lake Houston, such as during 2011 and to a lesser degree during dry periods in other years such as 2012 through 2015, the salinity would increase. In 2014, the measured salinity (Figure 10) steadily rose to 0.15 ppt in May and then quickly dropped due to a series of large inflow events from the tributaries. Salinity then steadily rose again to 0.11 ppt by the end of the 2014 after bottoming out at 0.05 ppt. In contrast, the Hurricane Harvey effect can clearly be seen in late August and early September 2017 (Figure 11). Water-surface elevations rose by approximately 3.5 m (11.5 ft) to nearly 16.5 m (54.1 ft), whereas measured salinity dropped to 0.02 ppt. This forcing event equalized LBIT Scenarios 1 and 2 to the same as the measured salinity—both events had elevated salinity before the event. This effect of equalized salinity lasted for over a month past the end of Hurricane Harvey.

Hydrological and climatological forcing had a strong effect on salinity over shorter periods, but the simulated LBIT flow did have a long-term effect on Lake Houston water. As the Trinity River water generally had higher salinity than the tributary inflows into Lake Houston, the simulated scenarios indicated that this water would cause Lake Houston's salinity to increase during much of the simulated period. This relative increase in

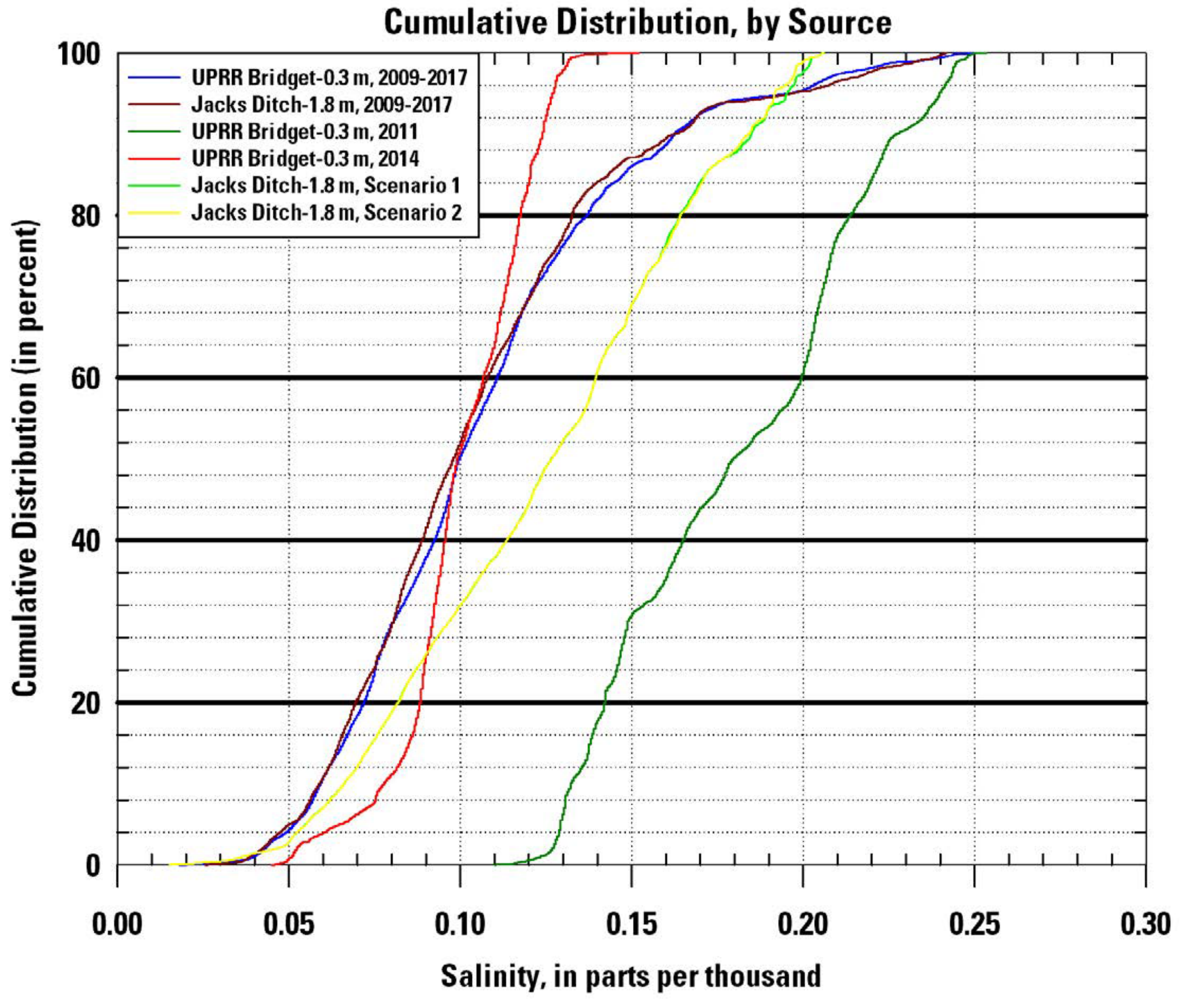

Figure 13. Cumulative distribution, by source, of the salinity (in parts per thousand) for the following measured data: UPRR Bridge at 0.3-meter (1-foot) depth (2009–2017), UPRR Bridge at 0.3-meter (1-foot) depth (2011), UPRR Bridge at 0.3-meter (1-foot) depth (2014), and Jack's Ditch at 1.8-meters (5.9-feet) depth (2009–2017). Also shown is Jack's Ditch at 1.8-meters (5.9-feet) depth (2009–2017) for Scenario 1 and Scenario 2.

salinity from LBIT flow can be seen across a wide spectrum of the 2009–2017 period. Scenario 1 (Figure 7) and Scenario 2 (Figure 8) both show elevated salinity over the measured salinity for most of the 9-year period. The LBIT effect in Scenarios 1 and 2 could also be large, often greater than 0.05–0.06 ppt (Figure 10). While increased salinities (i.e., increased total dissolved solids) could potentially increase treatment costs, the LBIT scenarios did not introduce salinities beyond the natural variation observed from 2009 to 2017. Therefore, the necessity for increased treatment capacity due to substantial changes in total dissolved solids from LBIT flow would be unlikely.

The effect of the LBIT flow on salinity can also be shown through the ratio of LBIT flow to the cumulative sum of LBIT flow and the seven tributaries for Scenario 1 (240 MGD) and Scenario 2 (320 MGD; Figure 12). In 2016, simulated periods with low LBIT flow relative to the overall flow, such as late April and early May 2016, had a lower salinity. Alternatively, simulated periods with mostly high LBIT ratios, such as the periods starting in July 2016 and later in October 2016, had larger deviations for both scenarios from the baseline model (Figure 12). In October and November, the LBIT flow was up 68% and 74% of the entire inflow into Lake Houston for

Scenarios 1 and 2, respectively—this period also had the higher salinities and the largest deviations between the baseline model and the two LBIT scenarios.

Another way to understand the effects of both hydrological/climatological forcing and LBIT flow on Lake Houston salinity is to look at measured (or simulated) salinity (in ppt) as cumulative distributions (Figure 13). This shows the percent of measurements for the different locations or scenarios that are at or below a salinity value. For example, the 2011 measured data for the UPRR Bridge at 0.3 m (1 ft) depth was at or below 0.20 ppt for 60% of the measurements. In contrast, 40% of the measurements for this location were above 0.20 ppt in 2011. This year was isolated from the 2009–2017 cumulative measured results, shown with the UPRR Bridge at 0.3 m (1 ft) and Jack's Ditch at 1.8 m (5.9 ft), to show the much higher salinities throughout 2011. Alternatively, almost all measured salinities in 2014 for the UPRR Bridge at 0.3 m (1 ft) were below 0.12 ppt. The cumulative results show a wide distribution of salinities, with only about 5% of the values exceeding 0.20 ppt. These two cumulative curves for the two different locations also show there is not a large difference between these two measured locations, despite differences in depth and location.

For Scenario 1 and Scenario 2, the cumulative distributions were almost identical between the two scenarios. When viewed over time, these two scenarios did have subtle differences across the 9-year period (Figure 7; Figure 8), but clearly these differences were small when shown as cumulative distributions. Both scenarios also had higher salinities over more time compared to the measured cumulative distributions (2009–2017; Figure 13), so the LBIT did cause elevated Lake Houston salinities over most of the modeled time. However, the highest values were in the measured data and baseline scenario. The two LBIT scenarios did not go above 0.21 ppt whereas the baseline scenario was above 0.21 ppt approximately 5% of the time at Jack's Ditch (Figure 13).

Another conclusion from the LBIT flow scenarios was the simulated effect of LBIT flow on water-surface elevations. Scenario 2A was meant to help understand whether LBIT flow could be used to augment water-surface elevations during periods of drought or prolonged dry periods. Based on Figure 9, the water-surface elevation only dropped to 12.4 m (40.7 ft) for Scenario 2A as opposed to close to 11 m (36.1 ft) for both the measured water-surface elevations and Scenario 2. Scenario 2A added an extra 80 MGD for over a year, a substantial amount of additional flow. Less flow could have been added to the 320 MGD for Scenario 2, and the water-surface elevation drop would have increased but still not have been as much as during the actual 2011 drought. This shows that LBIT flow could be used during a drought, assuming Trinity River flows would support pulling an additional amount of water. Until more modeling has been done with the Trinity River, such as utilizing a linked reservoir operations management model similar to the upper Brazos River framework (Zhao et al. 2016), it remains to be determined the maximum amount of overall LBIT flow from the Trinity River that could occur during a drought such as 2011.

SUMMARY

The USGS, in cooperation with Exxon Mobil Corporation, updated the original Lake Houston EFDC model (Rendon and Lee 2015) for predicting water-surface elevation, residence time, water temperature, and salinity. With modifications to the original Lake Houston EFDC model, the potential effects of the upcoming LBITP on water-surface elevations and salinity in Lake Houston were evaluated using three hypothetical scenarios. The modeling scenarios focused on the long-term effects of sustained pumping of Trinity River water through the LBIT to Lake Houston.

Overall, the long-term flow simulations indicated that the LBIT would affect salinity in Lake Houston. During very dry periods, the LBIT flow acted as a buffer on Lake Houston, limiting maximum salinity. Otherwise, the LBIT flow generally caused the salinity of Lake Houston to increase over the measured data that did not include LBIT flow. While increased salinities (i.e., increased total dissolved solids) could potentially increase treatment costs, the LBIT scenarios did not introduce salinities beyond the natural variation observed from 2009 to 2017.

Hydrological and climatological forcing has the largest effect on salinity in Lake Houston, at least in terms of the extreme salinity values. The highest salinity levels during the entire 2009–2017 period was in 2011. Long periods of evapotranspiration concentrated the dissolved constituents within Lake Houston. As the water-surface elevation dropped without freshwater replenishing Lake Houston, the salinity would rise substantially. Also, large inflow events caused by large storms or hurricanes cause very low salinity and would equalize the effects of the LBIT flow because the LBIT flux would be overwhelmed by tributary inflows and runoff.

LBIT flow could also be used to supplement water levels during extreme droughts. This study found that an extra 80 MGD above a balanced 320-MGD LBIT flow would substantially diminish water-level elevation drops during a 2011-type drought event. However, this scenario would need further evaluation using a linked reservoir operations management model for the entire linked system, because this would affect the water management plan for the entire region, including Lake Houston, Lake Livingston, and the lower Trinity River.

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REFERENCES

[AECOM] AECOM Technical Services, Inc. 2011. Preliminary engineering report for Luce Bayou Interbasin Transfer Project. Los Angeles (California): AECOM Technical Services, Inc. 272 p. Prepared for Coastal Water Authority. Available from: https://www.coastalwaterauthority.org/files/contractoroutreach/lucebayouproject/documents/PER-VOL1-01282011.pdf.

Atekwana EA, Rowe RS, Werkema DD Jr, Legall FD. 2004. The relationship of total dissolved soils measurements to bulk electrical conductivity in an aquifer contaminated with hydrocarbon. Journal of Applied Geophysics. 56(4):281-294. Available from: https://doi.org/10.1016/j.jappgeo.2004.08.003.

Bawden GW, Johnson MR, Kasmarek MC, Brandt J, Middleton CS. 2012. Investigation of land subsidence in the Houston-Galveston region of Texas by using the Global Positioning System and interferometric synthetic aperture radar, 1993–2000. Reston (Virginia): U.S. Geological Survey. 98 p. Scientific Investigations Report 2012-5211. Available from: https://pubs.usgs.gov/sir/2012/5211/pdf/sir2012-5211.pdf.

Beussink AM, Burnich MR. 2009. Continuous and discrete water-quality data collected at five sites on Lake Houston near Houston, Texas, 2006–08. Reston (Virginia): U.S. Geological Survey. 30 p. Data Series 485. Available from https://pubs.usgs.gov/ds/485/pdf/ds485.pdf.

Brashier V. 2011 Aug 16. Pictures tell the story: Drought draining Lake Houston, leading to mandatory conservation order. Houston Chronicle. Available from: https://www.chron.com/neighborhood/article/Pictures-tell-the-story-Drought-draining-Lake-9421465.php.

Chow VT, Maidment DR, Mays LW. 1988. Applied hydrology. New York (New York): McGraw-Hill Book Co. 572 p.

[COH DWO] City of Houston Drinking Water Operations. 2006. City of Houston surface water supply sources. Available from: https://www.publicworks.houstontx.gov/sites/default/files/assets/003-regional_water_supply_map.pdf.

[COH DWO] City of Houston Drinking Water Operations. n.d. Drinking water operations. Available from: https://www.publicworks.houstontx.gov/pud/drinkingwater.html.

Combs S. 2012. The impact of the 2011 drought and beyond. Austin (Texas): Texas Comptroller of Public Accounts. 16 p. Available from: https://texashistory.unt.edu/ark:/67531/metapth542095/m2/1/high_res_d/txcs-0790.pdf.

Craig PM. 2017. User's manual for EFDC_Explorer 8.3: A pre/post processor for the Environmental Fluid Dynamics Code. Edmonds (Washington): DSI, LLC. 454 p.

[CWA] Coastal Water Authority. 2019. Coastal Water Authority: Minutes of regular meeting, February 13, 2019. Available from: https://www.coastalwaterauthority.org/files/meetingnotices/publicminutes/Feb_13_2019_Meeting_Minutes.pdf.

[CWA] Coastal Water Authority. n.d. What is the Luce Bayou Interbasin Transfer Project? Available from: https://www.coastalwaterauthority.org/contractor-outreach/luce-bayou-project/about-cwa/what-is-the-luce-bayou-interbasin-transfer-project.

Dynamic Solutions. 2013. Lake Thunderbird report for nutrient, turbidity, and dissolved oxygen TMDLs. Oklahoma City (Oklahoma): Oklahoma Department of Environmental Quality. 306 p. Prepared for Oklahoma Department of Environmental Quality. Available from: https://www.epa.gov/sites/production/files/2015-10/documents/lakethunderbird_ok.pdf.

Elçi S, Work PA, Hayter EJ. 2007. Influence of stratification and shoreline erosion on reservoir sedimentation patterns. Journal of Hydraulic Engineering. 133(3):255-266. Available from: https://doi.org/10.1061/(ASCE)0733-9429(2007)133:3(255).

Eltagouri M. 2016 May 19. Chicago losing population, could be overtaken by Houston as 3rd-largest. Chicago Tribune. Available from: https://www.chicagotribune.com/news/breaking/ct-census-chicago-losing-population-met-20160518-story.html.

ESRI. 2018. ArcGIS Desktop 10. Redlands (California): Environmental Systems Research Institute.

EWT Water Technology. 2018. Demineralized water in boiler feed water treatment applications: comparison between ion exchange and membrane separation processes. Available from: http://www.ewt-wasser.de/en/knowledge/demineralised-water.html.

[Fondreist] Fondreist Environmental Learning Center. 2014. Conductivity, salinity, and total dissolved solids. Available from: https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/.

Gabrysch RK. 1982. Ground-water withdrawals and land-surface subsidence in the Houston-Galveston region, Texas, 1906–80. Austin (Texas): U.S. Geological Survey. 74 p. Open File Report 82-571. Available from: https://pubs.usgs.gov/of/1982/0571/report.pdf.

Hamrick JM. 1992. A three-dimensional Environmental Fluid Dynamics Computer Code: Theoretical and computational aspects. Gloucester Point (Virginia): Virginia Institute of Marine Science. 65 p. Special Report No. 317. Available from: http://publish.wm.edu/cgi/viewcontent.cgi?article=1713&context=reports.

Hamrick JM. 1996. User's manual for the Environmental Fluid Dynamics Computer Code. Gloucester Point (Virginia): Virginia Institute of Marine Science. 224 p. Special Report No. 331. Available from: https://publish.wm.edu/cgi/viewcontent.cgi?article=2043&context=reports.

Helsel DR, Hirsch RM. 2002. Statistical methods in water resources. Reston (Virginia): U.S. Geological Survey. 524 p. Techniques of Water-Resources Investigations 4-A3. Available from: https://pubs.usgs.gov/twri/twri4a3/twri4a3.pdf.

[HGSD] Harris-Galveston Subsidence District. 2020. About the District. Available from: https://hgsubsidence.org/about/.

Ji ZG, Morton MR, Hamrick JM. 2004. Modeling hydrodynamic and water quality processes in a reservoir. In: Spaulding ML, editor. Estuarine and Coastal Modeling. Monterey (California): American Society of Civil Engineers. p. 608-627. Available from: https://doi.org/10.1061/40734(145)38.

Ji ZG. 2017. Hydrodynamics and water quality: Modeling rivers, lakes, and estuaries. 2nd edition. Hoboken (New Jersey): John Wiley and Sons. 612 p.

Jin KR, Ji ZG, James RT. 2007. Three-dimensional water quality and SAV modeling of a large shallow lake. Journal of Great Lakes Research. 33(1):28-45. Available from: https://doi.org/10.3394/0380-1330(2007)33[28:TWQASM]2.0.CO;2.

Kasmarek MC, Johnson MR. 2013. Groundwater withdrawals 1976, 1990, and 2000–10 and land-surface-elevation changes 2000–10 in Harris, Galveston, Fort Bend, Montgomery, and Brazoria Counties, Texas. Reston (Virginia): U.S. Geological Survey. 25 p. Scientific Investigations Report 2013-5034. Available from: https://pubs.usgs.gov/sir/2013/5034/pdf/sir2013-5034.pdf.

Legates DR, McCabe GJ Jr. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research. 35(1):233-241. Available from: https://doi.org/10.1029/1998WR900018.

Liscum F, Goss RL, Rast W. 1999. Characteristics of water-quality data for Lake Houston, selected tributary inflows to Lake Houston, and the Trinity River near Lake Houston (a potential source of interbasin transfer), August 1983–September 1990. Austin (Texas): U.S. Geological Survey. 62 p. Water-Resources Investigations Report 99-4129. Available from: https://pubs.usgs.gov/wri/wri99-4129/pdf/wri99-4129.pdf.

Liscum F, East JW. 2000. Estimated effects on water quality of Lake Houston from interbasin transfer of water from the Trinity River, Texas. Austin (Texas): U.S. Geological Survey. 55 p. Water-Resources Investigations Report 00-4082. Available from: https://pubs.usgs.gov/wri/wri00-4082/pdf/wri00-4082.pdf.

Miller D, Marks JS. 2018. Coastal Water Authority Luce Bayou Interbasin Transfer project update. Proceedings of the 23rd Annual Conference of the Center for Innovative Grouting Materials and Technology; 2018 March 2; Houston, TX. 2 p. Available from: http://cigmat.cive.uh.edu/sites/cigmat/files/files/conference/presentation/2018/david-miller.pdf.

Mueller DS, Wagner CR, Rehmel MS, Oberg KA, Rainville F. 2013. Measuring discharge with Acoustic Doppler Current Profilers from a moving boat. Reston (Virginia): U.S. Geological Survey. 116 p. Techniques and Methods 3–A22. Available from: https://pubs.usgs.gov/tm/3a22/.

Nash JE, Sutcliffe IV. 1970. River flow forecasting through conceptual models, Part I — A discussion of principles. Journal of Hydrology. 10(3):282-290. Available from: https://doi.org/10.1016/0022-1694(70)90255-6.

Rantz SE. 1982. Measurement and computation of streamflow. Washington (District of Columbia): U.S. Geological Survey. 313 p. Water-Supply Paper 2175. Available from: https://pubs.usgs.gov/wsp/wsp2175/wsp2175.pdf.

Rendon SH, Lee MT. 2015. Simulation of the effects of different inflows on hydrologic conditions in Lake Houston with a three-dimensional hydrodynamic model, Houston, Texas, 2009–10. Reston (Virginia): U.S. Geological Survey. 52 p. Scientific Investigations Report 2015-5153. Available from: https://doi.org/10.3133/sir20155153.

Rogers GO, Moore GW, Saginor J, Brody SD. 2012. Impact of lake-level reductions on Lake Conroe area: lake area property values, property tax revenues and sales tax revenue. 54 p. Available from: https://www.lakeconroe.com/wp-content/uploads/2012/08/Lake-Conroe-Final-Report.pdf.

Smith EA. 2019. Lake Houston (Texas) EFDC hydrodynamic model for water-surface elevation and specific conductance simulations, 2009–2017. U.S. Geological Survey data release. Available from: https://doi.org/10.5066/P9AVUJ73.

Sneck-Fahrer D, Milburn MS, East JW, Oden JH. 2005. Water-quality assessment of Lake Houston near Houston, Texas, 2000–2004. Reston (Virginia): U.S. Geological Survey. 64 p. Scientific Investigations Report 2005-5241. Available from: https://pubs.usgs.gov/sir/2005/5241/pdf/sir2005-5241.pdf.

[TWDB] Texas Water Development Board. n.d. Lake Houston (San Jacinto River Basin). Available from: https://www.twdb.texas.gov/surfacewater/rivers/reservoirs/houston/.

[USGS and USDA NRCS] U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service. 2013. Federal Standards and procedures for the National Watershed Boundary Dataset (WBD) (4th ed.). Reston (Virginia): U.S. Geological Survey. 63 p. Techniques and Methods 11–A3. Available from: https://pubs.usgs.gov/tm/11/a3/.

[USGS] USGS Water Data for Texas. 2020. Reston (Virginia): U.S. Geological Survey. Available from: https://waterdata.usgs.gov/tx/nwis/.

Wagner RJ, Boulger RW Jr, Oblinger CJ, Smith BA. 2006. Guidelines and standard procedures for continuous water-quality monitors: station operation, record computation, and data reporting. Reston (Virginia): U.S. Geological Survey. 96 p. Techniques and Methods 1–D3. Available from: https://pubs.usgs.gov/tm/2006/tm1D3/pdf/TM1D3.pdf.

[WHCRWA] West Harris County Regional Water Authority. 2019. WHCRWA/NFBWA surface water supply project. Available from: https://www.surfacewatersupplyproject.com/.

Winters KE. 2013. A historical perspective on precipitation, drought severity, and streamflow in Texas during 1951–56 and 2011. Reston (Virginia): U.S. Geological Survey. 34 p. Scientific Investigations Report 2013–5113. Available from: https://pubs.usgs.gov/sir/2013/5113/pdf/sir20135113.pdf.

Zhao G, Gao H, Naz BS, Kao SC, Voisin N. 2016. Integrating a reservoir regulation scheme into a spatially distributed hydrological model. Advances in Water Resources. 98:16-31. Available from: https://doi.org/10.1016/j.advwatres.2016.10.014.

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Dams Are Coming Down, but Not Always by Choice: The Geography of Texas Dams, Dam Failures, and Dam Removals

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Abstract: This study examines spatial and temporal trends in Texas dams, dam failures, and dam removals. Dams were examined from a statewide perspective and within 10 major river basins that collectively account for over 80% of all dams in the state. The state-scale and basin-scale analyses revealed similar patterns of dam occurrence, but there was greater variation in the patterns observed in both the purpose of dams and the timing for when most of the storage was created in each basin. Climate factors, mainly precipitation, influenced dam location. Population was not directly measured in this study but was an obvious influence on the spatial distribution of dams and their functions. While new dams are being built in Texas to secure future water supplies, documented dam incidents/failures have occurred in 15 of the 23 major river basins in Texas, with 328 total instances occurring since 1900. As the number of newly constructed dams and dam failures continue to grow across the state, so should the number of planned dam removals. Between 1983 and 2016, 50 dams were removed across the state. The purpose for the majority of removals was to eliminate liability concerns associated with aging dams. Future dam removals will likely continue to occur based on the number of older, smaller dams with potential liability concerns. As Texas' dam infrastructure continues to age, dam removal is a practical management option for mitigating potential dam-related hazards and improving the connectivity and ecological function of river systems.

Keywords: dams, Texas, dam removal, dam failure

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Terms used in paper

Acronym / Initialism	Descriptive Name
ac-ft	acre-feet
ASCE	American Society of Civil Engineers
CGIAR-CSI	CGIAR Consortium for Spatial Information
DRIP	Dam Removal Information Portal
FEMA	Federal Emergency Management Association
FRRN	functionally reconnected river network
ft	feet
in	inches
km	kilometers
km^2	square kilometers
LCRA	Lower Colorado River Authority
mi	miles
mi^2	square miles
mm	millimeters
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NPDP	National Performance of Dams Program
PET	global potential evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model Climate Group of Oregon State University
SWIFT	State Water Implementation Fund of Texas
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
USACE	United States Army Core of Engineers
USGS	United States Geologic Society
WCID	Water and Control Improvement Districts

INTRODUCTION

In 2011, Texas experienced the worst single-year drought in recorded history (Folger et al. 2013). During October of 2011, 88% of the state experienced exceptional drought, and much of the state continued to experience extreme to exceptional drought conditions through January 2012 (Folger et al. 2013). The winter of 2012 brought relief through increased precipitation to the eastern portion of Texas, but much of the state remained in drought conditions ranging from moderate to exceptional (Folger et al. 2013; USDM 2000–).

In response to the 2011 drought and other major water-resource related concerns in Texas, the 2013 Texas Legislature passed Proposition 6, which provided funding for water projects outlined in the state water plan (Henry 2013). Proposition 6 was a constitutional amendment that transferred two billion dollars from Texas's rainy day fund to create the State Water Implementation Fund of Texas (SWIFT; Henry 2013). The 2012 Texas state water plan included recommendations for 26 new major reservoir sites to be built by 2060, a major reservoir being one that generates 5000 acre-feet (ac-ft) or more of water storage (TWDB 2012). By late 2017, four major dam projects received the necessary permits and funding to begin construction, including the Lake Ralph Hall Reservoir planned for the upper Trinity River Basin, the Turkey Peak Reservoir in the upper Brazos River Basin, the Lower Basin Reservoir in the lower Colorado River Basin, and the Lower Bois d'Arc Reservoir in the Red River Basin (TWDB 2017; Kellar 2017).

While dams are being built to secure Texas' future water supply, there is increasing concern about the future quality of riverine and aquatic habitats due to fragmentation from barriers such as dams (Graf 1999; Chin et al. 2008; Erős et al.

2015). Across the United States, dams are being removed at an increasingly rapid pace to the benefit of hazard mitigation and river restoration (Grabowski et al. 2018). Yet in Texas, dam removal receives substantial negative connotation and can be highly controversial, as documented by the rhetoric surrounding examples such as Cape's Dam in San Marcos, Texas (Rollins 2015; Thorne 2016a, 2016b; Brusuelas 2018; Green 2019). A 2011 news article by Eva Hershaw was even titled "Dams Are Coming Down, But Not in Texas" (Hershaw 2011). Despite this seemingly negative connotation, little in the way of actual data has been presented showing dam removal trends in Texas.

The Texas Commission on Environmental Quality (TCEQ) is responsible for the monitoring and regulation of public and private dams that meet their criteria (DamFailuresPIR9267 1900–). A 2008 audit of the TCEQ's Dam Safety Program concluded that the program was not able to accomplish its mandate to ensure the safe construction, maintenance, repair, and removal of dams (Keel 2008). The report found that the high number of dams in Texas compared to the available program resources was a major reason for the program's ineffectiveness (Keel 2008). Additionally, the report stated that a goal of the Dam Safety Program should be to estimate the rehabilitation cost of the "structurally deficient and hydraulically inadequate dams" throughout the state (Keel 2008, pii). According to data reported in the Texas Observer, 314 dams have failed in Texas since 1910, the majority of which impounded less than 1000 ac-ft and failed between the years 2000 and 2019 (Sadasivam 2019). With limited funding available for dam repairs and maintenance, and as dams continue to age, issues related to structural inefficiency and hydraulic inadequacy are likely to increase the risk of dam incidents and failures throughout the state. Instead of increasing the number and frequency of dam inspections, Texas passed House Bill No. 677 in 2013, which exempts thousands of state documented dams from safety regulations based on the following five criteria: they are privately owned, impound a maximum capacity less than 500 ac-ft, retain a hazard criteria of low or significant (measured by potential loss of life downstream of the reservoir), occur in a county with a population less than 350,000, and are not located within the corporate limits of a municipality (H.B. 677 2013). Dam owners must still comply with maintenance and operation requirements; however, with limited resources available through the Dam Safety Program, uncertainty exists regarding dam owner compliance.

The purpose of this study is to explore the spatial and temporal trends in the available data on extant dams, dam failures, and dam removals. To an extent, this study builds on previous research containing data on Texas dams presented by Chin et al. (2008) by incorporating new data and an additional scale of analysis. This analysis addresses the following four questions: (1) What are the spatial patterns of dam occurrence in Texas and how do these patterns change over time and relate to climate? (2) How do these patterns vary among the 10 major river basins in the state? (3) What are the spatial and temporal trends of dam removals in Texas? and (4) What are the spatial and temporal trends of dam failures? In addition to answering these questions, the authors aim to provide some insight into how patterns of dam occurrence, failure, and removal are potentially related. Dam distributions, failures, and removals involve many physiographic, social, political, and historical factors. The intent of this paper is not to provide a comprehensive overview of all these interacting factors. The focus is to provide a broadscale overview of state- and basin-scale distributions and bring much needed attention to discussions involving the hazards and management of aging dam infrastructure and the opportunity for using dam removal to benefit river ecology.

A brief history of dams

From a global perspective, the earliest dams were constructed 5,000 years ago (Petts and Gurnell 2005). They were small impoundments, built as earthen structures to store water for use during drier periods (ICOLD 2007). As civilizations grew, dam use began to diversify to include water supply, irrigation, flood control, navigation, water quality purposes, sediment control, energy generation, and recreation (ICOLD 2007). The Romans built a large and complex system of dams for water supply, many of which are still in use today (ICOLD 2007). During the 16th century, Spain began to build large dams for irrigation, and in the 1800s dams began to be built for navigation and hydropower (ICOLD 2007). The construction of mega dams was begun by European engineers in the 19th century (ICOLD 2007), but by the 20th century the United States led the world in dam construction (Clark 2009).

Large dams became symbols of technological and social advancement (Petts and Gurnell 2005; Duchiem 2009). This was especially true of hydropower projects that were viewed as important for both the prosperity of the nation and national defense (Reinhardt 2011). While the Hoover Dam ushered in the modern era of dam building in the United States (Reisner 1986; Petts and Gurnell 2005), the number of large dams constructed did not drastically increase until after WWII (Petts and Gurnell 2005).

In the United States, the Bureau of Reclamation alone constructed 40 hydropower dams between 1945 and 1955 (Reinhardt 2011), and during the 1960s, the number of dams continued to increase at a rate of nearly two dams a day worldwide (Petts and Gurnell 2005). According to the National Inventory of Dams (NID), a total of 20,145 documented dams were completed in the United States between 1960 and 1969 (NID 2013–), and the 1960s has become known as the "dam-building" decade (Graf 2005). This rapid pace of dam construction would not slow until the 1980s (WCD 2000; Petts and Gurnell 2005).

As dams increased in number and size across the landscape, so did the understanding of their impacts on river systems. Studies on downstream effects of dams began in the 1920s, yet as early as 1784 efforts were made to prevent dam construction, due to the already apparent impact on migratory fishes along East Coast rivers in the United States (Graf 2005). Despite the growing scientific understanding of environmental impacts created by dams, the dam-building era would continue until the 1970s, when American attitudes toward the environment shifted. By this time, ideal sites to build new large dams had already become scarce (Reisner 1986), and today every major river in the United States is, in part, controlled and impacted by dams and reservoirs (Graf 2006).

Nationwide data on dam failures differs relative to how a dam failure is defined, and it is important to note that discrepancies exist in how different organizations obtain, classify, and report dam failures. The National Performance of Dams Program (NPDP) compiles one of the most comprehensive national-scale databases, reporting a total of 1,645 dam failures in the United States (1848–2017), from sources including the U.S. Committee on Large Dams, Federal Emergency Management Association (FEMA), United States Army Corps of Engineers (USACE), Association of State Dam Safety Officials, voluntary contributions by state dam safety programs, and supplemental searches (McCann 2018). However, the NPDP database still differs from that reported in other publications. The NPDP (McCann 2018) report lists 53 dam failures for Texas, defined as events that resulted in the uncontrolled reservoir release.

A database on Texas dam failures reported by Sadasivam (2019) in the Texas Observer included 314 dam incidents ranging from catastrophic failures to minor overtopping documented by the TCEQ. However, the TCEQ only defined 119 of those incidents as official failures, which they define by overtopping or breaching and draining of the reservoir. The conservative 53 failures reported by the NPDP rank Texas in the top 10 U.S. states with the most dam failures; if all 119 state-defined failures were reported, Texas would rank second after Georgia (McCann 2018). The American Society of Civil Engineers (ASCE) Texas Section reports only eight failures, one partial failure, and 108 other incidents in their 2017 Infrastructure Report Card, based on data obtained from multiple sources (ASCE 2017). The lack of consistency among sources indicates a need for the standardization of terms regarding dam failures and how they are categorized and discussed.

As of 2019, over 1,722 dams have been removed in the United States primarily for reducing hazard risks and improving ecologic functions (ARDRD 1912–2019), and this number is expected to increase as many dams in the United States reach the end of their usefulness (Doyle et al. 2003a). The increasing number of dam removals is emblematic of the paradoxical shift in the United States from trying to control and manipulate rivers to attempting to restore them. The rate of dam removals has been climbing rapidly (Grant and Lewis 2015). In 2017 alone, 86 dam removals occurred (Thomas-Blate 2018), which was nearly four times the number of new dams completed in the same year (NID 2013–). Some states, such as Wisconsin and Pennsylvania, have removed well over 100 dams (Bellmore et al. 2017).

While the majority of dam removals involved smaller, older damaged structures requiring expensive repairs (Stanley and Doyle 2003; Bellmore et al. 2017), the number of larger dam removals to restore fish habitat are increasing. In 2011, the largest dam removal in U.S. history took place with the removal of Condit Dam from the White Snake River in Washington (Gillman 2016). This was followed by the removal of two even larger dams on the Elwha River: the 210-foot-tall Glines Canyon Dam and the 108-foot-tall Elwha Dam, both also in Washington (Gillman 2016; Souers Kober 2016). Four large dam removals are planned on the Klamath River (Gosnell and Kelly 2010; Gillman 2016), which will result in 482 kilometers (km; 299.5 miles [mi]) of reconnected river habitat (Souers Kober 2016).

Of all the dam removals in the United States, over half of them have occurred during the last 10 years (Grant and Lewis 2015). During this time, scientists have transitioned from calling for empirical and predictive environmental studies (Bednarek 2001; Poff and Hart 2002) to generalizing the geomorphic and ecological impacts of dam removals (Bednarek 2001; Doyle et al. 2003; Doyle et al. 2003a; Stanley and Doyle 2003; Grant and Lewis 2015).

DATA AND METHODS

Data

The analyses in this study used a variety of data sources. The state-scale analyses included available data for documented dams that meet state and/or federal regulations and subsets of national precipitation and global potential evapotranspiration (PET) datasets to analyze the temporal and spatial patterns of dams in Texas. Two dam datasets exist for the state of Texas; one is managed by NID and includes 7,338 registered dams (NID 2013–) and the other is managed by the TCEQ and includes 7,280 documented dams that meet state regulations as of 2014 (Dams.gdb 1800–). Due to federal limitations on NID data use, this research used the state-level TCEQ dataset. Through a memorandum of user agreement from this research, the TCEQ provided a geodatabase with the location and attributes of dams. Dam attributes used for these analyses included year complete, purpose, and maximum storage capacity.

Of the documented dams, 7,161 included a year of completion (98.4%), and 6,567 had at least one purpose identified (90.3%). For dams with multiple purposes listed, only the first purpose listed was considered. The TCEQ reportedly does not list dam purpose by any order, but the NID still reports the first purpose listed as the primary or most important purpose. All dams had a maximum storage value (defined as the maximum impoundment capacity at the top of the dam). There were 37 (0.005%) dams that reported a maximum storage value of 0 ac-ft, indicating a lack of data.

A table of ownership information, including the organization type of the owner, was provided as a separate file. There were over 10,000 entries in the ownership table, the result of multiple owners for individual dams. Entries in the ownership file that matched a corresponding ID in the dam shapefile were joined to the attribute table of the dam shapefile. Dams that did not have an owner listed or that did not have a matching owner ID were less than 0.01% (n = 69). An additional six dams did not have a listed owner organization type or affiliation.

Precipitation data was obtained from a national 4-km (2.5-mi) resolution raster file of the 30-year annual average (1981–2010) precipitation produced by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group of Oregon State University (30-Year Normals 2012–). Potential evapotranspiration (PET) data was acquired from the Consortium for Spatial Information (CGIAR-CSI) Global Aridity and Global-PET Database (CGIAR-CSI 2007–2019). The Global-PET Database is a global 1-km (.6-mi) resolution raster of the 50-year annual average (1950–2000; Zomer et al. 2007, 2008). The precipitation and PET datasets are freely available online and were used to account for climatic trends across Texas. The United States Census Bureau (TIGER 2015–2016) provided shapefiles of Texas, and the Texas Water Development Board (Major River Basins 2014) provided shapefiles of the 23 major Texas river basins.

Data on dam incidents and dam failures were provided from the TCEQ Dam Safety Program through an open records request (DamFailuresPIR9267 1900–). There was a total of 209 dam incidents, which resulted in damage to the dam but not a draining of the reservoir, and 119 dam failures, which included either overtopping or breaching and resulted in the draining of the reservoir. The data included the Texas dam ID, geographic coordinates, the date of the reported damage, the mode of failure, the dam name, type, height, and normal storage. Of the original 328 records of damaged dams, 18 had no associated geographic coordinates, resulting in a reduced dataset of 310 dams.

Data to analyze the patterns of dam removal in Texas were obtained from the TCEQ's Dam Safety Program (Dam Removals 1983–). This dataset included information for 49 dam removals and provided attributes and locations for the removed dams, including the year and reason for removal. An additional dam removal was added to the original dataset of 49 removals by the authors: the Ottine Dam removal. The Ottine Dam, located in the Guadalupe River Basin, was damaged in 2008 by a storm and scheduled for removal in 2012 (Montagne and Jobs 2016). This dam was 104 years old when it was removed in 2016 (Montagne and Jobs 2016).

Analyses of temporal and spatial patterns in Texas dams

Analyses used ArcGIS to organize and analyze the available data on documented dams and climate. Twelve of the 7,280 dams in the TCEQ geodatabase had inaccurate or problematic geographic coordinates. Of these 12, six were relocated to the correct location using aerial imagery validation, and six were deleted as their true coordinates could not be determined. This resulted in a final dataset of 7,274 dams. This statewide dataset was subdivided by river basin, generating 23 additional sub-datasets, for a total of 24 dam datasets. Analysis of the Global-PET and national precipitation datasets determined the average, minimum, and maximum precipitation and PET values for each river basin using spatial analysis. The drainage area (square miles [mi²]) for the land surface of each river basin was also calculated in ArcGIS.

The statistics package, IBM SPSS Statistics 22, was used to analyze the dam and climate data. The authors calculated the total reservoir storage and percentage of total storage for all 24 datasets. To further investigate spatial patterns of dam occurrence in Texas, the variables of size, time period (year of completion), purpose, and ownership from the dam attributes of maximum storage, year complete, purpose, and organization type (of owner) were assigned to each dam in the statewide dataset. This was also done for 10 major river basins: the Trinity, Brazos, Colorado, Red, Nueces, Sabine, Rio Grande, Neches, Guadalupe, and San Antonio river basins (Figure 1). These 10 basins contain nearly 90% of all the dams and 85% of the storage and drain over 80% of the land area in Texas.

There were 17 separate organization types in the TCEQ database for ownership, including null values. The authors aggregated these original organization types into six classifications: federal, state, and other governments, private entities, other, and not listed (Appendix 1). The authors recognize that categorizing the 7,274 dams into six categories minimizes the diversity of entities involved with dam ownership and management. While the federal, state, and private categories are fairly intuitive, the "other government" category includes the full array of cities, counties, county level Water and Control Improvement Districts (WCID), the Texas Soil and Water Conservation Districts, and river authorities, among others. The Guadalupe-Blanco River Authority, Sabine River Authority of Texas, and the Coastal Water Authority were listed as state governments by the TCEQ, but all other river authorities were included in other governments. The head of the TCEQ's Dam and Safety Program confirmed that other governments is the preferred organization type for river authorities (2020 email

Table 1. Size classifications based on Graf 2005.

Size classification	Max. reservoir storage (cubic meters)	Max. reservoir storage (acre-feet)
Small	< 100,000	< 100
Medium	100,000–10,000,000	100–10,000
Large	10,000,000–1,000,000,000	10,000–1,000,000
Very large	>1,000,000,000	>1,000,000

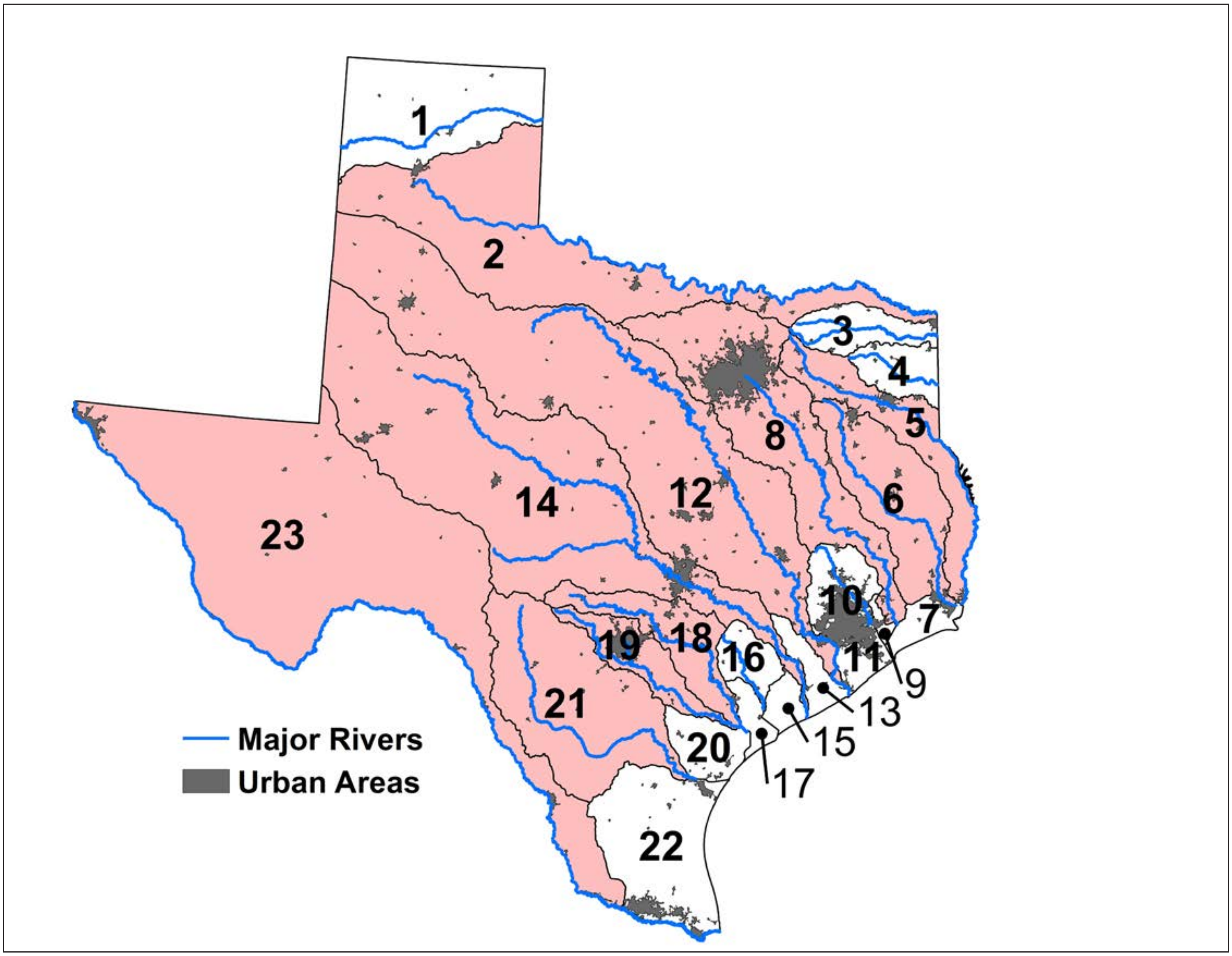

Figure 1. Map of Texas and 23 major river basins with major rivers and urban areas. River basins highlighted in rose represent the river basins analyzed in this study. Numbers correspond to river basin names: 1) Canadian, 2) Red, 3) Sulphur, 4) Cypress, 5) Sabine, 6) Neches, 7) Neches-Trinity, 8) Trinity, 9) Trinity-San Jacinto, 10) San Jacinto, 11) San Jacinto-Brazos, 12) Brazos, 13) Brazos-Colorado, 14) Colorado, 15) Colorado-Lavaca, 16) Lavaca, 17) Lavaca-Guadalupe, 18) Guadalupe, 19) San Antonio, 20) San Antonio-Nueces, 21) Nueces, 22) Nueces-Rio Grande, 23) Rio Grande.

to Kimberly Meitzen from Warren D. Samuelson, TCEQ; unreferenced), so these three organizations were reclassified and included in the "other government" category. The "other" category includes diverse entities such as ranches, water treatment facilities, utility facilities, homeowner associations, and churches, among others. Dams with multiple owners listed were included in the "other" category if the owners represented disparate owner categories. The first listed purpose for each dam was identified as the purpose; this same ordering logic is used by the federal government for the NID data set, and both NID and the TCEQ contained the same purpose order for each dam. The TCEQ specifically indicates that this order is not relevant to a dam's purpose, revealing an inconsistency in federal and state data reporting.

There were multiple size classifications available for dams; the TCEQ used a size classification based on dam height and reservoir storage. For the purposes of this analysis, the authors used the size classification developed in 2002 by the Heinz Center and later modified by Graf (2005; Table 1). This classification system was used due to its ease of calculation and because reservoir size is more directly related to potential impacts to downstream hydrology than other measures of dam size (Graf et al. 2002). The authors sorted dams by size and used descriptive statistics to analyze the variables of time period, purpose, and ownership for each size class.

The temporal analysis followed similar logic. The authors sorted dams by five time periods and used descriptive statistics to analyze each time period by size, purpose, and ownership. The first time period included dams completed between 1800 and 1899. A large number of dams were completed in 1800 (n = 282), and few were completed between 1800 and 1899 (n = 10), instigating suspicion of these completion dates. It is likely that many older dams potentially built in the 1800s had 1800 listed as the year of completion, when the exact year of completion was unknown. While 1800 is likely a placeholder rather than an accurate year of completion, it is similarly unlikely that only 10 documented dams were built in Texas between 1800 and 1899. Despite some uncertainty regarding the age of these dams, for this analysis the authors have included dams with the year 1800 listed as the year of completion in the 1800–1899 time period. It should be noted that the TCEQ reports dams with a completion year of 1800 as having an unknown year of completion, and the NID lists only 15 dams completed before 1900 (NID 2013–).

The second time period represented an early age in dam building between 1900 and 1939 (n = 518). The third time period, 1940–1959 (n = 1382), designated the time when dam building began to progressively develop. The 1960–1979 time period (n = 4154) captures the peak of dam construction in Texas, and 1980–2014 (n = 814) represents the most recent time period.

Analysis of dam failures

The authors classified the damaged dam dataset by damage category, divided first by incident or failure and then sub-classified by type/mode. Dam incidents are events that resulted in some damage to the dam but not an event that resulted in the draining of the reservoir and are therefore not recognized as official dam failures by the TCEQ. Dam failures resulted in overtopping or breaching and draining of the reservoir. There were originally 85 unique values for mode of failure; these were grouped into six failure mode classifications: other or not provided, spillway or gate damage, slide/erosion, breach or collapse, overtopping, and piping. Additional information for the 310 damaged dams was obtained by linking the dataset to the Texas dam dataset via the Texas dam IDs. This resulted in additional information on the age and size of 261 of the damaged dams. Presumably, the 49 damaged dams without matching records were only included or added to the TCEQ's dam database after 2015 or represented structures smaller than those regulated by the TCEQ. Descriptive statistics were used to categorize records of damaged dams by year, basin, mode of failure, dam age, and dam size.

Analysis of dam removals in Texas

The dam removal dataset was analyzed in a GIS framework in combination with the National Hydrography Dataset (NHD). The most current version of the NHD, the NHD High Resolution, is mapped at a 1:24,000 scale or better, representing the nation's drainage networks and related features (NHD 1999–). It is part of The National Map maintained by the United States Geological Society (USGS) and is the most current and detailed hydrography dataset for the United States (NHD 1999–). The NHD and aerial imagery were used for the following four tasks: (1) to confirm the location of each dam removal; (2) to determine if it was located on the river network; (3) to validate if the dam was still absent or had been rebuilt; and (4) to measure the length of resulting functionally reconnected river network (FRRN). The river network was considered functionally reconnected if the NHD flowlines were connected and there was no documented dam located on the river network. The extent of FRRN was measured as the length of the upstream NHD flowlines from each removal by either summing the length of the flowlines in the attribute table and/or using the measure tool in ArcGIS. Descriptive statistics were used to summarize the dam removal dataset by river basin, height, owner, year built, year removed, reason for removal, and the calculated FRRN length.

Table 2. Climatic and geographic variables for major Texas river basin.

	General	Precipitation (inches)			Potential ET (inches)			Area (square miles)		Dams		Total Reservoir Storage	
	Location	Mean	Min	Max	Mean	Min	Max	N	%	N	%	Million acre-feet	%
Texas	---	28.7	8.1	61.5	58.9	44.3	73.9	268,580	100.0	7,274	100.0	104.3	100.0
Cypress	Eastern	48.2	44.5	51.6	55.6	54.1	56.6	2,941	1.1	161	2.2	2.6	2.5
Neches	Eastern	51.4	42.0	60.1	57.4	53.5	59.0	9,984	3.7	308	4.2	8.6	8.2
Sabine	Eastern	49.6	41.0	61.4	56.4	53.3	58.5	7,603	2.8	335	4.6	8.8	8.4
San Jacinto	Eastern	49.6	44.1	56.1	56.6	51.8	58.5	3,954	1.5	162	2.2	1.5	1.5
Sulphur	Eastern	47.3	43.3	51.0	54.7	53.2	56.2	3,591	1.3	162	2.2	7.5	7.1
Trinity	Eastern	41.4	30.1	60.2	56.7	52.6	59.4	17,987	6.7	1,787	24.6	17.0	16.3
Canadian	Northern	19.5	15.0	24.5	54.1	51.3	57.4	12,837	4.8	153	2.1	2.8	2.6
Red	Northern	26.9	18.2	52.0	56.0	51.7	60.2	24,335	9.1	619	8.5	12.5	12.0
Brazos	NW - SE	29.9	17.4	54.3	57.7	51.9	60.8	43,034	16.0	1,391	19.1	14.80	14.2
Colorado	NW - SE	24.3	13.4	47.9	59.7	51.1	62.9	39,605	14.7	775	10.7	12.2	11.7
Guadalupe	South-central	34.4	28.1	40.4	59.5	54.8	61.6	5,977	2.2	215	3.0	1.60	1.5
San Antonio	South-central	32.0	27.9	38.8	60.1	54.4	62.6	4,196	1.6	160	2.2	0.70	0.7
Nueces	Southwest	25.2	19.5	33.7	63.3	56.9	67.4	16,749	6.2	456	6.3	1.80	1.7
Rio Grande	W - S	15.3	8.1	27.1	63.1	44.3	74.0	49,590	18.5	329	4.5	10.9	10.4
Brazos-Colorado	Coastal	47.0	41.4	52.3	56.2	51.1	59.6	1,871	0.7	26	0.4	0.04	0.04
Colorado-Lavaca	Coastal	44.5	40.6	47.6	54.4	49.1	58.2	1,270	0.5	11	0.2	0.30	0.25
Lavaca	Coastal	41.5	36.9	46.3	58.3	53.3	60.0	2,318	0.9	24	0.3	0.30	0.32
Lavaca-Guadalupe	Coastal	41.2	37.3	44.0	54.5	48.7	59.3	1,289	0.5	8	0.1	0.01	0.01
Neches-Trinity	Coastal	57.9	49.0	60.9	52.9	46.0	56.3	1,692	0.6	15	0.2	0.01	0.01
Nueces-Rio Grande	Coastal	25.1	20.1	35.3	61.2	49.6	65.6	11,455	4.3	101	1.4	0.03	0.32
San Antonio-Nueces	Coastal	34.0	28.7	39.1	57.7	49.6	62.0	3,033	1.1	10	0.1	0.004	0.005
San Jacinto-Brazos	Coastal	52.6	45.6	57.8	52.5	45.2	57.6	1,741	0.6	51	0.7	0.02	0.142
Trinity-San Jacinto	Coastal	55.9	54.0	56.8	54.1	52.0	56.7	390	0.1	14	0.2	0.05	0.05

RESULTS

Climatic and geographic trends

As expected with general climate gradients across Texas, PET generally increased from east to west, with the highest PET values located in parts of the southwest (Table 2). Inversely, precipitation declined from east to west, with an average yearly precipitation range of 8.1 to 61.5 inches (in; 205.7 to 1562.1 millimeters [mm]; Table 2). There was a 42.6-in (1082-mm) range of average yearly precipitation variables by basin, with the Rio Grande Basin's 15.3 in (388.62 mm) being the driest and the Neches-Trinity River Basin's 57.5 in (1460.7 mm) basin being the wettest (Table 2).

In general, river basins receiving less than 30 in (762 mm) of average annual rainfall had larger percentages of dams and storage, with the exception of the Trinity River Basin. The Trinity River Basin contained the largest percentage of dams and storage and an average of 41.4 in (1051.6 mm) annual rainfall (Figure 2; Table 2). Larger river basins contained a larger proportion of dams, except for the Trinity River Basin and the Rio Grande Basin (Table 2). The Trinity River Basin contained nearly a fourth of all dams but only the fifth largest drainage area (46,586 square kilometers [km²; 17,987 mi²], 6.7%), while the Rio Grande Basin with the largest drainage area

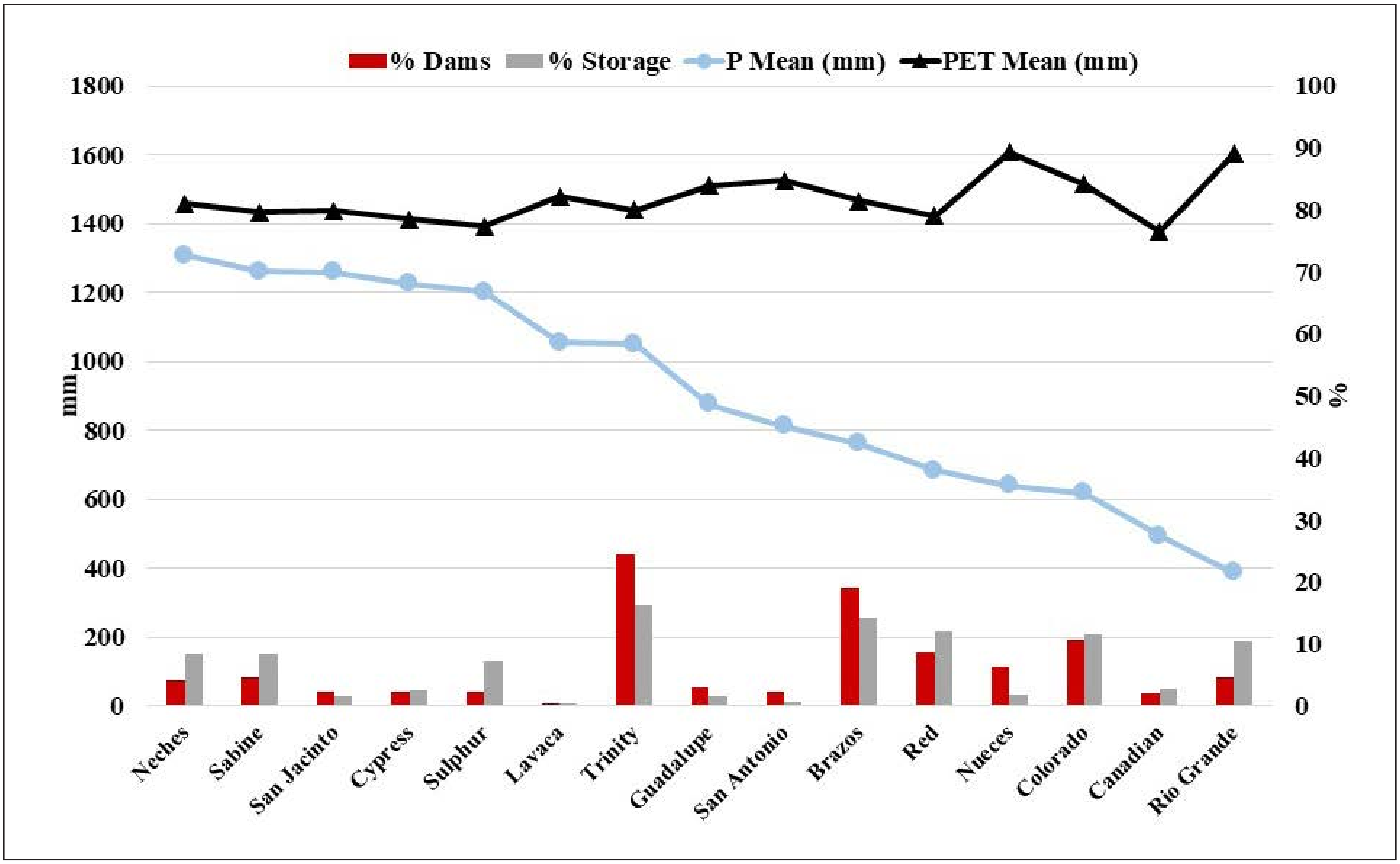

Figure 2. Climate and geographic distribution of dams. Percent of all Texas dams (red bars) and total reservoir storage (grey bars), with mean precipitation (blue line with circles) and potential evaporation (black line with triangles) in major river basins. Note that basins containing less than 1% of the total number of dams and/or reservoir storage in Texas are omitted from this graph. [mm, millimeters]

(128,437.5 km² [49,590 mi²], 18.5%) contained less than 5% of the total number of dams (Table 2). Coastal basins, being among the smallest major river basins, each contained less than 1% of the total number of dams in Texas (Table 2).

Analysis of 10 selected major river basins

The 10 largest river basins revealed a few notable patterns. The combined Trinity (n = 1787, 24.6%), Brazos (n = 1391, 19.1%), Colorado (n = 776, 10.7%), Red (n = 619, 8.5%), and Nueces (n = 456, 6.3%) river basins contained 69.2% of Texas dams (Table 2). The Rio Grande Basin had the largest drainage area in Texas and 4.5% of dams (n = 329). The Guadalupe (n = 215, 3%), San Antonio (n = 160, 2.2%), Sabine (n = 335, 4.6%), and Neches (n = 308, 4.2%) river basins represented an additional 14% of the total number of dams. Together these 10 river basins accounted for 87.7% of dams and 81.5% of the drainage area in Texas.

Dam size

Medium dams were the most abundant at the state scale (n = 5586, 76.8%). Similarly, medium dams comprised more than 70% of the total number of dams at the basin scale (Appendix 2). Small dams comprised the second largest proportion (n = 1452, 20%) at the state scale and represented 14.9% to 26% of the dams in each river basin, except for the Trinity River Basin, where small dams constituted only 1.8% of dams (Appendix 2). Large (n = 207, 2.8%) and very large (n = 29, 0.4%) dams represented the smallest proportion of dams (Appendix 2).

While the amount of large and very large dams was low compared to medium and small dams, together they accounted for nearly 95% of the total reservoir storage in Texas and over 90% of the reservoir storage in each river basin (Appendix 2). The exception was the San Antonio River Basin; in this basin, large dams constituted over 70% of the storage, with no very large dams (Appendix 2). Very large dams alone accounted for 50% or more of the storage in each basin and nearly 70% of the storage in Texas (Appendix 2).

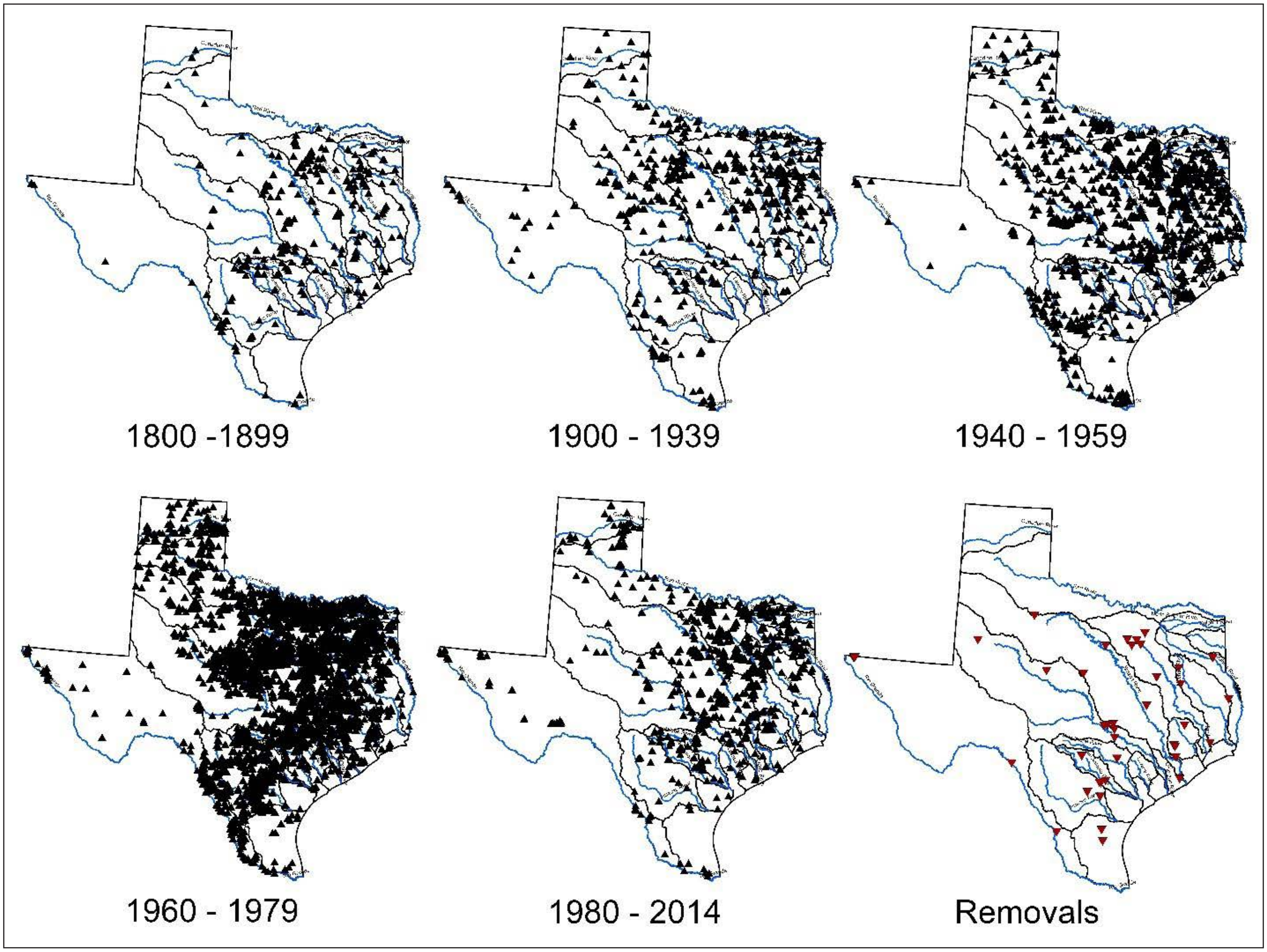

Figure 3. Location of dams completed during each time period and all dam removals (1983-2016) in Texas. Major rivers shown in blue.

Time periods and reservoir storage

A general trend existed relative to the number of dams completed during each time period; dam construction increased during the first four time periods and then declined in the 1980–2014 time period (Figure 3). In the 1800s, the most commonly built dams were small and medium; only three large and no very large dams were built during this same time (Appendix 3). The majority of dams built for all other time periods were medium dams (Appendix 3). The number of large and very large dams constructed increased throughout 1900–1979. The largest number of dams were built between 1940 and 1979, and most of the large and very large dams were also completed during this time. Specifically, 1940–1959 saw the construction of 59 large and nine very large dams. An additional 72 large dams and 12 very large dams were constructed from 1960 to 1979 (Appendix 3).

Most reservoir storage capacity by volume was created between 1940 and 1979, with the largest percentage created during 1960–1979, and this same pattern applied to the Trinity, Brazos, Sabine, Rio Grande, Neches, and Guadalupe river basins (Figure 4). However, in the Colorado and Red river basins the majority of reservoir storage was created in the 1940s (Figure 4). The Nueces River Basin gained over 60% of its reservoir storage during the 1980s, while in the San Antonio River Basin nearly half of the reservoir storage was built in the early 1900s (Figure 4).

The Trinity River Basin experienced the construction of one very large and 10 large dams from 1940 to 1959, and between 1960 and 1979, two very large and eight large dams were completed. An additional six large and two very large dams were completed in the Trinity River Basin between 1980 and 2014. The Brazos River Basin gained 11 large dams and three very large dams between 1940 and 1959, and an additional 19 large

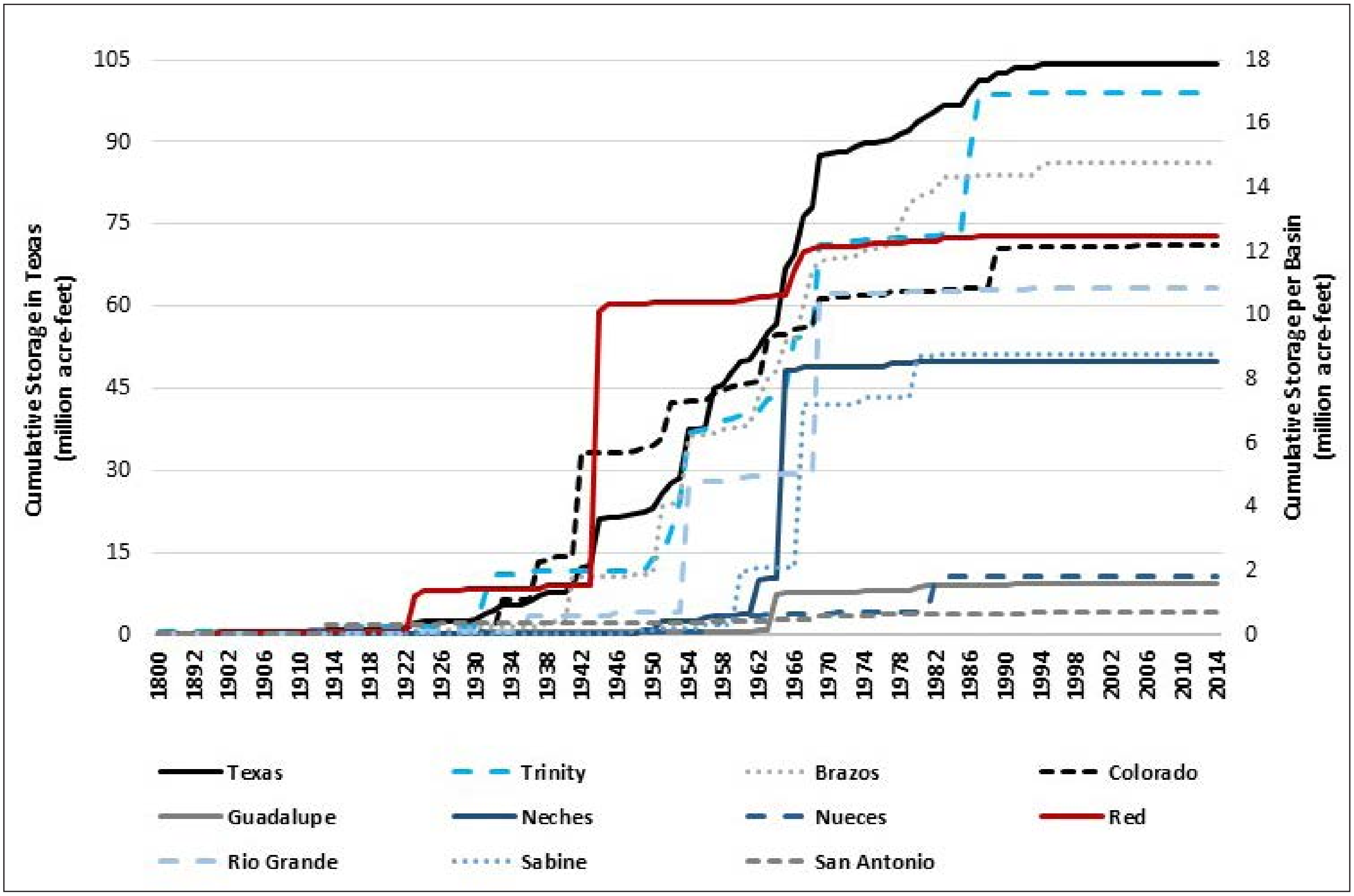

Figure 4. Total maximum cumulative reservoir storage in Texas and 10 major river basins.

and two very large dams were constructed between 1960 and 1979.

In the Sabine River Basin, two of the three very large dams were built between the years of 1960 to 1979. These two dams were the Iron Bridge Dam, completed in 1960 with a maximum storage of over 1 million ac-ft, and the Toledo Bend Dam, built in 1967 with a maximum storage of over 5 million ac-ft. Together these two dams constituted 77.3% (6,757,523 ac-ft) of the total reservoir storage in the river basin (8,776,518 ac-ft).

The Rio Grande Basin had a total reservoir storage of nearly 11 million ac-ft and only two very large dams. The international Falcon Dam, with a maximum storage of over 4 million ac-ft, was completed in 1954, and the international Amistad Dam, with a maximum storage of over 5.5 million ac-ft, was completed in 1969. The only two very large dams in the Neches River Basin were both completed during the 1960–1979 time period and together had a maximum storage capacity of over 7.5 million ac-ft. The Guadalupe River Basin had one very large dam, Canyon Dam, completed in 1964 with a maximum reservoir storage of over 1 million ac-ft. Canyon Dam was over eight times larger than the second largest dam in the river basin and accounts for 71.7% of the total reservoir storage.

Most of the large dams in the Colorado River Basin were built between 1940 and 1959, with one very large dam built during this period. The Denison Dam was completed on the Red River in 1944, with a maximum storage capacity of 8,600,000 ac-ft, and was the largest dam in this basin by over 7.5 million ac-ft.

The only very large dam in the Nueces River Basin was completed in 1982. With a storage capacity of over 1 million ac-ft, the Choke Canyon Dam had twice the maximum storage capacity of the second largest dam in the river basin. The San Antonio River Basin had no very large dams but did have five large dams. Two were built between 1900 and 1939, with a combined maximum storage of 349,220 ac-ft, that accounted for nearly half of the total reservoir storage in the river basin. The other three had a combined maximum storage of 148,787 ac-ft and were constructed during the 1960–1979 time period.

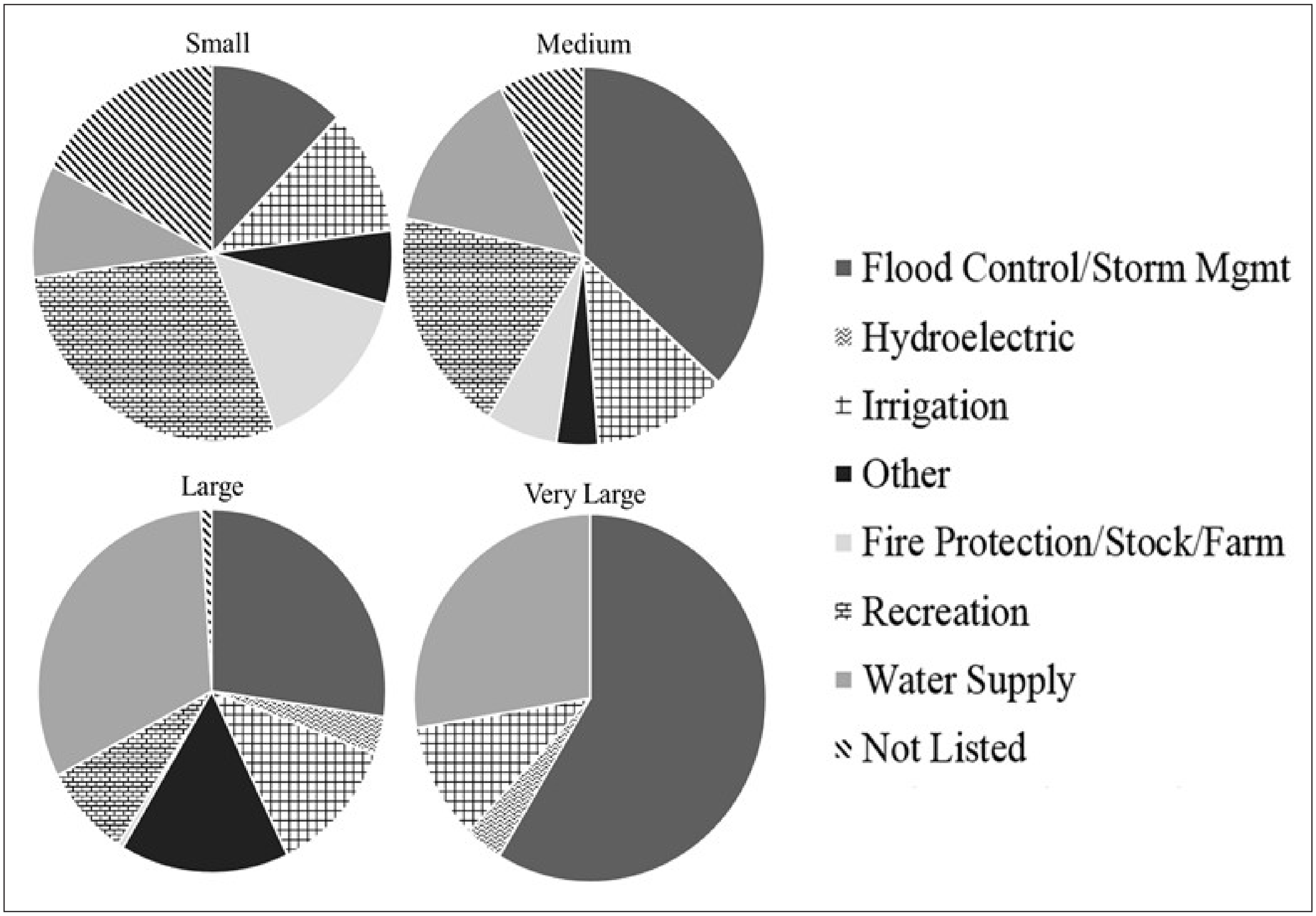

Figure 5. Purpose for all dams (1800-2014) in Texas based by dam size.

Owners

The largest percentage of dam owners in Texas were private entities (n = 4263, 58.6%), and the second largest percentage were other governments (n = 2359, 32.4%). This was also true for each river basin, except for the Trinity and Colorado river basins, where other governments owned the majority of dams, 54.3% (n = 970) and 56.4% (n = 438) respectively. Private entities owned 78.9 % (n = 1146) of small dams and 55% (n = 3072) of medium dams in the state, over 60% of total small dams in each river basin, and 30% to over 90% of the total medium dams in the majority of the river basins. Other governments owned the majority of large dams in all river basins. The federal government owned over 50% of the very large dams in Texas, and this was fairly consistent across most river basins. In the Colorado and Sabine river basins, other governments owned most of the very large dams. Data is shown in Appendix 4.

Purpose

The most common first listed purpose for all dams in Texas was flood control and stormwater management (31.5%), followed by recreation (20.7%) and water supply (13.8%; Figure 5). Only a small percentage of dams in Texas listed no purpose (9.7%) or "other" as the purpose (3.4%; Figure 5). The variety of purposes declined as dam size increased, and the sharpest decline occurred from large to very large dams.

For small dams, the most common purpose was recreation (27.8%), followed by fire protection, stock and farm pond (14.6%; Figure 5). Most medium dams had flood control and stormwater management (36.6%) as a purpose, followed by recreation (19.4%) and water supply (14.2%; Figure 5). Very large dams listed flood control and stormwater management (n =17, 58.6%), water supply (n = 8, 27.6%), irrigation (n = 3, 10.3%), and hydroelectric power generation (n = 1, 3.5%) as their purpose (Figure 5). Over 19% of small dams and 7.6% of

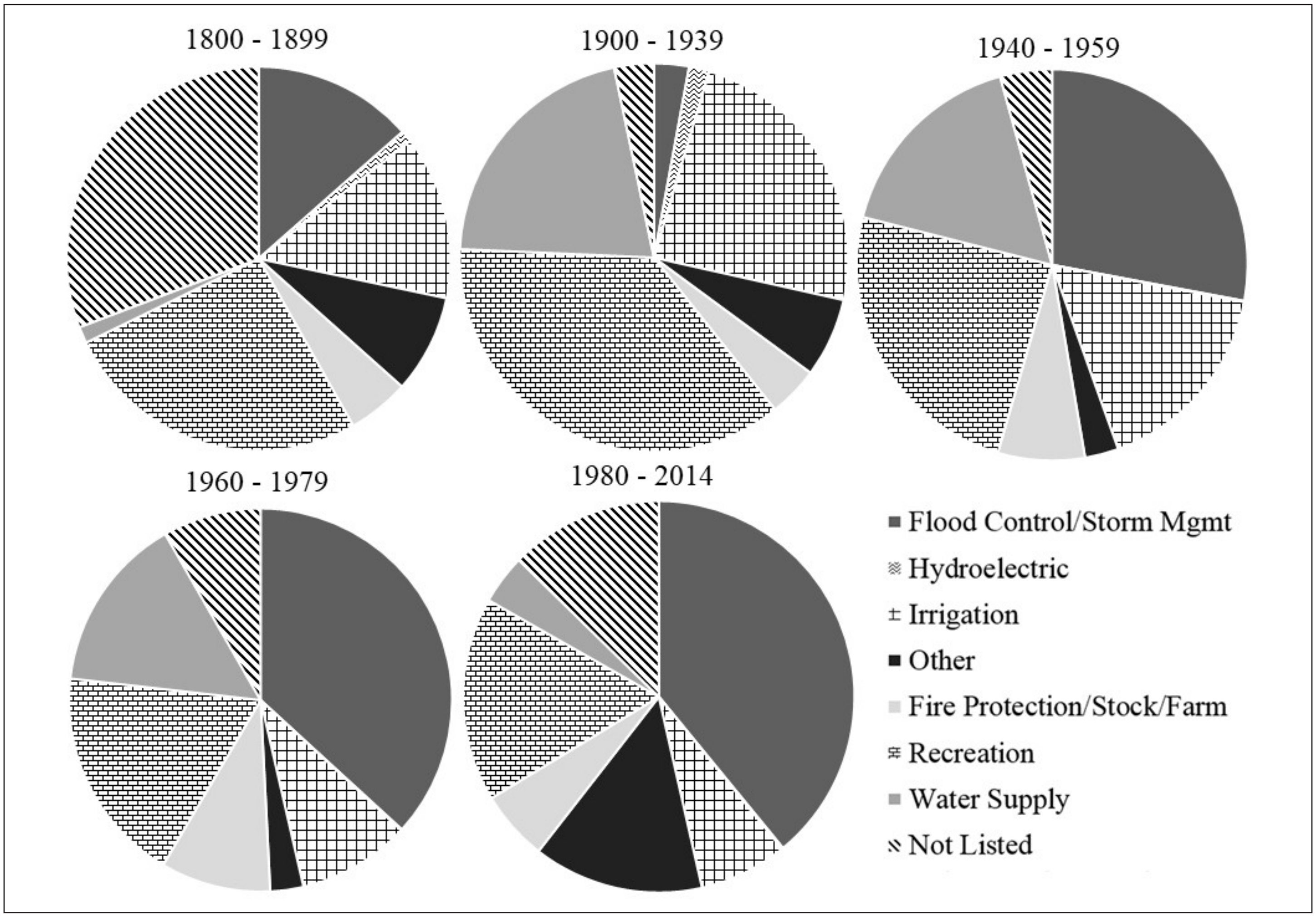

Figure 6. Purpose of dams by time period.

medium dams had no recorded purpose (Figure 5), while only two large dams had no purpose listed and all very large dams had a recorded purpose (Figure 5).

Over 30% of dams completed between 1800 and 1899 had no purpose listed. The most common recorded purpose for dams built between 1800 and 1899 was recreation (26%), followed by flood control and stormwater management (13.4%) and irrigation (14%; Figure 6). Recreation was the most prevalent purpose for dams completed during the 1900–1939 time period (36.5%), while irrigation (23.9%) and water supply (21%) were the next most common (Figure 6). Flood control and stormwater management (28%) and recreation (24.5%) were the most common purposes for dams built from 1940 to 1959 (Figure 6). Dams completed during 1960–1979 had flood control and stormwater management (36.8%), recreation (18.3%), and water supply (14.9%) listed as the top purposes (Figure 6). Similarly, dams constructed from 1980 to 2014 had the purpose of flood control and stormwater management reported most frequently (39.1%), followed by recreation (16.8%) and irrigation (7.2%; Figure 6). Only 3.3% of dams built during 1900–1939 did not include a purpose. Of the dams built during the most recent time period, 1980–2014, 12.8% listed no purpose (Figure 6).

The Brazos, Red, and Guadalupe river basins generally followed state trends for purpose (Figure 7). A noticeably larger proportion of the dams in the Trinity, Colorado, and San Antonio river basins reported flood control as their purpose, 56.9%, 45.9%, and 34.4% respectively (Figure 7). In the Sabine (42.7%) and Neches (50.6%) river basins recreation was the purpose for the majority of dams, while the majority of dams in the Nueces River Basin listed water supply (45.6%) as the purpose (Figure 7). In the Rio Grande and Nueces river basins, there were a larger number of dams without a purpose listed (25.8%, 19.7% respectively; Figure 7).

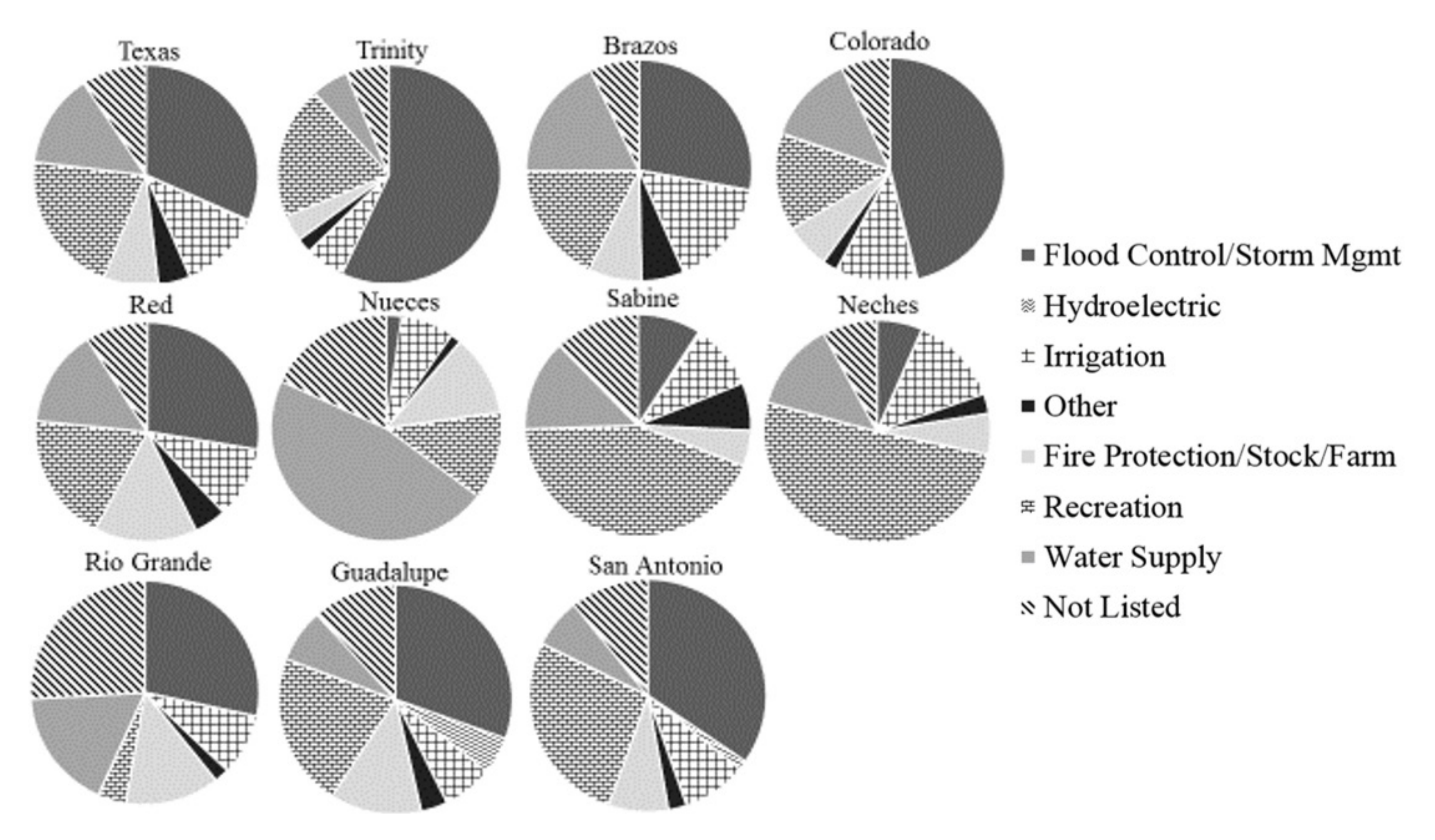

Figure 7. Purpose of dams (1800-2014) in 10 major river basins.

Dam failures in Texas

Dam failures, defined as overtopping or breaching events that resulted in the draining of the reservoir, occurred in 14 of the 23 major river basins, while dam incidents, involving all modes of damage with the exception of a drained reservoir, occurred in 15. Nearly 10% (29 dams) of the original 328 dams reported as damaged were listed more than once. Nine dams were listed as having failed twice, and one dam was recorded as having failed on three separate occasions. Two dams had four separate incidents reported, one had three reports of incidents, and an additional 10 dams had two separate incidents recorded. There were five dams listed as having failed, and then at a later date had one or more separate incidents occur. One dam had an incident reported and then failed at a later date.

The majority of dam damage reports were incidents rather than failures, with the vast majority of incidents occurring in the Trinity River Basin (Figure 8). Only five reports of dam incidents and two reports of dam failures involved dams built during the 1800s, while 16 incidents and 36 failures involved dams with unknown dates of completion. Over 75% (n = 151) of dam incidents involved medium dams and 59% (n = 119) involved dams built between 1960 and 1979 (Figure 9). Similarly, 50% (n = 54) of dam failures involved medium dams, but only 22% (n = 24) involved dams built between 1960 and 1979 (Figure 9). Thirty-three percent (n = 36) of reported dam failures involved dams with unknown dates of completion, and 21% (n = 23) were dams built between 1900 and 1939 (Figure 9).

The first recorded dam failure occurred in 1900, while the first incident was not recorded until 1926 (Figure 10). Between 1900 and 1986 there were 41 reported dam failures and an additional 19 incidents (Figure 10). The next 20 years, 1987 to 2006, would see a doubling of dam failures (n = 43) and incidents (n = 21; Figure 10). There were nine additional failures and 39 incidents from 2007 to 2014 (Figure 10). In 2015 alone there were seven dam failures and 93 separate incidents recorded (Figure 10), with over 58% of the reported damaged dams occurring in the Trinity River Basin (Figure 11). The vast majority of the reports of dam damage in the Trinity River Basin occurred on two separate dates, May 30th, 2015 (n = 24) and December 25th, 2015 (n = 37). Nine more dam failures and 32 incidents were recorded between 2016 and 2019 (Figure 10, 11).

The majority of reported incidents involved spillway damage (n = 114, 57%), while the majority of reported failures involved

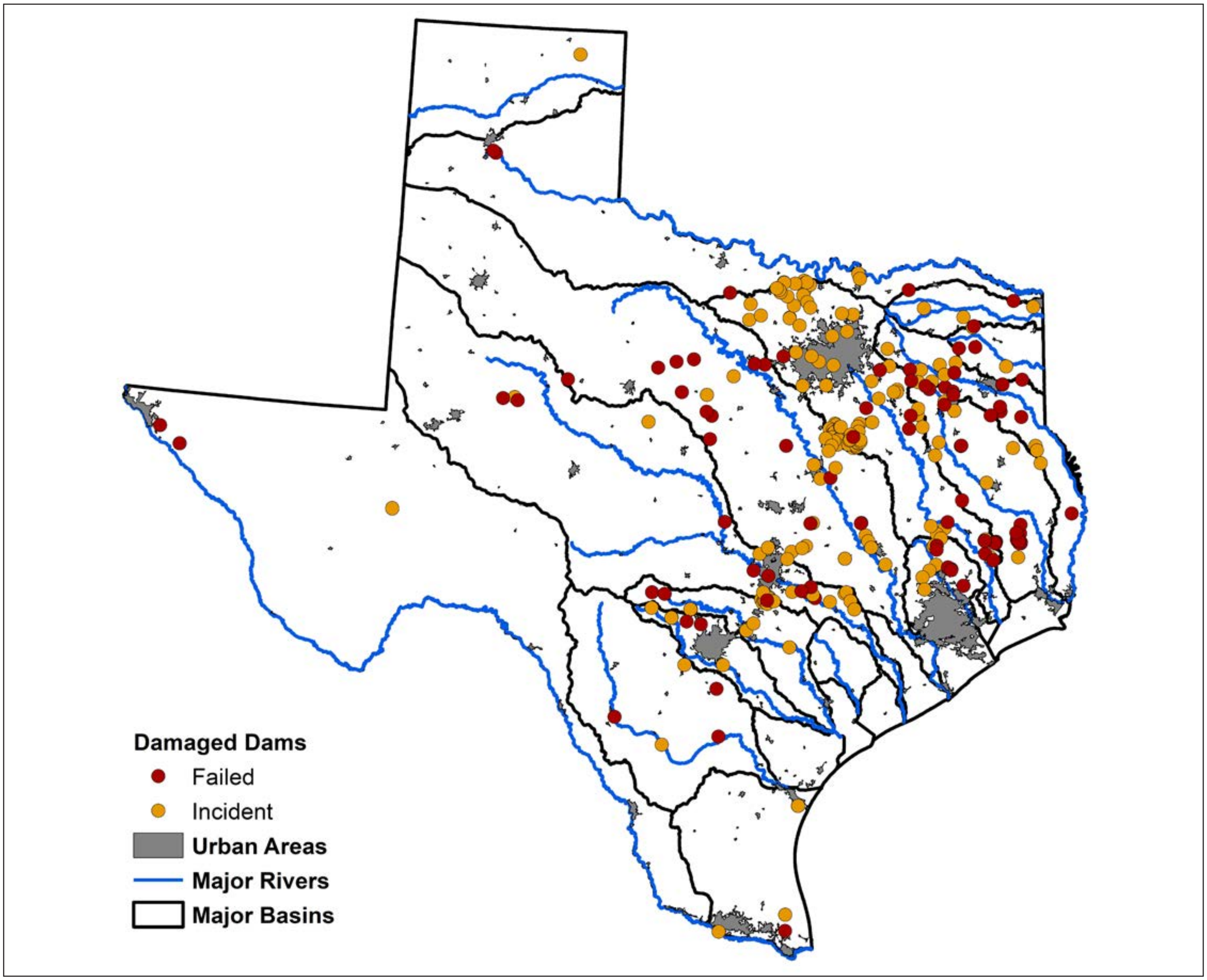

Figure 8. Reported dam incidents and failures (1900-2019).

overtopping (n = 67, 62%; Figure 12). Across the major river basins, spillway or gate damage and overtopping constituted the largest percentage of reported damage, followed by piping (Figure 13). The Association of Dam Safety Officials (2018) describes piping as the internal erosion of the soil or embankment of the dam's foundation caused by seepage that often begins at the downstream end of the dam and erodes towards the reservoir. Spillway or gate damage accounted for 20% or more of the reported incidents and failures in all river basins except the Nueces-Rio Grande Basin, which had no occurrences of spillway or gate damage reported, and the Neches River Basin, where spillway or gate damage accounted for only 13% of damaged dams. The Neches River Basin was the only basin to have more recorded failures than incidents (Figure 14) and had the second highest percentage of overtoppings reported (Figure 13). The San Antonio River Basin had the highest percentage of overtopping events listed (Figure 13), but this is the result of three of five damaged dam reports, as opposed to 26 reports of overtopping out of 46 total reports of damaged dams in the Neches River Basin (Figure 13). Similarly overtopping accounted for 20% or more of the reports of damage, except for the Red and Canadian river basins (Figure 13). Slide/erosion accounted for less than 26% of reported occurrences of dam damage across all basins (Figure 13). Reports of damaged dams categorized as other or not provided accounted for less than 25% of reports in all basins, except for the Nueces-Rio Grande Basin, where 50% (n = 3) of damaged dam reports were classified as other or not provided (Figure 13).

Figure 9. Year built and size for dams with reported incidents or failures (1900-2019).

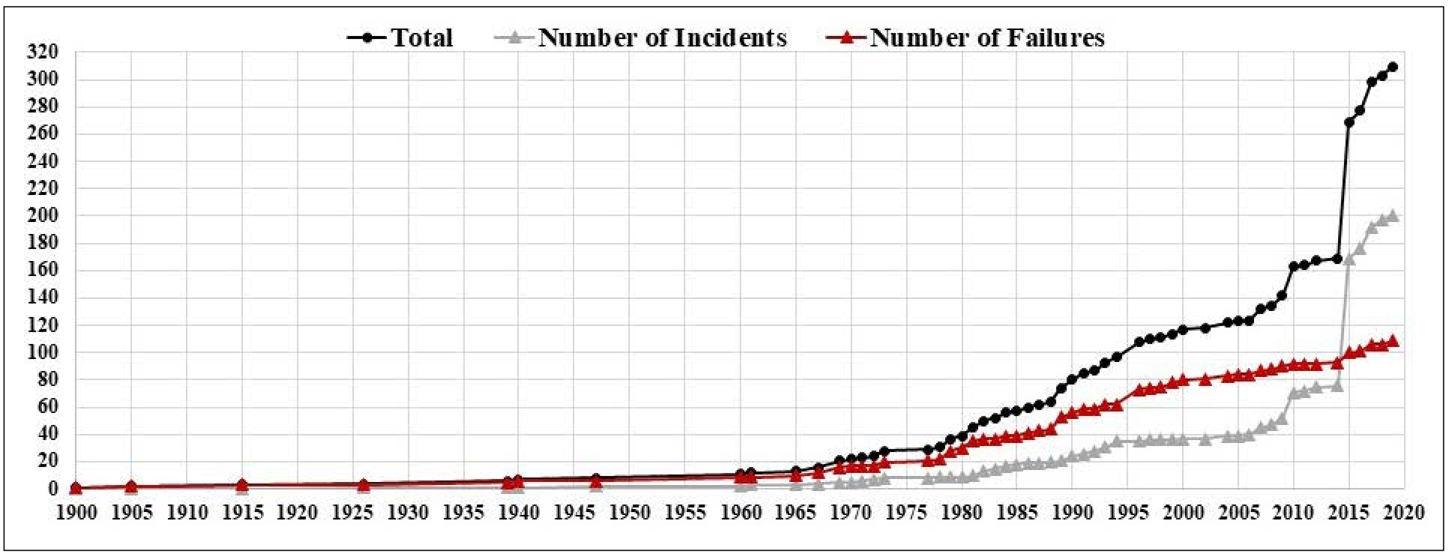

Figure 10. Cumulative number of dam incidents and failure by year reported.

Dam removals in Texas

There have been 50 dam removals in Texas between 1983 and 2016, resulting in a total of 1816.1 km (1128.5 mi) of FRRN. There was a noticeable spike in dam removals between 1994 and 1996 (Figure 15). Four tailing ponds were removed in 1995, and another four oxidation dams were removed in 1996. These four tailing pond dams did not occur on the NHD-defined river network and thus resulted in 0 km (0 mi) of FRRN. Dam removals in 2006 and 2015 sharply increased the cumulative length of FRRN (Figure 15).

Dams have been removed in 13 of the 23 major river basins in Texas, and many appear to be clustered around urban centers within these basins (Figure 16). Three removals have occurred within coastal basins, and the largest number of removals have occurred in the Colorado (n = 9), Rio Grande (n = 7), and Trinity (n = 7) river basins (Figure 17). Dams with an unknown or unrecorded year of completion accounted for 26% of the removals (n = 13). Of the dams removed, most were at least 37 years old, built between 1960 and 1979 (n = 17, 34%). (Figure 18). Over 80% of removed dams had a height of less than 30 feet (Figure 18), and nearly all were privately owned (n = 40, Figure 18). The main purpose for dam removals (n = 20) was the removal of a liability and state agency involvement (Figure 18). Removal of liability and state agency involvement was the

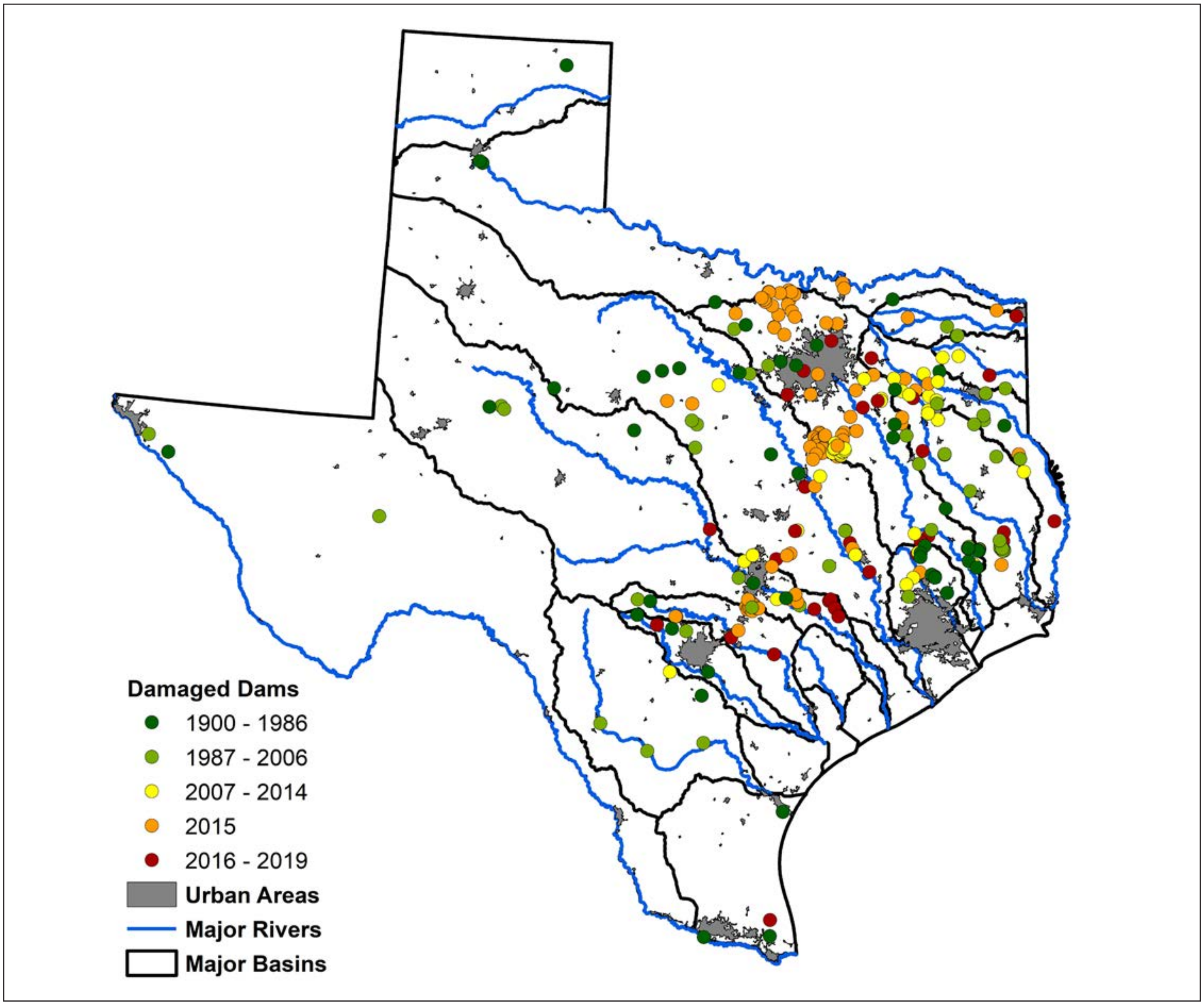

Figure 11. Dam incidents and failures by year reported.

listed reason for the three dam removals that resulted in over 100 km (62 mi) of FRRN (Figure 19).

The Bolch Pond Dam, formerly located in the upper portion of the Colorado River Basin, had an unknown age, was 16 feet (ft) tall, and resulted in 115.5 km (71.8 mi) of FRRN when it was removed in 2009. The Patricio Lake Dam, located in the Nueces-Rio Grande Basin on the Santa Gertrudis Creek, was 19 ft tall and built in 1939. Its removal in 2007 resulted in the second largest FRRN length,305.3 km (189.7 mi). The removal of the Ottine Dam, which was 15 ft tall when it was built in 1911, occurred on the San Marcos River in the Guadalupe River Basin in 2016. This removal resulted in 1283 km (797.2 mi) of FRRN, 70.6% of the total FRRN.

The removal of the Patricio Lake, Ottine, and the Bolch Pond dams were responsible for 93.8% of the total FRRN. The average FRRN length was 36.3 km (22.6 mi), but the median was 0.2 km (0.12 mi), revealing the strongly skewed distribution driven by the Ottine Dam removal. Nine dams were rebuilt, and 15 dam removals did not occur on the river network, so 24 dam removals resulted in 0 km (0 mi) of FRRN (Figure 19). Of the dam removals that resulted in FRRN, the majority resulted in less than 10 km (6.2mi; n = 20), and nine of these dams resulted in less than 1 km (0.62 mi) of FRRN (Figure 19). Additionally, the total amount of FRRN was likely overestimated as only documented dams were considered as river barriers in the study.

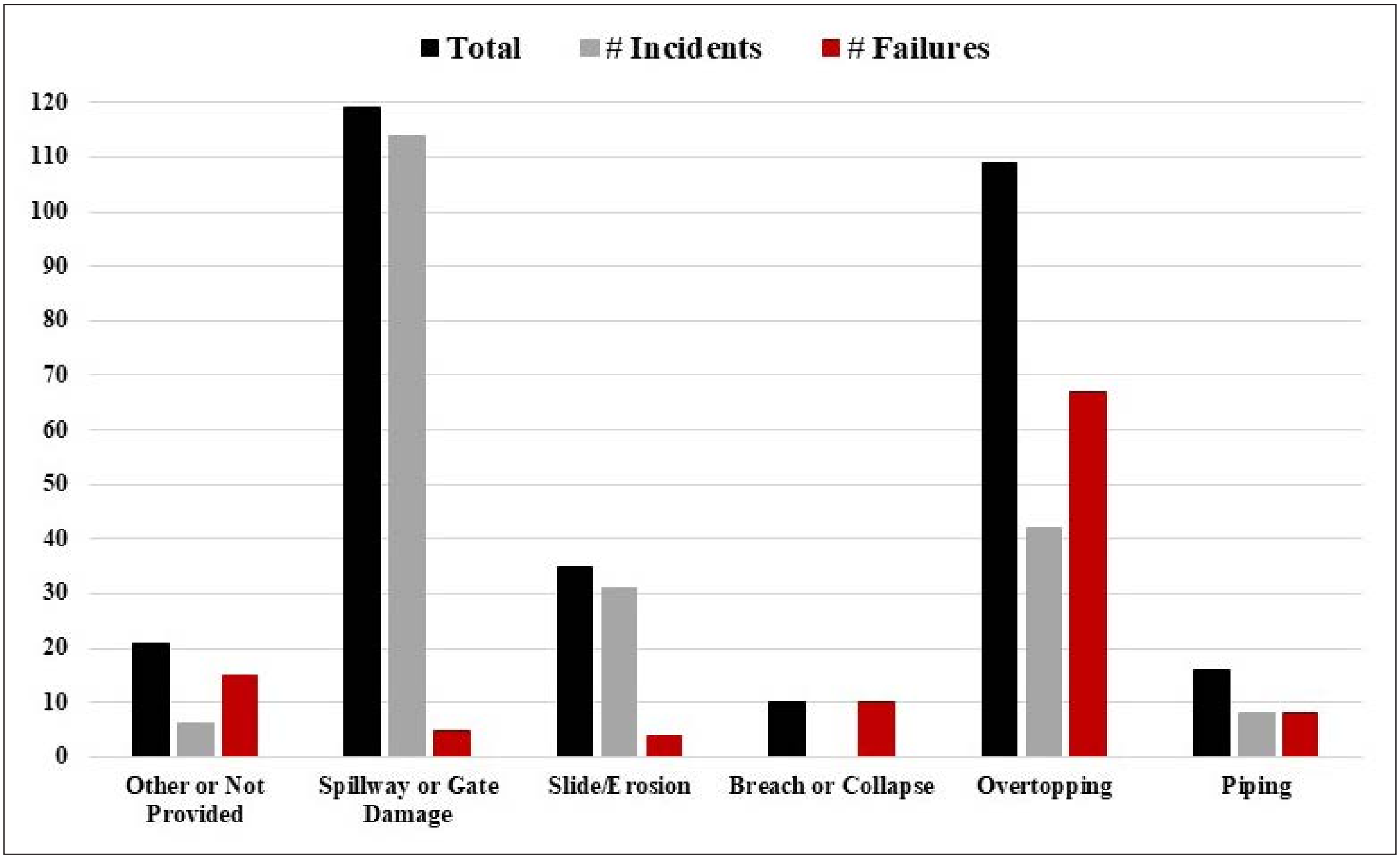

Figure 12. Dam incidents and failures (1900-2019) by mode of failure.

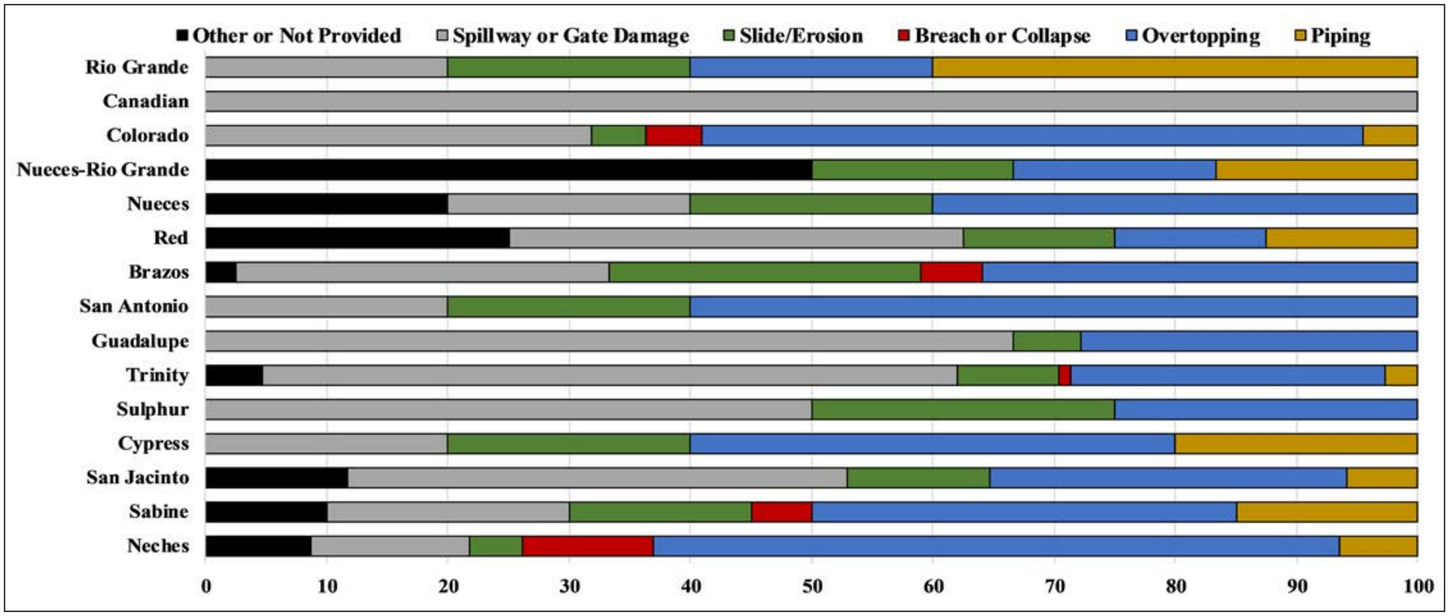

Figure 13. Mode of failure for dam incidents and failures (1900-2019) by major river basin.

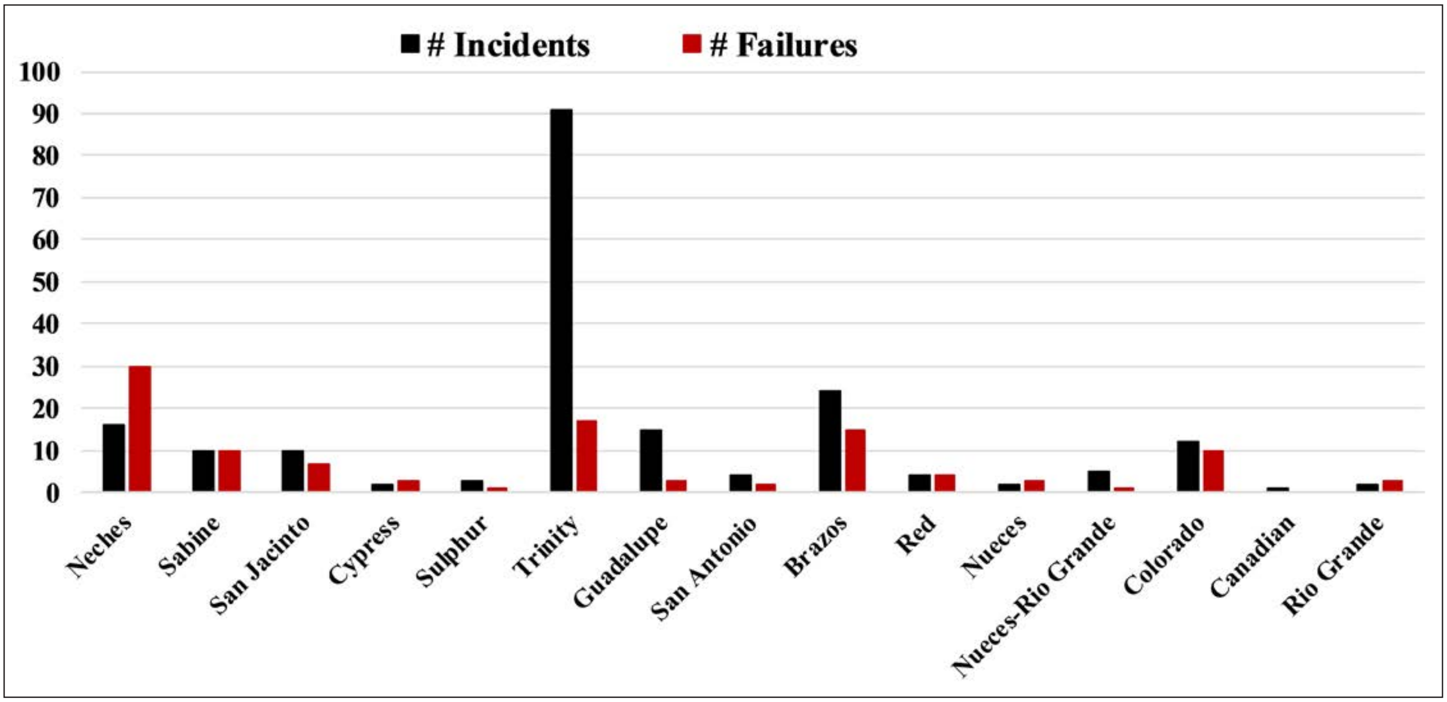

Figure 14. Number of dam incidents and failures (1900-2019) by major river basin.

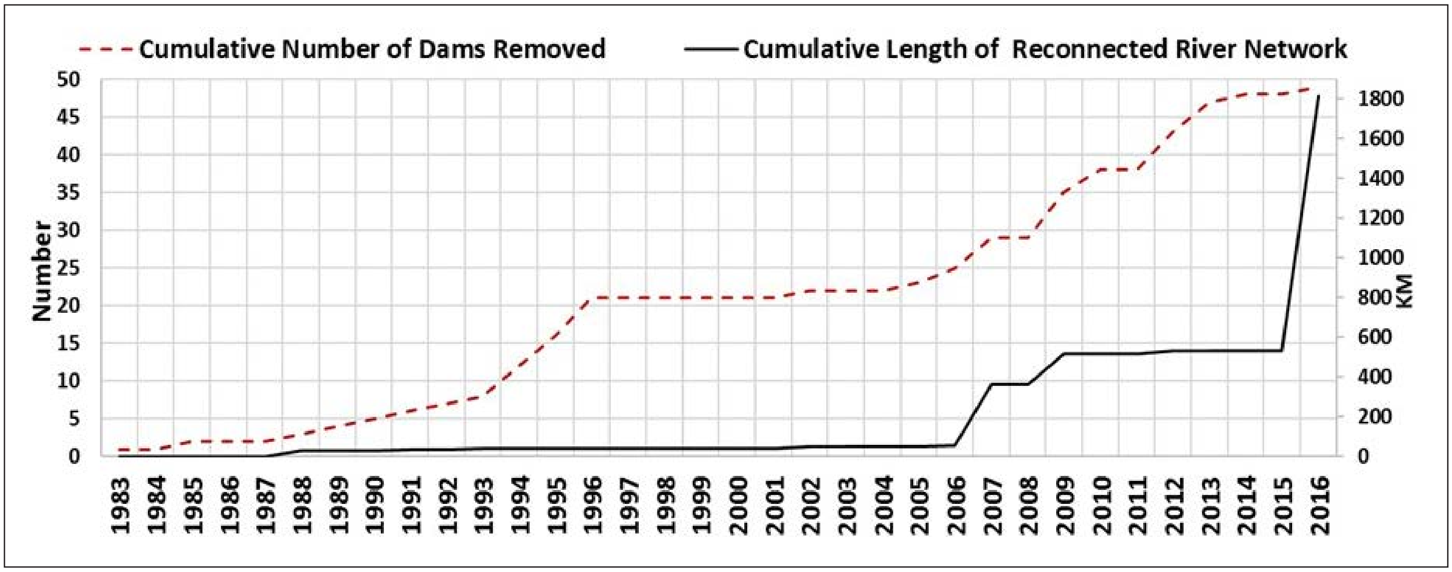

Figure 15. Cumulative number of dam removals in Texas and resulting functionally reconnected stream network (FRRN). [km, kilometer]

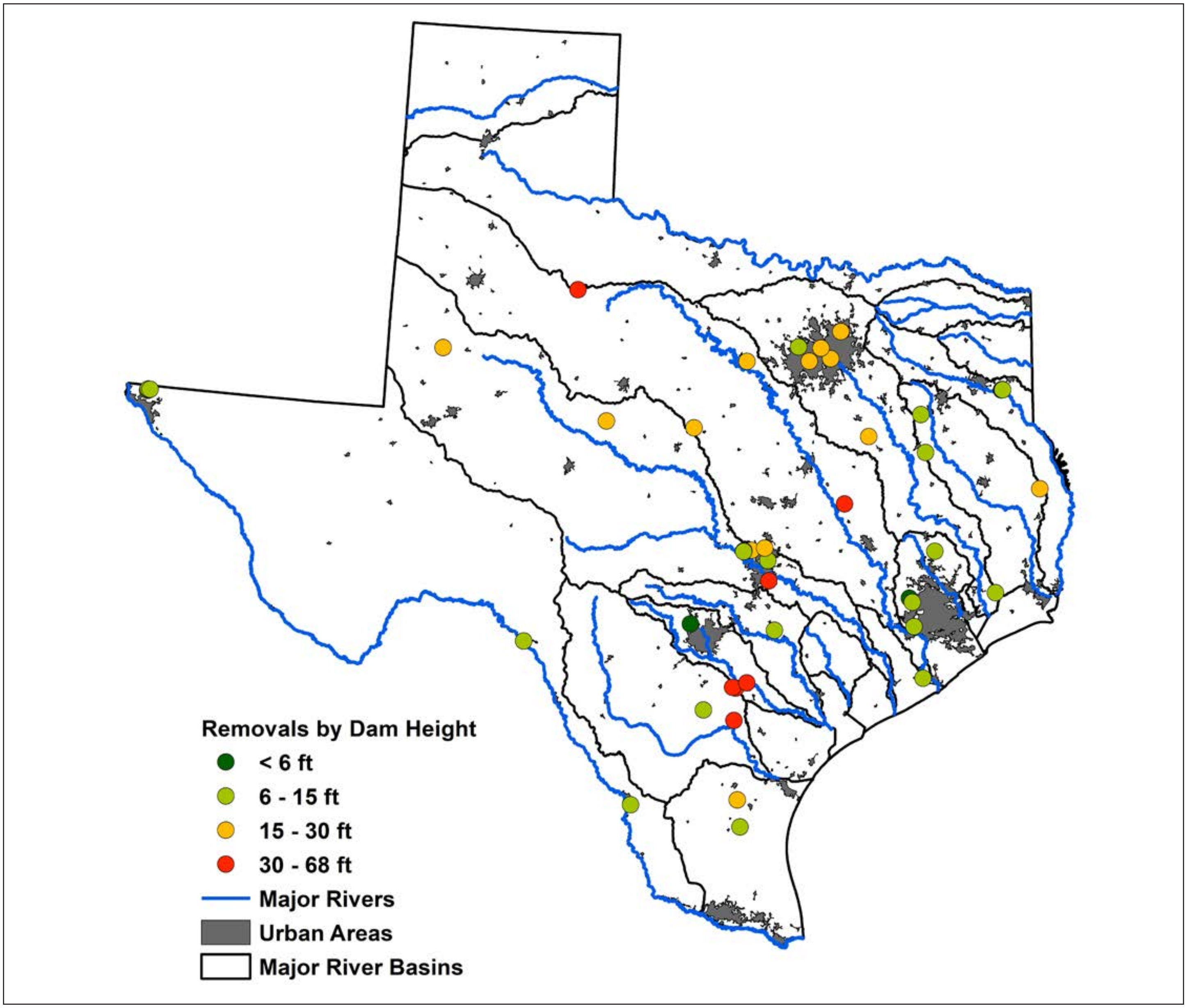

Figure 16. Dam removals (1983-2016) by location and height. [ft, feet]

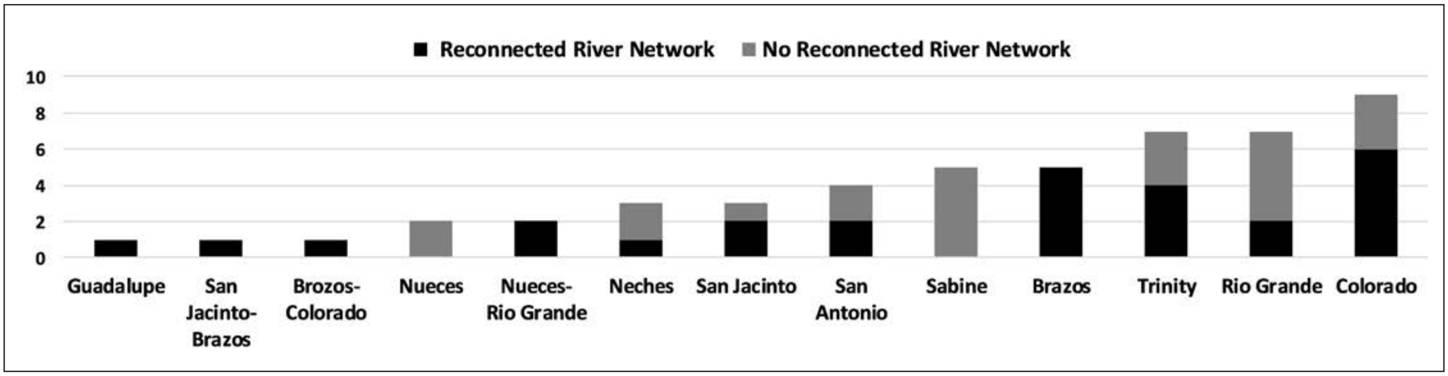

Figure 17. Number of dam removals (1983-2016) by major river basin.

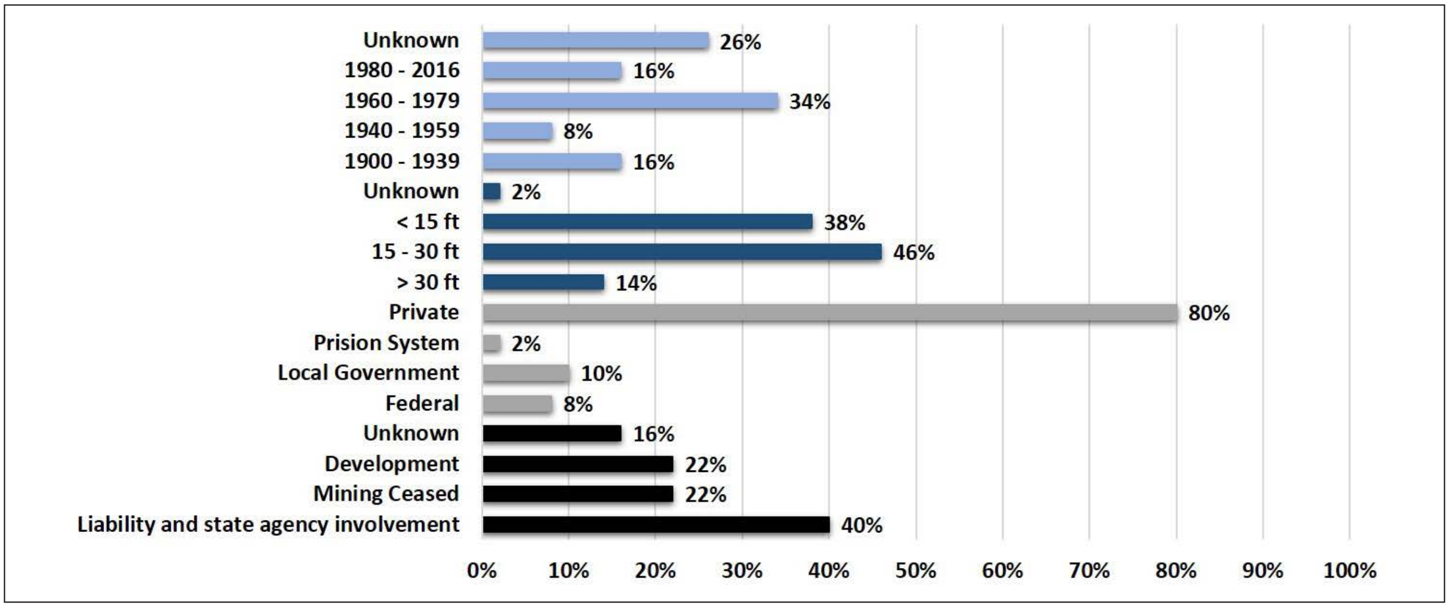

Figure 18. Percent of dam removals (1983-2016) by time period of completion (relative age), height, owner, and reason for removal. [ft, feet]

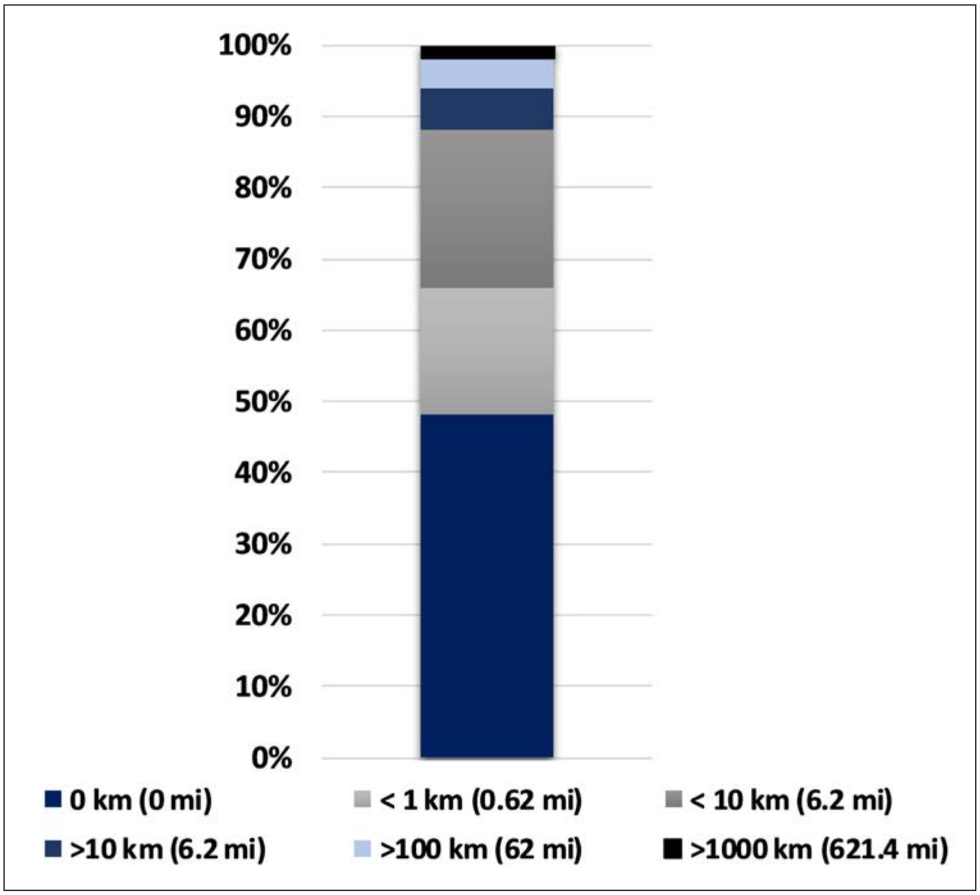

Figure 19. Number of dam removals (1983-2016) by resulting length of FRRN. [mi, miles; km, kilometers]

DISCUSSION

Compared to the 2005 NID data presented in Chin et al. (2008), the number of dams in Texas increased for all sizes except large dams. Chin et al. counts 212 large dams (Chin et al. 2008), while this analysis counts only 207. This decline in large dams was accounted for by differences in state and federal data recording. The NID included dikes and levees and used average reservoir storage to classify size. Since 2005 the total amount of reservoir storage increased for all dam sizes (Appendix 1), and small and medium dams continued to dominate by sheer numbers.

Climatic and geographic trends

As documented in previous studies, dam distribution is related to the climate gradient and location of urban centers in Texas (Chin et al. 2008; Graf 1999). Precipitation decreases and PET increases from east to west, and most of the dams in Texas occur in the wetter eastern portion of the state. Further, basins that receive 30 in (762 mm) or less of average annual precipitation have a larger percentage of dams, indicating the importance of irrigation demand to dam storage. Additionally, the Nueces River Basin has the highest PET, receives less than 30 in (762 mm) of water a year on average, and is the only river basin where the majority of dams are used for water supply. This may indicate the added importance of securing elusive water supplies in this west Texas river basin.

The Rio Grande Basin contains nearly 20% of Texas' land mass but less than 5% of its dams, and the majority of these dams occur in south Texas where irrigation is critical to the agriculture land use of the lower Rio Grande Valley region. The low number of dams compared to drainage area in this river basin is due to climate and international politics. The western part of the Rio Grande receives extremely low precipitation and is even characterized as the "Forgotten Reach" between El Paso and Presidio, because there are no major tributaries or surface flow draining into the mainstem (Sansom 2008). The waters of the Rio Grande are governed by international treaties mandated by the International Boundary Water and Commission (IBWC) and dam construction and management require complex international cooperation between the United States and Mexico. The IBWC manages the large and very large mainstem dams (e.g. American Dam, Amistad Dam, Falcon Dam, and Anzalduas Dam) for water supply, diversion to Mexico, flood control, and other uses, whereas many of the other small and medium dams are owned by other government organizations.

In contrast to the Rio Grande Basin, the Trinity River Basin has less than 7% of Texas' drainage area but has nearly a fourth of all Texas dams. Additionally, other governments own higher percentages of dams in the Trinity River Basin, and a much larger percentage of the dams are for flood control. These trends are probably best explained by the eastern location of the Trinity River Basin, where there are relatively higher amounts of precipitation, and the presence of the Dallas-Fort Worth area with a population over 7 million people in the upper portion of the river basin (U.S. Census 2018).

The Colorado River Basin has the third highest numbers of dams with 776 total dams. As with the Trinity River Basin, other governments own higher percentages of dams, and a much larger percentage of dams are primarily for flood control, likely accounted for by the large urban areas and downstream agricultural communities located in the river basin. Nearly 350 dams were built in the Colorado Basin between 1960–1970, and 69 of those were constructed within the Austin city limits. The city of Austin's current population is nearly 1 million (U.S. Census 2019). Although this basin receives less than 30 in (762 mm) of precipitation a year, it occurs in one of the most flash flood prone areas in the United States according to the National Weather Service (NWS 2000). The increased chances for both floods and droughts, and the location of a large urban area within its boundaries demonstrates how both climate and population have led to increased numbers of dams in this river basin, especially with regard to the numerous small to medium-sized structures built for stormwater management and flood control.

An exception to the urban population trend within the Colorado Basin includes the six Highland Lakes dams and four other downstream dams owned by the Lower Colorado River Authority (LCRA) built between 1935 and 1951. Situated in the Hill Country characterized by high-relief bedrock incised limestone canyons, these dams were specifically constructed to capture large volumes of runoff, providing flood control, irrigation (to downstream coastal community rice farmers), municipal water supply, hydroelectric power, and recreation (Williams 2016). The safety provided by flood control, the increased reservoir storage for water supply, and the electricity revenue generated by the LCRA dams likely supported the increased population growth throughout the basin that led to the increased dam construction for stormwater and urban flood control in the later time periods. This increased population within the basin has ultimately led to intermittent conflict between the LCRA and the water-intensive rice farming industry over municipal water allocations. During a recent drought, the LCRA reduced water delivery to the coastal irrigation communities for 3 straight years, 2012–2014, to meet the municipal demand fueled by the growing Hill Country population. These conflicts highlight the changing social and political dynamics influencing dam purpose and management.

Texas has more dams than any other state (NID 2013–), and in a previous study, the Texas-Gulf water resource region had one of the highest ratios of storage capacity to drainage area (Graf 1999), further demonstrating the fragmented state of the Texas' rivers. The main hydrologic effect of medium and small dams on river landscapes has been fragmentation (Chin et al. 2008), and 97% of the dams in Texas were small and medium. River fragmentation has led to declining fish and mussel populations (Richter et al. 1997; Wofford et al. 2005) and altered migration routes (Jager et al. 2001).

The amount of storage established in the United States rapidly increased during 1950s through the 1970s, with only minor increases after 1980 (Graf 1999). Texas has a pronounced history of flooding and drought (TWDB 2017), and its river basins have been documented as having some of the highest runoff to storage ratios (Graf 1999). In Texas, very large dams accounted for the smallest number of dams, and unlike other size categories their temporal pattern of construction was not uniform across the different basins. A variety of factors likely influence this spatial variation including physiographic settings suitable for very large dams coupled with the amount of precipitation runoff available to store. The temporal variation in dam construction is partially due to the federal and state legislative politics linked to dam purpose, available capital, and the engineering required to build them. Rubinstein (2015) provides a detailed, though not comprehensive, timeline from 1900 — the contemporary period highlighting significant drought and flood events, federal and state legislative acts, and the historical evolution of Texas water management organizations and plans that have collectively contributed to the temporal variability of dam construction statewide. The time period when the bulk of storage is created in a basin is directly linked to when these very large reservoirs are built. This is particularly well demonstrated in the Red, Nueces, and Rio Grande river basins (Figure 4).

Recreation was the main listed purpose for dams built before 1900, most of which were small or medium dams. The shift in the purpose to flood control for dams built in the 1940s and 1950s is in part linked to federal funding through the New Deal programs and the Flood Control Act of 1936, which provided funding for river surveys and dam construction that occurred during the proceeding decade. Irrigation increased from slightly over 10% in the 1800s to nearly a fourth of all purposes for dams built during the mid-20th century. After this time period irrigation declined as a purpose, potentially exhibiting the increased agriculture in Texas during the 1800s and early 1900s, followed by the impact of the drought of record in the 1950s on the industry.

The 1960s and 1970s have often been referred to as the dam-building era in the United States, and the greatest national increase in dams occurred from the late 1950s to the late 1970s (Graf 1999). Similarly, in Texas, the majority of dams dated back to this time period. After 1980, the pace of dam construction slowed in the United States (Graf 1999), including in Texas. In addition, the small number of dams constructed post-1979 with water supply recorded as the purpose potentially reflects the increased scarcity of locations to build large water supply dams after this time period, as was also observed nationwide (Reisner 1986). The vast abundance of Texas' dams provides numerous benefits to society and the economy, and as a result more reservoirs are still desired across the state, as evidenced by the 26 new major reservoirs designated by the TWDB to secure the state's future water supply and help mitigate drought impacts (TWDB 2017). These new dams will increase the fragmentation of Texas river systems and make it even harder to maintain a balance between the competing interest for human-related water uses and maintaining the ecological integrity of rivers, bays, and estuaries.

Dam failures in Texas

Both the number and rate of dam incidents and failures are increasing across Texas. Patterns of dam incidents appear related to patterns of dam occurrence. The majority of dams in Texas are medium dams built between 1960 and 1979, so it makes sense that the majority of incidents involve dams with these attributes. Similarly, nearly a quarter of all dams in Texas reside within the Trinity River Basin, and this is where the majority of dam incidents have occurred.

The majority of dams in Texas are small to medium privately owned dams that are either beyond or nearing the end of their usable lifespan (Buchele 2013a). Despite their small size, these dams can still pose a serious risk. After Hurricane Harvey made landfall in August of 2017, 20 dams across East Texas either failed or were damaged (Sadasivam 2019). Of these 20 dams, all were classified as small dams by the TCEQ, and 11 were exempt from state regulations due to their small size (Sadasivam 2019). Overtopping was the most common mode of failure, and this highlights the impacts of large precipitation events on the dam infrastructure in Texas. This trend is particularly concerning given the increased rainfall magnitude, frequency, and recurrence intervals predicted by the new NOAA Atlas 14 Volume 11 Precipitation-Frequency Atlas of the United States for Texas (Perica et al. 2018). In 2015, over half of all dam incidents/failures were the result of increased amounts of precipitation and flooding within the Trinity River Basin.

There was a flash flood warning issued for Johnson and Tarrant counties near Dallas-Fort Worth on May 30th, 2015 (The Associated Press 2015). In the proceeding weeks the Dallas area had already experienced over 16 in of rainfall, enough to break a 1982 record. This precipitation came on the heels of a severe drought throughout the state. Torrential downpours lead to flooding and loss of life and are the most likely cause of the 24 dam incidents/failures that were reported on the Trinity River Basin on May 30th, 2015. Similarly, December 2015 was the 13th wettest December on record for Texas (NOAA 2016), and on December 25th, 37 dam incidents/failures were reported in the Trinity River Basin. On the same day a large storm complex dubbed Winter Storm Goliath by the Weather Channel formed and began to move through parts of the United States, including Texas (MacFarlane 2015, Warren 2015). There had been heavy snow and flooding from a storm the weekend before in the Dallas area (Warren 2015), and several tornadoes touched down during Winter Storm Goliath in the same area (MacFarlane 2015).

While heavy rains can lead to dam failure, as seen with the clusters of dam incidents and failures in 2015 and more recently during Hurricane Harvey, prolonged drought followed by severe flooding also contributes to the deteriorating condition of dams. Over 95% of dams in Texas are earthen dams (NID 2013–), meaning they are particularly susceptible to cracking during dry conditions (Marks 2013). Once damaged, a dam is more likely to fail or experience problems during a rain event, as the water can potentially increase the size of existing cracks and places more pressure on the damaged dam by increasing the amount of water it must retain (Marks 2013). This unique cycle of extended dry periods punctuated by torrential rains and/or flash floods is particularly relevant to the Flash Flood Alley that runs along Interstate-35 with the Balcones Fault Zone to the west and the Blackland Prairie to the east. This corridor collectively encompasses multiple major urban areas, including Dallas, Austin, and San Antonio, where these drying/wetting cycles of natural land surfaces and earthen dams may exacerbate the issue of Texas' aging dam infrastructure.

The likelihood of a dam incident or failure is related to dam age. A larger percentage of dams built between 1900 through 1939 have had an incident or have failed compared to dams built during more recent time periods. Older antiquated engineering styles are often more difficult to maintain and pose greater failure risks, as has been the case with a series of six dams on the Lower Guadalupe River, all of which are greater than 90 years old and have exceeded their useful life capacity. Two of the six dams experienced spill gate failures and partial lake draining, Lake Wood in 2016 and Lake Dunlap in 2019, with the remaining four dams expected to follow a similar fate (Black & Veatch 2019). Though neither the Lake Wood or Lake Dunlap dam incidents met the TCEQ classification of a dam failure, they were portrayed as such in the media, and their very publicized damage sparked a highly controversial debate on what entity is responsible for the hazard liability, maintenance, and repair of aging dam infrastructure and who ultimately benefits from the dams. The six dams, owned and managed by the Guadalupe-Blanco River Authority (GBRA), are primarily recreational and serve as pass-by structures for downstream water supply. They do not provide flood control and are admittedly generating hydroelectric power at an "unsustainable deficit" (GBRA n.d.).

Following the incident with Lake Dunlap and the subsequent publication of the Black & Veatch (2019) engineering report, GBRA made the decision to dewater all six reservoirs to reduce the risk of a future failure. This action was halted by a temporary injunction issued in favor of the lakefront property owners, motivated by aesthetics and property values, who did not want the lakes drained. This same group of plaintiffs initiated litigation with the GBRA challenging the organization's expenditures with the goal to require them to burden the majority costs of repairing or replacing the six dams. Although public access to the lakes is limited, the lakeside property tax base benefits the county school districts and is at risk of reduction if the lakes are drained or the dams are removed. As of June 2020, stakeholders formed three new WCIDs, the Lake Dunlap WCID, Lake McQueeney WCID, and Lake Placid WCID, to provide a financing and planning process for replacing the dams. The Lower Guadalupe Valley Lakes case study highlights the social, institutional, and economic challenges of managing dam infrastructure for very different stakeholders and purposes.

A study of flood fatalities across the United States reported 309 fatalities associated with nine structural failures, constituting 12% of the flood fatalities in the United States between 1959 and 2005 (Ashley and Ashley 2008). A 2015 review of flood fatalities in Texas found that no deaths were due to structural failures between 1959 and 2008 (Sharif et al. 2015). However, a 2018 study reported that four dam failures in Texas had resulted in at least one fatality (McCann 2018). The 2013 Texas law that exempts a large number of dams from safety regulations could prevent awareness of hazard risks in many rural areas experiencing rapid population growth and development. As dams continue to fail across the state and the population continues to grow, there is a serious and increasing potential for loss of life.

In addition to loss of life, dam failure can lead to possible toxic pollutant releases downstream as exhibited by recent dam failures in Michigan. On March 20th, 2020, the Edenville and Sanford dams on the Tittabawassee River in Midland County, Michigan failed due to rapidly rising water. The failure resulted in the evacuation of 10,000 people, massive flooding (Holden 2020a), and fears that a containment system for contaminated soil at a Dow Chemical superfund site might breach and distribute toxic soil through the community (Holden 2020b). The Edenville Dam was a hydropower dam with a high hazard potential rating (Holden 2020a) built in 1924 and owned by Boyce Hydro (CBS/AP 2020). The Federal Energy Regulatory Commission revoked the dam's license in 2018 due to issues of noncompliance, particularly related to the dam's spillway capacity, and cited a long history of noncompliance (CBS/AP 2020). After its federal license was revoked, the Edenville Dam was regulated by the state and received a rating of unsatisfactory in 2018 (CBS/AP 2020; Holden 2020a). The Edenville Dam failure serves as a canary in the coal mine example of the hazards posed to downstream communities from aging dams in disrepair and noncompliance and should serve as a warning for future disasters.

Dam failure is not the only risk that outdated dams pose to human life and well-being. There have been 555 fatalities at 276 low-head dams throughout the United States since the 1950s (Kern et al. 2015), 19 of which occurred in Texas between 1995 and 2016 (Kern et al. 2015). Low-head dams generally result in fatalities when someone goes over top of the dam and becomes trapped in the submerged jump the dams create (Wright et al. 1995; Elverum and Smalley 2012; Kern et al. 2015). River users are often unaware of the hazard these dams present (Tschantz and Wright 2011), and older structures may often go unregulated (Kern 2014). Removal of low-head dams that pose a threat to human life can help make Texas' waterways safer for recreationists and other river users.

There are 29 dams that have had two or more instances of either an incident or failure reported to the TCEQ. This may be evidence that after a reported incident/failure some dams may not be fully or adequately repaired, leading to future instances of damage. In 2013, StateImpact Texas ran a three-part series investigating the conditions of Texas' dam infrastructure (Buchele 2013a, 2013b, 2013c). The series highlighted the number of dams in bad condition and the lack of available funds (Buchele 2013a), how a large number of dams go undocumented or unregulated due to state legislation (Buchele 2013b), and the lack of transparency regarding dam hazard classifications (Buchele 2013c). Between 2012 and 2017, 217 dams received higher hazard classifications, and eight dam failures, one partial dam failure, and 108 additional incidents including damaged spillways, slides, and pipe failures occurred across the state (ASCE 2017). The cost to rehabilitate Texas' dam infrastructure has also risen to over an estimated $800 million in 2017 (ASCE 2017), yet this amount is likely an underestimate given the low numbers of dam failures included in their report. The GBRA has already spent $25 million to date on maintenance repairs to the six aging dams in the lower Guadalupe Valley lakes system, with the full cost of repairs currently unknown. A recent partnership between GBRA and Preserve Lake Dunlap Association have agreed to share the costs for at least one of the dam-reservoir complexes (GBRA n.d.).

An even larger high-risk dam, such as the Lewisville Dam (Trinity Basin, upstream of Dallas metropolitan area) with its variety of problems, including seepage, sand boils, and embankment instability, warrants costly repairs due to its importance for water supply and flood control (Getschow 2015). In response to catastrophic failure warnings in 2015, the Fort Worth District USACE created the Lewisville Dam Safety Modification project with a full cost of $150 million to be funded by multiple stakeholders (Scruggs 2019). As of 2019, only $39.1 million has been allocated to the initial phases of hard and soft engineering related to dam repairs and flood mitigation projects (Scruggs 2019). The Lewisville Dam serves multiple purposes, in contrast to the example of Lake Dunlap dam on the Guadalupe River, which is managed primarily for recreation, and the two dams have very different stakeholder groups. However, they share a similar discourse regarding uncertainty around what organization should be accountable for their repair, maintenance, and liability in the event of a failure. It can be expected for these contentious proceedings to increase in frequency as more large dams face imminent failure risks.

The discrepancies in defining dam failures and incidents highlights the need to standardized terms or at the very least to clearly demarcate how such distinctions are made at different institutional levels. A preliminary inquiry by the authors into how such terms were defined by reporting agencies other than the TCEQ yielded no new insights beyond the definitions already provided on websites or within existing publications. These definitions were not sufficient to determine which cases of failure versus incidents were being counted compared to those listed by the TCEQ.

The TWDB is the regulatory authority charged with administering the Texas state water plan planning process and preparing and adopting it every 5 years (TWDB 2017). In 2019 the governor and state legislature expanded the TWDB's role in flood planning and financing (TWDB 2019). The TWDB will now be responsible for the state and regional flood planning process; the first state flood plan is due to be completed by September 2024 (TWDB 2019). To support this new endeavor, the legislature transferred $793 million from the rainy day fund to the TWDB for the creation of a new flood funding program (TWDB 2019). Before 2019, there was no unified flood plan for Texas, and existing flood programs consisted of grant programs for flood protection and mitigation and federal insurance programs (TWDB 2019). Considering the relationship between dam incidents/failures and flooding in Texas, it would seem prudent that future flood plans include evaluations of and recommendations for managing Texas' dam infrastructure, particularly in terms of aging and damaged dams. While only a small number of dams built in the 1800s have failed, a third of all failed dams have unknown years of completion. It is possible that many these dams also represent older structures at a greater risk of failure, and their removal could be a priority for hazard mitigation.

Dam removals in Texas

In the Trinity and Colorado river basins, dam removals appear to be grouped around major cities, such as Austin and the Dallas-Fort Worth Area (Figure 11), and dam removals after 2002 (Figure 15) were motivated by liability and development issues, according to the records received from the TCEQ (Dam Removals 1983–). While the authors do not have the specific details for each dam removal with this reasoning, they may reflect increasing population growth in these areas associated with increased land values. Removing dams for development purposes may signify land use change in these areas, such as agricultural to urban land use. Additionally, as urbanization continues in these areas, older, damaged dams may become increasingly dangerous with increased population downstream, and this increased liability may be a catalyst to dam removal in these areas.

Other clusters of dam removals, such as those in the Sabine River and Rio Grande basins, were the result of ceased industrial operations where multiple dams were removed together. Dam removals that resulted in 0 km (0 mi) of FRRN were mostly industrial use ponds. These industrial use ponds were connected to the river network through artificial canals, and when the ponds were no longer needed, both the ponds and canals were removed.

Dam removals in Texas generally follow national dam removal trends, with the majority of removals involving smaller, older structures (Graf et al. 2002; Stanley and Doyle 2003; Bellmore et al. 2017). Most of the dams in Texas are smaller, privately owned structures built before 1980. These patterns indicate a potentially considerable number of outdated structures that likely require expensive upkeep or repairs. Such dams are prime candidates for removal (Graf et al. 2002; Stanley and Doyle 2003). Additionally, removing these structures involves working with private individuals as opposed to coordinating with multiple stakeholders.

It has been suggested that a deterrent to private owners removing dams in Texas is the lengthy permitting process (Hershaw 2011). Potentially, a dam owner is responsible for obtaining multiple permits before removal can begin (TCEQ 2006), but according to the manager of the Dam Safety Program, the permitting process is in reality fairly simple (Hershaw 2011). While the Dam Safety Program recommends multiple permits, there are no penalties for removing a private dam without them (TCEQ 2006; Hershaw 2011). Additionally, if a dam owner wants permission to remove a dam, all they have to do is provide the Dam Safety Program with the dam's engineering plans (Hershaw 2011). However, some owners may not have these plans, and the appearance of a cumbersome permitting process may still prevent private dam owners from proceeding with removal. The permitting process should be streamlined where possible and provide additional resources and outreach about the removal process to the public to eliminate the permitting process' perceived barrier to dam removal in Texas.

While larger dams such as those at Lake Lewisville and Lake Dunlap have multiple interest groups lobbying for their repairs, many smaller aging and damaged dams exist that no longer serve their original purposes yet pose risks to downstream communities and continue to fragment rivers. For these derelict dams, removal may provide a more cost-efficient solution. Online decision support tools such as the Southeast Aquatic Barrier Prioritization Tool managed by the Southeast Aquatic Resource Partnership (SARP) provide a user-friendly platform to view dam inventories for a select set of basins and prioritize dam removals using a set of metrics related to increasing the amount of functionally connected river networks (SARP 2019). SARP's dam removal prioritization tool currently includes all 215 documented dams in the Guadalupe Basin and an additional inventory consisting of numerous smaller dams in the upper portion of the basin that do not meet criteria for federal or state documentation.

In addition to removing damaged and potentially hazardous dams from Texas waterways, dam removal provides a way to restore riverine habitat for Texas' aquatic species. In particular, freshwater mussels have been receiving increased attention in Texas due to concerns over their conservation status (Randklev et al. 2010; Winemiller et al. 2010; Burlakova et al. 2011a, 2011b; Karatayev et al. 2012; Randklev et al. 2013a, 2013b; Karatayev et al. 2018; Dascher et al. 2018). There are approximately 50 known species of mussels that inhabit Texas (Howells et al. 1996). In addition, three new species of freshwater mussels were recently described, including the Guadalupe Fatmucket (Inoue et al. 2019) and the Guadalupe Orb (Burlakova et al. 2018), both endemic to the Guadalupe River Basin, and the Brazos Heelsplitter (Smith et al. 2019) in the Brazos River Basin. Currently 15 mussel species are listed as state-threatened in Texas. Of these, five are currently candidates for federal listing and one, the Texas Hornshell, was recently listed as federally endangered (FWS 2018). Due to the importance of fish hosts in the life cycle of freshwater mussels, the positive response of fish to dam removal may result in an increase of native mussels (Gottgens 2009). Dam removal is a potential tool for restoring freshwater mussel habitat and conserving these imperiled species, but to date no dam has been removed solely or primarily for ecological concerns in Texas.

The Ottine Dam was over 100 years old, damaged, and no longer performing its intended purpose (Montagne and Jobs 2016). The removal of this dam reconnected over 1000 km (621.4 mi) of river and is a powerful example of the ability of dam removals to restore river connectivity. However, most of the dam removals in Texas resulted in less than 1 km (0.62 mi) of FRRN. Three dam removals accounted for nearly 90% of the total FRRN: the Ottine Dam removed from the Guadalupe Basin in 2016, the Bolch Pond Dam removed from the Colorado Basin in 2009, and the Patricio Lake Dam removed from the Nueces-Rio Grande Basin in 2007. All three dams were removed with state agency involvement to eliminate liability issues. These results highlight the isolated and opportunistic nature of most dam removals (Bellmore et al. 2017;

Magilligan et al. 2016) and further support the need for more strategic planning and management of dam removals (Magilligan et al. 2016).

Previous studies have called for more reliable record keeping and communication between organizations regarding dam removals (Graf et al. 2002; Bellmore et al. 2017). American Rivers (2016) only lists seven dam removals for Texas, as opposed to the 49 recorded by the TCEQ, not including the Ottine Dam. These additional removals potentially make Texas sixth in the nation for number of dams removed, but other states likely also have undocumented dam removals and thus underrepresented totals. Because permits are required to remove a dam, there is already a mechanism in place for obtaining data on dam removal. This data, however, unless voluntarily reported to American Rivers, is not collected or maintained in a national database.

A congressionally authorized national inventory of dam removals that assigns formal responsibility to a single agency, similar to the National Inventory of Dams maintained by the USACE, has previously been recommended (Graf et al. 2002). Such a national inventory would provide a way to reliably maintain and organize data about dam removals and would standardize record keeping and data reporting.

The USGS maintains the USGS Dam Removal Science Database (USGS 2018–). The USGS Dam Removal Science Database is a collection of empirical monitoring data from 214 publications for 181 dam removals worldwide (USGS 2018–). This data has been combined with the American Rivers Dam Removal Database, which is updated on a regular basis, to create an online database tool, the USGS Dam Removal Information Portal (DRIP; Bellmore et al. 2017; Duda et al. 2016; DRIP 2016–; ARDRD 2019). Thus, the USGS would be a reasonable choice to maintain a national inventory of dam removals.

CONCLUSIONS

Currently, dam removals in Texas appear to occur as isolated incidents. Broadscale prioritization models would allow for dam removals to be planned more strategically in terms of providing safety, ecological, and economic benefits and in terms of securing funding for these projects. There is an emerging body of research on dam removal prioritization (McKay et al. 2017), particularly at the regional and watershed scale (Kuby et al. 2005; Mader and Maier 2008; Martin and Apse 2011; Martin and Apse 2013; Benner et al. 2014; Hoenke et al. 2014; Martin 2018). Texas has an opportunity to develop regional or river basin-scale prioritization models based on maintaining important water resource infrastructure while removing hazardous dams and restoring stream habitat. Such models should be developed so that their results are easily interpretable and can act as decision support tools to help inform the complex decision making behind dam removal (McKay et al. 2017).

Developing such models requires a need for standardized and expanded datasets of dams and other instream barriers (McKay et al. 2017). State and federal datasets should be better coordinated so there is less discrepancy between the reported data. Additionally, there are a vast number of undocumented smaller dams in Texas (Chin et al. 2008), and efforts should be made to catalogue these dams to address both issues of liability and ecological restoration.

The utilitarian services provided by dams yield substantial benefits to society, most notably in Texas through flood control and water supply. Texas supports an immense dam infrastructure with plans to expand the number of major reservoirs, as evidenced by the continued recommendation of new dams in the Texas state water plan and the progression of at least a few of these projects. Although the analyses presented here focused only on dams that meet state regulatory criteria, a critical management question needs to be addressed regarding the persistence of the thousands of smaller undocumented dams that are no longer serving their original purpose and become hazardous as they age. The authors recommend a statewide inventory of the location, size, purpose, and condition of these undocumented structures. Many of these undocumented dams, along with many of the documented dams, may be good candidates for removal to help mitigate the hazard liability and ecological impacts of the abundant state-documented dams and future dam projects. Dam removal is a viable option for addressing human safety concerns and restoring rivers and should be given equal consideration when making decisions to repair dams and construct new dams.

NOTES

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REFERENCES

30-Year Normals. 2012–. Corvallis (Oregon): PRISM Climate Group. [Updated 2019; accessed 2014 April 5]. Available from: https://prism.oregonstate.edu/normals/.

[ARDRD] American Rivers Dam Removal Database. 1912–2019. Version 7. Washington (District of Colubia): American Rivers. [Updated 2020 Feb 12; accessed 2020 May 20]. Available from: https://figshare.com/articles/_/5234068.

[ASCE] American Society of Civil Engineers Texas Section. 2017. Report card for Texas' infrastructure. Austin (Texas): American Society of Civil Engineers Texas Section. 47 p. Available from: https://www.texasce.org/wp-content/uploads/2018/11/FullReport-TX_2017.pdf.

Ashley ST, Ashley WS. 2008. Flood fatalities in the United States. Journal of Applied Meteorology and Climatology. 47(3):805-818. Available from: https://doi.org/10.1175/2007JAMC1611.1.

Association of Dam Safety Officials. 2018. Dam ownership fact sheet. Topic: Earth dam failures. Lexington (Kentucky): Association of Dam Safety Officials. Available from: https://damsafety.s3.amazonaws.com/s3fs-public/files/Eart%20Dam%20Failure%20Fact%20Sheet%202018.pdf.

Bednarek AT. 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management. 27(6):803- . Available from: https://doi.org/10.1007/s002670010189.

Bellmore, JR, Duda JJ, Craig LS, Green SL, Torgersen CH, Collins MJ, Vittum K. 2017. Status and trends of the dam removal research in the United States. WIREs Water. 4(5): e1164. Available from: https://doi.org/10.1002/wat2.1164.

Benner R, Barnett A, Olivero A. 2014. North Carolina's freshwater resilience. Durham (North Carolina): The Nature Conservancy. 33 p. Available from: https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/Documents/ED_TNC_NC_FreshwaterResilience.pdf.

Black & Veatch. 2019. Dunlap spillgate hinge inspection report. Seguin (Texas) Guadalupe Blanco River Authority. 17 p. Black & Veatch project no. 400368. Available from: https://gvlakes.com/wp-content/uploads/2019/08/Dunlap-Spillgate-Hinge-Inspection-Report.pdf.

Brusuelas C. 2018 Aug 26. A history of Cape's Dam. San Marcos Daily Record. Available from: https://www.sanmarcosrecord.com/opinions/history-cape's-dam.

Buchele M. 2013a Oct 17. Aging dams, booming growth, and the search for solutions. StateImpact. Available from: https://stateimpact.npr.org/texas/2013/10/17/aging-dams-booming-growth-and-the-search-for-solutions/.

Buchele M. 2013b Oct 15. How hundreds of 'significant hazard' dams escape state inspection in Texas. StateImpact. Available from: https://stateimpact.npr.org/texas/2013/10/15/how-hundreds-of-significant-hazard-dams-escape-state-inspection/.

Buchele M. 2013c Oct 16. Want to learn about a nearby dam? In Texas, some questions are off limits. StateImpact. Available from: https://stateimpact.npr.org/texas/2013/10/16/want-to-learn-about-a-nearby-dam-in-texas-some-questions-are-off-limits/.

Burlakova LE, Karatayev AY, Froufe E, Bogan AE, Lopez-Lima M. 2018. A new freshwater bivalve species of the genus Cyclonaias from Texas (Unionidae: Ambleminae: Quadrulini). The Nautilus. 132(2):45-50. Available from: https://www.researchgate.net/profile/Manuel_Lopes-Lima/publication/326059009_A_new_freshwater_bivalve_species_of_the_genus_Cyclonaias_from_Texas_Unionidae_Ambleminae_Quadrulini/links/5b35e7664585150d23e09ced/A-new-freshwater-bivalve-species-of-the-genus-Cyclonaias-from-Texas-Unionidae-Ambleminae-Quadrulini.pdf.

Burlakova LE, Karatayev AY, Karatayev VA, May ME, Bennett DL, Cook MJ. 2011a. Biogeography and conservation of freshwater mussels (Bivalvia: Unionidae) in Texas: patterns of diversity and threats. Diversity and Distributions. 17(30): 393-407. Available from: https://doi.org/10.1111/j.1472-4642.2011.00753.x.

Burlakova LE, Karatayev AY, Karatayev VA, May ME, Bennett DL, Cook MJ. 2011b. Endemic species: Contribution to community uniqueness, effect of habitat alteration, and conservation priorities. Biological Conservation. 144(1):155-165. Available from: https://doi.org/10.1016/j.biocon.2010.08.010.

[CBS/AP] CBS and the Associated Press. 2020 May 21. Michigan dam failures force 10,000 to evacuate and could leave one city under 9 feet of water. CBS News. Available from: https://www.cbsnews.com/news/michigan-dam-failures-state-of-emergency-10000-evacuated-flooding/.

[CGIAR-CSI] CGIAR-CSI Global-Aridity and Global-PET Database. 2007–2019. Internet: CGIAR-CSI. [Updated 2008; accessed 2019 July 22]. Available from: https://cgiarcsi.community/data/global-aridity-and-pet-database/.

Chin A, Laurencio LR, Martinez AE. 2008. The hydrologic importance of small- and medium-sized dams: examples from Texas. The Professional Geographer 60(2):238-251. Available from: https://doi.org/10.1080/00330120701836261.

Clark BT. 2009. River restoration in the American West: assessing variation in the outcomes of policy change. Society & Natural Resources. 22(5):401-416. Available from: https://doi.org/10.1080/08941920801914528.

DamFailuresPIR9267. 1900–. Austin (Texas): Texas Commission on Environmental Quality. [Updated 2019; accessed 2020 Aug 19] Retrieved through Open Records Request: https://www.tceq.texas.gov/agency/data/records-services/reqinfo.html.

Dam Removals. 1983–. Austin (Texas): Texas Commission on Environmental Quality. [Updated 2015; accessed 2016 Aug 08]. Retrieved by email request from Warren D. Samuelson Manager, Dam Safety Section, TCEQ; warren.samuelson@tceq.texas.gov.

Dams.gdb. 1800–. Austin (Texas): Texas Commission on Environmental Quality. [Updated 2014; accessed 2014 Sep 05]. Retrieved through email request sent to Morgan Dean, Dam Safety Section, Critical Infrastructure Division, TCEQ; morgan.dean@tceq.texas.gov.

Dascher ED, Burlakova LE, Karatayev AY, Ford DF, Schwalb AN. 2018. Distribution of unionid freshwater mussels and host fishes in Texas: a study of broad-scale spatial patterns across basins and a strong climate gradient. Hydrobiologia. 80(1):315-331. Available from: https://doi.org/10.1007/s10750-017-3168-5.

Doyle MW, Stanley EH, Harbor JM. 2003. Channel adjustments following two dam removals in Wisconsin. Water Resources Research. 39(1):1-15. Available from: https://doi.org/10.1029/2002WR001714.

Doyle MW, Harbor JM, Stanley EH. 2003a. Toward policies and decision-making for dam removal. Environmental Management. 31(4):453-465. Available from: https://doi.org/10.1007/s00267-002-2819-z.

[DRIP] Dam Removal Information Portal. 2016–. Reston (Virginia): United States Geologic Survey. [Updated 2016; accessed 2020 May 20]. Available from: https://www.sciencebase.gov/drip/.

Duchemin M. 2009. Water, power, and tourism: Hover Dam and the making of the New West. 86(4):60-78. Available from: https://www-jstor-org.ezproxy.library.ewu.edu/stable/40495234.

Duda JJ, Wieferich DJ, Bristol RS, Bellmore JR, Hutchison VB, Vittum KM, Craig L, Warrick JA. 2016. Dam Removal Information Portal (DRIP)—a map-based resource linking scientific studies and associated geospatial information about dam removals. Reston (Virginia): United States Geological Survey. 23 p. Open-File Report 2016-1132. Available from: https://doi.org/10.3133/ofr20161132.

Elverum KA, Smalley T. 2012. The drowning machine. St. Paul (Minnesota): Minnesota Department of Natural Resources. 2 p. Available from: http://files.dnr.state.mn.us/education_safety/safety/boatwater/drowningmachine.pdf.

Erős T, Campbell Grant EH. 2015. Unifying research on the fragmentation of terrestrial and aquatic habitats: patches, connectivity and the matrix in riverscapes. Freshwater Biology. 60(8):1487-1501. Available from: https://doi.org/10.1111/fwb.12596.

Folger P, Cody BA, Carter NT. 2013. Drought in the United States: causes and issues for congress. Washington (District of Columbia): Congressional Research Service. 36 p. RL34580. Available from: https://fas.org/sgp/crs/misc/RL34580.pdf.

[FWS] Fish and Wildlife Service. 2018. Endangered and Threated Wildlife and Plants; Endangered Species Status for Texas Hornshell. Washington, District of Columbia: Department of the Interior; [Accessed 2019 Aug 10]. Available from: https://www.govinfo.gov/content/pkg/FR-2018-02-09/pdf/2018-02672.pdf.

[GBRA] Common Misconceptions. n.d. Seguin (Texas): Guadalupe Blanco River Authority. Available from: https://gvlakes.com/common-misconceptions/.

Getschow G. 2015 Dec 12. The dam called trouble. The Dallas Morning News. Available from: http://interactives.dallasnews.com/2015/lewisville-dam/#_ga=2.48353318.1459774468.1558914694-1934865605.1558914694.

Gilman S. 2016 Apr 11. This will be the biggest dam-removal project in history. National Geographic. Available from: http://news.nationalgeographic.com/2016/04/160411-klamath-glen-canyon-dam-removal-video-anniversary/.

Gosnell H, Kelly EC. 2010. Peace on the river? Social-ecological restoration and large dam removal in the Klamath Basin, USA. Water Alternatives. 3(2):361-383. Available from: http://www.water-alternatives.org/index.php/alldoc/articles/vol3/v3issue2/98-a3-2-21/file.

Gottgens J. 2009. Impact of the removal of the Secor Road Dam on the fish community structure and composition in the Ottawa River, Ohio. Toledo (Ohio): Toledo Metropolitan Area Council of Governments. 16 p. Final Report - Project 06(h) EPA 10. Available from: https://www.utoledo.edu/commissions/river/pdfs/secor%20dam%20removal%20report%20November%202009.pdf.

Grabowski ZJ, Chang H, Granek EL. 2018. Fracturing dams, fractured data: empirical trends and characteristics of existing and removed dams in the United States. River Research and Applications. 34(6):1-12. Available from: https://doi.org/10.1002/rra.3283.

Graf WL. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research. 35(4):1305-11. Available from: https://doi.org/10.1029/1999WR900016.

Graf WL. 2005. Geomorphology and American dams: The scientific, social, and economic context. Geomorphology 71(1–2):3-26. Available from: https://doi.org/10.1016/j.geomorph.2004.05.005.

Graf WL. 2006. Downstream hydrologic and geomorphic effects of large dams on American Rivers. Geomorphology 79(3–4):336-360. Available from: https://doi.org/10.1016/j.geomorph.2006.06.022.

Graf WL, Boland JJ, Dixon DA, Downs TC, Kraeuter JJ, Soscia ML, Wegner DL, Williams PB, Wingo CS, Zeizel EP. 2002. Dam removal: Science and decision making. Washington (District of Columbia): The H. John Heinz Center for Science, Economics and the Environment. 235 p. Available from: https://semspub.epa.gov/work/01/273439.pdf.

Grant GE, Lewis SL. 2015. The remains of the dam: What have we learned from 15 years of US dam removal? Engineering Geology for Society and Territory. 3:31-35. Available from: https://doi.org/10.1007/978-3-319-09054-2_7.

Green C. 2019 Apr 9. Uncertain future for Cape's Dam. The University Star. Available from: https://universitystar.com/28919/news/uncertain-future-for-capes-dam/.

Hardy TB, Raphelt N. 2015. Effects of changing height of Cape's Dam on recreation, Texas wild rice and fountain darter habitat in the San Marcos River, Texas. San Marcos (Texas): City of San Marcos. 36 p. Available from: http://www.sanmarcostx.gov/DocumentCenter/View/3237/Capes-Dam-Removal-Study-PDF.

H.B. 677, 83rd Legislature, 83rd Session (Texas 2013). Available from: https://capitol.texas.gov/BillLookup/History.aspx?LegSess=83R&Bill=HB677.

Henry T. 2013 Nov 5. How Prop 6 assed, and what's up next for water projects in Texas. StateImpact. Available from: https://stateimpact.npr.org/texas/2013/11/05/texas-water-fund-passes/.

Hershaw E. 2011 Dec 9. Dams are Coming Down, But Not in Texas. Reporting Texas. Available from: http://reportingtexas.com/dams-come-down-around-u-s-but-not-in-texas/.

Hoenke KM, Kumar M, Batt L. 2014. AGIS based approach for prioritizing dams for potential removal. 64:27-36. Available from: https://doi.org/10.1016/j.ecoleng.2013.12.009.

Holden E. 2020a May 20. Michigan: thousand evacuated after 'catastrophic' dam failures. The Guardian. Available from: https://www.theguardian.com/us-news/2020/may/20/michigan-dams-break-thousands-evacuated-floods.

Holden E. 2020b May 20. Michigan: threat of toxic contamination looks after dam failures trigger flooding. The Guardian. Available from: https://www.theguardian.com/us-news/2020/may/20/michigan-flooding-dam-toxic-contamination-threat.

Howells RG, Neck RW, Murray HD. 1996. Freshwater Mussels of Texas. Austin (Texas): Texas Parks and Wildlife Press. 224 p.

[ICOLD] International Commission on Large Dams. 2007. Dams & the world's water. International Commission on Large Dams. Available from: https://www.icold-cigb.org/GB/publications/others.asp.

Inoue K, Harris JL, Robertson CR, Johnson NA, Randklev CR. 2019. A comprehensive approach uncovers hidden diversity in freshwater mussels (Bivalvia: Unionidae) with the description of a novel species. Cladistics. 36(1):88-113. Available from: https://doi.org/10.1111/cla.12386.

Jager HI, Chandler JA, Lepla KB, Van Winkle W. 2001. A Theoretical Study of River Fragmentation by Dams and its Effects on White Sturgeon Populations. Environmental Biology of Fishes. 60: 347–361. Available from: https://doi-org.ezproxy.library.ewu.edu/10.1023/A:1011036127663.

Karatayev AY, Miller TD, Burlakova LE. 2012. Longterm changes in unionid assemblages in the Rio Grande, one of the World's top 10 rivers at risk. Aquatic Conservation: Marine Freshwater Ecosystems. 22(2):206-219. Available from: https://doi.org/10.1002/aqc.2226.

Karatayev AY, Burlakova LE, Miller TD, Perrelli MF. 2018. Reconstructing historical range and population size of an endangered mollusc: long-term decline of Popenaias popeii in the Rio Grande, Texas. Hydrobiologia. 2018:333-349. Available from: https://doi.org/10.1007/s10750-015-2551-3.

Keel J. 2008. An audit report on the Dam Safety Program at the Commission on Environmental Quality. Austin (Texas): Texas State Auditor's Office. 71 p. Report No. 08-032. Available from: https://www.sao.texas.gov/Reports/Main/08-032.pdf.

Kellar B. 2017. More than $670 million approved for Lower Bois d'Arc Reservoir. Herald Banner. Available from: https://www.ntmwd.com/670-million-approved-lower-bois-darc-reservoir/.

Kern EW, Hotchkiss RH, Ames DP. 2015. Introducing a low-head dam fatality database and internet information portal. Journal of the American Water Resources Association. 51(5):1453-1459. Available from: https://doi.org/10.1111/jawr.12289.

Kern EW. 2014. Public safety at low-head dams: fatality database and physical model of staggered deflector retrofit alternative [thesis]. [Provo (Utah)]: Brigham Young University. Available from: https://scholarsarchive.byu.edu/etd/3984/.

Kuby MJ, Fagan WF, ReVelle CS, Graf WL. 2005. A multiobjective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the Willamette basin. Advances in Water Resources. 28(8):845-855. Available from: https://doi.org/10.1016/j.advwatres.2004.12.015.

MacFarlane A. 2015 Dec 31. Goliath: The deadliest U.S. storm system of 2015. The Weather Channel. Available from: https://weather.com/news/news/goliath-deadliest-storm-of-2015.

Mader H, Maier C. 2008. A method for prioritizing the reestablishment of river continuity in Austrian rivers. Hydrobiologia. 609:277-288. Available from: https://doi.org/10.1007/s10750-008-9406-0.

Magilligan FJ, Graber BE, Nislow KH, Chipman JW, Sneddon CS, Fox CA. 2016. River restoration by dam removal: enhancing connectivity at watershed scales. Elementa: Science of the Anthropocene. 4: p.000108 Available from: http://doi.org/10.12952/journal.elementa.000108.

Major River Basins. 2014. Austin (Texas): Texas Water Development Board. [Updated 2014; accessed 2016 Nov 14]. Available from: http://www.twdb.texas.gov/mapping/gisdata.asp.

Marks M. 2013 Nov 26. If rains refill reservoirs, can Texas' dams hold up?. StateImpact. Available from: https://stateimpact.npr.org/texas/2013/11/26/if-rains-refill-reservoirs-can-texas-dams-hold-up/.

Martin EH. 2018. Assessing and prioritizing barriers to aquatic connectivity in the Eastern United States. Journal of the American Water Resources Association. 55(2):1-10. Available from: https://doi.org/10.1111/1752-1688.12694.

Martin EH, Apse CD. 2013. Chesapeake fish passage prioritization: an assessment of dams in the Chesapeake Bay watershed. Boston (Massachusetts): The Nature Conservancy, Eastern Division Conservation Science. 114 p. Available from: https://easternbrooktrout.org/resources/science-publications/chesapeake-fish-passage-prioritization-an-assessment-of-dams-in-the-chesapeake-bay-watershed.

Martin EH, Apse CD. 2011. Northeast aquatic connectivity: an assessment of dams on northeastern rivers. Brunswick (Maine): The Nature Conservancy, Easter Freshwater Program. 102 p. Available from: https://rcngrants.org/sites/default/files/final_reports/NEAquaticConnectivity_Report.pdf.

McCann MW. 2018. Dam failures in the U.S. Stanford (California): National Performance of Dams Program, Department of Civil and Environmental Engineering, Stanford University. 11 p. NPDP-01 V1. Available from: http://npdp.stanford.edu/sites/default/files/reports/npdp_dam_failure_summary_compilation_v1_2018.pdf.

McKay SK, Cooper AR, Diebel MW, Elkins D, Oldford G, Roghair C, Wieferich D. 2017. Informing watershed connectivity barrier prioritization decisions: a synthesis. River Research and Applications. 33(6):847-862. Available from: https://doi.org/10.1002/rra.3021.

Montagne M, Jobs J. 2016 Jan 22. Ottine Dam Removal Will Benefit Fish and Wildlife in San Marcos River. United States Fish and Wildlife Service Southwest Region. Available from: https://www.fws.gov/news/ShowNews.cfm?_ID=35953.

[NID] National Inventory of Dams. 2013–. Washinton (District of Columbia): United States Army Corps of Engineers. [Updated 2020 Jan; accessed 2020 Aug 06]. Available from: https://catalog.data.gov/dataset/national-inventory-of-dams.

[NHD] National Hydrography Dataset. 1999–. Version 2.3. Reston (Virginia): United States Geologic Survey. [Updated 2020; accessed 2017 May 10]. Available from: https://gdg.sc.egov.usda.gov/.

[NOAA] State of the climate: national climate report for December 2015. 2016. Asheville (North Carolina): NOAA National Centers for Environmental Information; [Accessed 2019 Nov 25]. Available from: https://www.ncdc.noaa.gov/sotc/national/201512.

[NWS] National Weather Service. 2000. Flash floods: where they occur. Silver Spring (Maryland): National Weather Service; [Accessed 2019 Aug 10]. Available from: https://www.floodsafety.com/media/pdfs/national/Flashfloodnational.pdf.

Perica S, Pavlovic S, St. Laurent M, Trypaluk C, Unruh D, Wilhite O. 2018. NOAA Atlas 14 precipitation-frequency atlas of the United States. Volume 11 Version 2.0: Texas. Silver Spring (Maryland): National Oceanic and Atmospheric Administration. p.283. Available from: https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume11.pdf.

Petts GE, Gurnell AM. 2005. Dams and geomorphology: research progress and future directions. Geomorphology. 71(1–2):27-47. Available from: https://doi.org/10.1016/j.geomorph.2004.02.015.

Poff L N, Hart DD. 2002. How Dams Vary and Why It Matters for the Emerging Science of Dam Removal. BioScience. 52(8):659-668. Available from: https://doi.org/10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2.

Randklev CR, Lundeen BJ, Howells RG, Kennedy RG. 2010. Habitat preference and first account of a living population of Texas Fawnsfoot, Truncilla macrodon (Bivalvia: Unionidae), in the Brazos River, Texas. The Southwestern Naturalist. 55(2):297-298. Available from: https://doi.org/10.1894/JS-31.1.

Randklev CR, Tsakiris ET, Johnson MS, Skorupski J, Burlakova LE, Groce J, Wilkins N. 2013a. Is False Spike, Quadrula mitchelli (Bivalvia: Unionidae), extinct? First account of a very-recently deceased individual in over thirty years. The Southwestern Naturalist. 58(2):268-273. Available from: https://doi.org/10.1894/0038-4909-58.2.247.

Randklev CR, Johnson MS, Tsakiris ET, Groce J, Wilkins N. 2013b. Status of the freshwater mussel (Unionidae) communities of the mainstem of the Leon River, Texas. Aquatic Conservation: Marine and Freshwater Ecosystems. 23(3):390-404. Available from: https://doi.org/10.1002/aqc.2340.

Reinhardt BH. 2011. Drowned Towns in the Cold War West: Small communities and federal water projects. Western Historical Quarterly. 42(2):149-172. Available from: https://doi.org/10.2307/westhistquar.42.2.0149.

Richter BD, Braun DP, Mendelson MA, Master LL. 1997. Threats to imperiled freshwater fauna. Conservation Biology. 11(5):1081-1093. Available from: https://doi.org/10.1046/j.1523-1739.1997.96236.x.

Reisner M. 1986. Cadillac Desert: The American West and its disappearing water. New York (New York): Viking. 582 p.

Rollins B. 2015 Sep 1. Future of Cape's Dam, Thompson's Island on San Marcos council agenda. San Marcos Mercury. Available from: http://smmercury.com/2015/09/01/future-of-capes-dam-thompsons-islands-on-san-marcos-council-agenda/.

Rubinstein C. 2015. Texas water policy appendix: the weather. Texas Water Journal. 6(1):121-135. Available from: https://journals.tdl.org/twj/index.php/twj/article/view/7033.

Sadasivam N. 2019 Apr 1. Dammed to fail. The Texas Observer. Available from: https://www.texasobserver.org/dammed-to-fail/.

Sansom A. 2008. Water in Texas: an introduction. Austin (Texas): University of Texas Press. 336 p.

[SARP] Southeast Aquatic Barrier Prioritization Tool. 2019. Southeast Aquatic Resource Partnership; [Accessed 2020 May 20]. Available from: https://connectivity.sarpdata.com/.

Scruggs B. 2019 Jun 3. USACE awards $39.1M contract for Lewisville Dam Safety Modification Project. Forth Worth (Texas): US Army Corps of Engineers Fort Worth District. Available from: https://www.swf.usace.army.mil/Media/News-Releases/Article/1864995/usace-awards-391m-contract-for-lewisville-dam-safety-modification-project/.

Sharif HO, Jackson TL, Hossain MM, Zane D. 2015. Analysis of flood fatalities in Texas. Natural Hazards Review. 16(1):0401416. Available from: https://doi.org/10.1061/(ASCE)NH.1527-6996.0000145.

Smith CH, Johnson NA, Inoue K, Doyle RD, Randklev CR. 2019. Integrative taxonomy reveals a new species of freshwater mussel, Potamilus streckersoni sp. nov. (Bivalvia: Unionidae): implications for conservation and management. Systematics and Biodiversity. 17(4):331-348. Available from: https://doi.org/10.1080/14772000.2019.1607615.

Souers Kober A. 2016 Apr 5. Could this be the world's biggest dam removal? American Rivers. Available from: https://www.americanrivers.org/2016/04/worlds-biggest-dam-removal/.

Stanley EH, Doyle MW. 2003. Trading off: the ecological effects of dam removal. Frontiers in Ecological Environments. 1(1):15-22. Available from: https://doi.org/10.1890/1540-9295(2003)001[0015:TOTEEO]2.0.CO;2.

[TCEQ] Texas Commission on Environmental Quality. 2006. Dam removal guidelines. Austin (Texas): Texas Commission on Environmental Quality. 6 p. GI-358. Available from: https://www.tceq.texas.gov/assets/public/comm_exec/pubs/gi/gi-358.pdf.

The Associated Press. 2015 May 30. U.S. storms, floods kill 29 people, 25 of them in Texas. Dow Jones Institutional News. Available from: https://search.proquest.com/docview/2066635428?rfr_id=info%3Axri%2Fsid%3Aprimo.

Thomas-Blate J. 2018 Feb 13. Dam good year for dam removals in 2017. American Rivers. Available from: https://www.americanrivers.org/2018/02/dam-removal-in-2017/.

Thorne B. 2016a Nov 17. San Marcos moves forward with Cape's Dam removal. Community Impact Newspaper. Available from: https://communityimpact.com/austin/san-marcos-buda-kyle/environment/2016/11/17/san-marcos-moves-forward-capes-dam-removal/.

Thorne B. 2016b Mar 16. San Marcos votes to remove Cape's Dam. Community Impact Newspaper. Available from: https://communityimpact.com/austin/city-county/2016/03/16/san-marcos-votes-remove-capes-dam/.

[TIGER] TIGER/Line Shapefile, 2016, nation, U.S., Current State and Equivalent National. 2015–2016. Suitland (Maryland): United States Census Bureau. [Updated 2016 May; accessed 2016 Apr 06]. Available from: http://www2.census.gov/geo/tiger/TIGER2016/STATE/tl_2016_us_state.zip.

Tschantz BA, Wright KR. 2011. Hidden dangers and public safety at low-head dams. ASDSO Journal of Dam Safety. 9(1):8-17. Available from: https://damsafety.org/sites/default/files/TschantzWright_PublicSftyLowDams_JDS2011_1.pdf.

[TWDB] Texas Water Development Board. 2012. Water for Texas 2012 State Water Plan. Austin (Texas): Texas Water Development Board. 314 p. Available from: https://www.twdb.texas.gov/waterplanning/swp/2012/index.asp.

[TWDB] Texas Water Development Board. 2017. Water for Texas 2017 State Water Plan. Austin (Texas): Texas Water Development Board. 150 p. Available from: https://www.twdb.texas.gov/waterplanning/swp/2017/index.asp.

[TWDB] TWDB Flood Programs. 2019. Austin (Texas): Texas Water Development Board; [Accessed 2019 Nov 25]. Available from: http://www.twdb.texas.gov/flood/index.asp.

[U.S. Census] American Community Survey 1-year estimates. 2018. Suitland (Maryland): United States Census Bureau; [Accessed 2020 Jun 15] Available from: http://censusreporter.org/profiles/31000US19100-dallas-fort-worth-arlington-tx-metro-area/.

[U.S. Census] Quick Facts Austin city, Texas. 2019. Suitland (Maryland): United States Census Bureau; [Accessed 2020 Jun 15]. Available from: https://www.census.gov/quickfacts/fact/table/austincitytexas/PST045219.

[USDM] United States Drought Monitor Tabular Data Archive. 2000–. [Updated 2000, accessed 2012 Sept 19]. Lincoln (Nebraska): The National Drought Mitigation Center. Available from: https://droughtmonitor.unl.edu/Data/DataTables.aspx.

[USGS] USGS Dam Removal Science Database. 2018–. Version 3. Reston (Virginia): United States Geological Survey. [Updated 2020 Jan 07, accessed 2020 Aug 08]. Available from: https://www.sciencebase.gov/catalog/item/5ace95e3e4b0e2c2dd1a688f.

[WCD] World Commission on Dams. 2000. Dams and development: a new framework for decision making. Sterling (Virginia): Earthscan Publications Ltd. Available from: https://pubs.iied.org/pdfs/9126IIED.pdf.

Warren D. 2015 Dec 27. At least 11 died in Texas storms that spawned tornadoes. Associated Press. Available from: https://web.archive.org/web/20160304070627/http://www.msn.com/en-us/news/us/tornadoes-sweep-through-dallas-area-significant-damage/ar-BBnRlgz?ocid=spartanntp.

Williams J. 2016. The untold story of the Lower Colorado River Authority. College Station (Texas): Texas A&M University Press. 320 p.

Winemiller K, Lujan NK, Wilkins RN, Snelgrove RT, Dube AM, Skow KL, Snelgrove AG. 2010. Status of freshwater mussels in Texas. College Station (Texas): Texas A&M Institute of Renewable Natural Resources. Available from: https://nri.tamu.edu/media/1109/status_of_freshwater_mussels_in_texas_tamu-irnr_05-2010_1.pdf.

Wofford JE, Gresswell RE, Banks MA. 2005. Influence of barriers to movement on within watershed genetic variation of coastal cutthroat trout. Ecological Applications. 15(2):628-637. Available from: https://doi.org/10.1890/04-0095.

Wright KR, Earles TA, Kelly JM. 1995. Public safety at low-head dams. Denver (Colorado): Wright Water Engineers, Inc. Available from: http://www.wrightwater.com/assets/25-public-safety-at-low-head-dams.pdf .

Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV. 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystems & Environment. 126:67-80. Available from: https://doi.org/10.1016/j.agee.2008.01.014.

Zomer RJ, Bossio DA, Trabucco A, Yuanjie L, Gupta DC, V.P. Singh VP. 2007. Trees and water: smallholder agroforestry on irrigated lands in northern India. Colombo (Sri Lanka): International Water Management Institute. 50 p. Research Report 122. Available from: https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB122/RR122.pdf.

APPENDIXES

CONTENTS

Table A1. Texas dam owner crosswalk. For instances where there are two or more owner organizations for a single dam, if the owner organizations are dissimilar these were included in the "Other" aggregation group.

Original owner organization	Aggregation group
City government	Other government
Corporation	Private
County government	Other government
Federal government	Federal government
Individual owner type	Private
Local government	Other government
Organization	Private
Other	Other
Other government	Other government
Partnership	Other
Sole proprietorship	Other
State government	State government
Trust	Other
Multiple owners - dissimilar	Other
<<null>>	Not listed

Table A2. Number of dams and total reservoirs storage sorted by size classification

	Number of dams	% Dams	Total reservoir storage (million acre-feet)	% Total storage
***Texas (2005)**	**7053**		**94.20**	
Small	1368	19.4	0.090	0.1
Medium	5446	77.2	5.60	5.9
Large	212	3.0	29.6	31.4
Very large	27	0.4	58.9	62.5
Texas (2014)	**7274**		**104.30**	
Small	1452	20	0.111	0.1
Medium	5586	76.8	6.92	5.4
Large	207	2.8	32.3	25.1
Very large	29	0.4	89.3	69.4
Trinity	**1787**		**17.00**	
Small	323	1.8	0.02	0.1
Medium	1426	79.8	1.62	7.7
Large	33	1.8	7.90	37.7
Very large	5	0.3	114	54.5
Brazos	**1391**		**14.80**	
Small	267	19.2	0.02	0.1
Medium	1072	77.1	1.1	7.4
Large	47	3.4	6.30	42.6
Very large	5	0.4	7.40	50.0
Colorado	**776**		**12.20**	
Small	144	18.6	0.008	0.1
Medium	600	77.3	0.9	7.4
Large	27	3.5	3.60	29.5
Very large	5	0.6	7.70	63.1
Red	**619**		**12.50**	
Small	147	23.7	0.01	0.1
Medium	449	72.5	0.40	3.2
Large	21	3.4	2.40	19.2
Very large	2	0.3	9.7	77.6
Nueces	**456**		**1.80**	
Small	87	19.1	0.01	0.3
Medium	364	79.8	0.20	11.1
Large	4	0.9	0.60	33.3
Very large	1	0.2	1.10	61.1

	Number of dams	% Dams	Total reservoir storage (million acre-feet)	% Total storage
Sabine	**335**		**8.80**	
Small	82	24.5	0.005	0.1
Medium	241	71.9	0.20	2.3
Large	9	2.7	0.60	6.8
Very large	3	0.9	8.00	90.9
Rio Grande	**329**		**10.90**	
Small	49	14.9	0.003	0.03
Medium	266	80.9	0.40	3.67
Large	12	3.6	0.70	6.42
Very large	2	0.6	9.70	88.99
Neches	**308**		**8.60**	
Small	67	21.7	0.004	0.05
Medium	229	74.4	0.20	2.3
Large	10	3.3	0.90	10.5
Very large	2	0.6	7.60	88.4
Guadalupe	**215**		**1.60**	
Small	56	26	0.003	0.2
Medium	152	70.7	0.20	12.5
Large	6	2.8	0.20	12.5
Very large	1	0.5	1.100	68.8
San Antonio	**160**		**0.70**	
Small	30	18.8	0.002	0.3
Medium	125	78.1	0.20	28.6
Large	5	3.1	0.50	71.4
Very large	0	0	0	0.0

*Note: Values for Texas (2005) are from Chin et al. 2008.
The total resevoir storages was converted from cubic meters reported in Chin at el. 2008, Tabel 3, p.245.

Table A3. Number of dams per time period sorted by size classification.

	1800–1899		1900–1939		1940–1959		1960–1979		1980–2014	
	N	%	N	%	N	%	N	%	N	%
Texas										
Small	146	50.0	63	12.2	180	13.0	774	18.6	219	26.9
Medium	143	49.9	415	80.1	1134	82.1	3296	79.3	556	68.4
Large	3	0.1	37	7.1	59	4.3	72	1.7	34	4.2
Very large	0	0.0	3	0.6	9	0.7	12	0.3	5	0.6
Total	292	100.0	518	100.0	1382	100.0	4154	100.0	814	100.1
Trinity										
Small	35	60.3	9	13.0	25	6.8	177	16.4	63	33.9
Medium	22	37.9	52	75.4	332	90.2	893	82.7	115	61.8
Large	1	1.7	8	11.6	10	2.7	8	0.7	6	3.2
Very large	0	0.0	0	0.0	1	0.3	2	0.2	2	1.1
Total	58	100.0	69	100.0	368	100.0	1080	100.0	186	100.0
Brazos										
Small	24	47.1	8	8.2	28	13.1	168	20.2	31	16.9
Medium	27	52.9	81	82.7	172	80.4	644	77.3	145	79.2
Large	0	0.0	9	9.2	11	5.1	19	2.3	7	3.8
Very large	0	0.0	0	0.0	3	1.4	2	0.2	0	0.0
Total	51	100.0	98	100.0	214	100.0	833	100.0	183	100.0
Colorado										
Small	16	57.1	11	18.0	13	9.2	71	15.3	19	29.2
Medium	12	42.9	45	73.8	116	82.3	383	82.7	40	61.5
Large	0	0.0	3	4.9	11	7.8	8	1.7	5	7.7
Very large	0	0.0	2	3.3	1	0.7	1	0.2	1	1.5
Total	28	100.0	61	100.0	141	100.0	463	100.0	65	100.0
Red										
Small	4	66.7	6	11.5	17	21.8	100	24.8	19	24.7
Medium	2	33.3	38	73.1	57	73.1	293	72.7	57	74.0
Large	0	0.0	7	13.5	3	3.8	10	2.5	1	1.3
Very large	0	0.0	1	1.9	1	1.3	0	0.0	0	0.0
Total	6	100.0	52	100.0	78	100.0	403	100.0	77	100.0
Nueces										
Small	4	23.5	2	9.5	19	21.4	51	16.7	1	8.3
Medium	13	76.5	19	90.5	67	75.3	255	83.3	9	75.0
Large	0	0.0	0	0.0	3	3.3	0	0.0	1	8.3
Very large	0	0.0	0	0.0	0	0.0	0	0.0	1	8.3
Total	17	100.0	21	100.0	89	100.0	306	100.0	12	100.0

	1800–1899		1900–1939		1940–1959		1960–1979		1980–2014	
	N	%	N	%	N	%	N	%	N	%
Sabine										
Small	8	50.0	5	11.1	29	29.3	18	15.0	13	36.1
Medium	8	50.0	40	88.9	67	67.7	95	79.2	21	58.3
Large	0	0.0	0	0.0	3	3.0	5	4.2	1	2.8
Very large	0	0.0	0	0.0	0	0.0	2	1.7	1	2.8
Total	16	100.0	45	100.0	99	100.0	120	100.0	36	100.0
Rio Grande										
Small	14	46.7	3	7.9	4	7.5	22	13.2	5	12.5
Medium	16	53.3	33	86.8	44	83.0	141	84.4	32	80.0
Large	0	0.0	2	5.3	4	7.5	3	1.8	3	7.5
Very large	0	0.0	0	0.0	1	1.9	1	0.6	0	0.0
Total	30	100.0	38	100.0	53	100.0	167	100.0	40	100.0
Neches										
Small	12	60.0	6	14.0	12	13.3	24	7.8	12	35.3
Medium	8	40.0	37	86.0	74	82.2	84	27.5	21	61.8
Large	0	0.0	0	0.0	4	4.4	5	1.6	1	2.9
Very large	0	0.0	0	0.0	0	0.0	2	0.7	0	0.0
Total	20	100.0	43	100.0	90	100.0	306	100.0	34	100.0
Guadelupe										
Small	12	57.0	3	23.1	6	28.6	23	17.7	7	29.2
Medium	9	43.0	7	53.8	15	71.4	106	81.5	14	58.3
Large	0	0.0	3	23.1	0	0.0	0	0.0	3	12.5
Very large	0	0.0	0	0.0	0	0.0	1	0.8	0	0.0
Total	21	100.0	13	100.0	21	100.0	130	100.0	24	100.0
San Antonio										
Small	9	81.8	2	25.0	4	10.8	11	13.9	3	13.6
Medium	2	18.2	4	50.0	33	89.2	65	82.3	19	86.4
Large	0	0.0	2	25.0	0	0.0	3	3.8	0	0.0
Very large	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total	11	100.0	8	100.0	37	100.0	79	100.0	22	100.0

*Note: Dams with out year compelte were ommitted.

Table A4. Number of dams in each size classification sorted by ownership.

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
Texas										
Federal	22	1.5	49	0.9	26	12.3	16	55.2	113	1.6
State	9	0.6	49	0.9	9	4.3	2	6.9	65	0.9
Other government	185	12.7	2039	36.5	125	59.2	10	34.5	2359	32.4
Private	1146	78.9	3072	55.0	44	20.9	1	3.4	4263	58.6
Other	45	3.1	347	6.2	7	3.3	0	0.0	399	5.5
Not listed	45	3.1	30	0.5	0	0.0	0	0.0	75	1.0
Trinity										
Federal	1	0.3	2	0.1	7	21.2	2	40.0	12	0.7
State	1	0.3	25	1.8	3	9.1	2	40.0	31	1.7
Other government	82	25.4	872	61.2	15	45.5	1	20.0	970	54.3
Private	221	68.4	420	29.5	7	21.2	0	0.0	648	36.3
Other	12	3.7	99	6.9	1	3.0	0	0.0	112	6.3
Not listed	6	1.9	8	0.6	0	0.0	0	0.0	14	0.8
Brazos										
Federal	16	6.0	25	2.3	5	10.6	4	80.0	50	3.6
State	2	0.7	7	0.7	1	2.1	0	0.0	10	0.7
Other government	24	9.0	329	30.7	28	59.6	1	20.0	382	27.5
Private	212	79.4	636	59.3	10	21.3	0	0.0	858	61.7
Other	6	2.2	72	6.7	3	6.4	0	0.0	81	5.8
Not listed	7	2.6	3	0.3	0	0.0	0	0.0	10	0.7
Colorado										
Federal	3	2.1	2	0.3	2	7.4	1	20.0	8	1.0
State	0	0.0	3	0.5	0	0.0	0	0.0	3	0.4
Other government	28	19.4	384	64.0	23	85.2	3	60.0	438	56.4
Private	101	70.1	201	33.5	2	7.4	1	20.0	305	39.3
Other	8	5.6	10	1.7	0	0.0	0	0.0	18	2.3
Not listed	4	2.8	0	0.0	0	0.0	0	0.0	4	0.5
Red										
Federal	1	0.7	5	1.1	4	19.0	1	50.0	11	1.8
State	2	1.4	5	1.1	0	0.0	0	0.0	7	1.1
Other government	4	2.7	126	28.1	12	57.1	1	50.0	143	23.1
Private	127	86.4	250	55.7	4	19.0	0	0.0	381	61.6
Other	12	8.2	62	13.8	1	4.8	0	0.0	75	12.1
Not listed	1	0.7	1	0.2	0	0.0	0	0.0	2	0.3

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
Nueces										
Federal	0	0.0	1	0.3	0	0.0	1	100.0	2	0.4
State	2	2.6	0	0.0	0	0.0	0	0.0	2	0.4
Other government	2	2.6	15	4.1	3	100.0	0	0.0	20	4.4
Private	73	93.6	343	94.2	1	0.0	0	0.0	417	91.4
Other	1	1.3	4	1.1	0	0.0	0	0.0	5	1.1
Not listed	9	11.5	1	0.3	0	0.0	0	0.0	10	2.2
Sabine										
Federal	0	0.0	1	0.4	0	0.0	0	0.0	1	0.3
State	0	0.0	1	0.4	0	0.0	0	0.0	1	0.3
Other government	3	3.7	17	7.1	5	55.6	3	100.0	28	8.4
Private	73	89.0	188	78.0	4	44.4	0	0.0	265	79.1
Other	1	1.2	30	12.4	0	0.0	0	0.0	31	9.3
Not listed	5	6.1	4	1.7	0	0.0	0	0.0	9	2.7
Rio Grande										
Federal	1	2.0	2	0.8	2	16.7	2	100.0	7	2.1
State	0	0.0	3	1.1	0	0.0	0	0.0	3	0.9
Other government	12	24.5	74	27.8	7	58.3	0	0.0	93	28.3
Private	36	73.5	180	67.7	2	16.7	0	0.0	218	66.3
Other	0	0.0	7	2.6	1	8.3	0	0.0	8	2.4
Not listed	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Neches										
Federal	0	0.0	2	0.9	1	10.0	1	50.0	4	1.0
State	0	0.0	3	1.3	0	0.0	0	0.0	3	1.0
Other government	3	4.5	32	14.0	9	90.0	1	50.0	45	14.7
Private	60	89.6	190	83.0	0	0.0	0	0.0	250	81.4
Other	1	1.5	2	0.9	0	0.0	0	0.0	3	1.0
Not listed	3	4.5	0	0.0	0	0.0	0	0.0	3	1.0
Guadalupe										
Federal	0	0.0	0	0.0	0	0.0	1	100.0	1	0.5
State	2	3.6	1	2.6	0	0.0	0	0.0	3	1.4
Other government	11	19.6	44	27.0	6	100.0	0	0.0	61	28.4
Private	39	69.6	81	53.3	0	0.0	0	0.0	120	55.8
Other	1	1.8	26	17.1	0	0.0	0	0.0	27	12.6
Not listed	3	5.4	0	0.0	0	0.0	0	0.0	3	1.4

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
San Antonio										
Federal	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
State	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Other government	2	6.7	45	36.0	5	100.0	0	0.0	52	32.5
Private	25	83.3	59	47.2	0	0.0	0	0.0	84	52.5
Other	0	0.0	21	16.8	0	0.0	0	0.0	21	13.1
Not listed	3	10.0	0	0.0	0	0.0	0	0.0	3	1.9

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Commentary: Fact vs. Fiction on Rio Grande Deliveries

The Honorable Jayne Harkins, P.E.[1]

Editor-in-Chief's Note: The Texas Water Journal invited The Honorable Jayne Harkins, P.E., U.S. Commissioner for the International Boundary and Water Commission to share her thoughts on water deliveries from Mexico to the Rio Grande. The opinion expressed in the resulting commentary is the opinion of Commissioner Harkins and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

[1] Jayne Harkins, P.E., U.S. Commissioner of the International Boundary and Water Commission, United States and Mexico.
Commissioner Harkins was appointed by President Donald Trump in 2018. As commissioner, she serves as head of the U.S. Section of the Commission, overseeing personnel in twelve offices along the U.S.-Mexico border and in Washington, DC. The Commission is responsible for applying the boundary and water treaties between the two countries.

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FACT VS. FICTION ON RIO GRANDE DELIVERIES

By The Honorable Jayne Harkins, P.E., U.S. Commissioner of the International Boundary and Water Commission, United States and Mexico

The Rio Grande water deliveries are front and center in the news these days and are certainly one of the priorities of the United States Section of the International Boundary and Water Commission (USIBWC). Learning the Rio Grande operations, and the various treaties and portions of treaties have been an interesting task. I'm taking this opportunity to share what I have learned through this process.

There are two water delivery treaties covering the shared resources between the United States and Mexico: the Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (hereinafter 1944 Water Treaty), which provides deliveries on the Colorado River and the lower Rio Grande, and the Convention between the United States and Mexico Equitable Distribution of the Waters of the Rio Grande, signed May 21, 1906 (hereinafter Convention of 1906), which provides water deliveries on the upper Rio Grande to Ciudad Juarez, Chihuahua.

I have heard that Mexico currently has a "debt" to the United States. As of September 12, Mexico is required to deliver 294,703 acre-feet (363.6 million cubic meters [mcm]) of water by October 24, 2020, which is the end of the five-year cycle. Only after October 24 will Mexico be in debt, with any remainder that has not been delivered to the Rio Grande on behalf of the United States. Mexico has repeatedly stated its intent to meet the deadline.

I have heard this is the largest amount of water ever owed by Mexico on the Rio Grande. It is a large amount of water to move in the last few weeks of the cycle. However, even if Mexico made no deliveries between now and the October 24 end of the cycle, it would be far from the largest amount of debt Mexico has owed at the end of a cycle. The 1992–1997 cycle ended with a debt of 1,024,000 acre-feet (1263 mcm). By the end of the next cycle, it had grown to over 1.3 million acre-feet (1603 mcm).

I have heard from Mexican stakeholders that Mexico can end this cycle in a debt because they paid off the debt of the last cycle in 2016. The USIBWC's view of the 1944 Water Treaty is that if a cycle ended in a debt, it ended in a debt. Period. More importantly, according to other USIBWC agreements that expand on the 1944 Water Treaty, Mexico cannot end two consecutive cycles in a debt. Mexican federal authorities understand this, but some Mexican state and local officials may not.

I have heard it will take a hurricane to wipe out the amount owed between now and October 24. Nope. Not true. Median precipitation will provide runoff into the Rio Grande and would help significantly towards providing water from the Conchos River and other tributaries. Precipitation has been trending dry

HECHOS VS FICCIÓN EN EL TEMA DE LAS ENTREGAS DEL RÍO BRAVO

Por La Honorable Jayne Harkins, P.E., Comisionada de los Estados Unidos de la Comisión Internacional de Límites y Aguas entre Estados Unidos y México

Las entregas de agua de Río Grande están al frente de las noticias en estos días y son sin duda una de las prioridades de la Sección de los Estados Unidos de la Comisión Internacional de Límites y Aguas (USIBWC). Aprender sobre las operaciones del Río Bravo, y los diversos tratados y partes de los tratados ha sido una tarea interesante. Aprovecho esta oportunidad para compartir lo que he aprendido a través de este proceso.

Existen dos tratados sobre el suministro de agua que regulan los recursos compartidos entre los Estados Unidos y México: el Tratado para la Utilización de las Aguas de los Ríos Colorado y Tijuana y del Río Bravo/Grande (en adelante, el Tratado del Aguas de 1944),que regula las entregas en el río Colorado y el bajo Río Bravo, y la Convención entre los Estados Unidos y México sobre la Distribución Equitativa de las Aguas del Río Bravo/Grande, firmada el 21 de mayo de1906 (en adelante Convención de 1906),que regula las entregas de agua en el alto Río Bravo a Ciudad Juárez, Chihuahua.

He oído que México tiene actualmente una "deuda" con los Estados Unidos. Hasta el 12 de septiembre, México está obligado a entregar 294,703 acres-pies (363.6 millones de metros cúbicos [mcm]) de agua para el 24 de octubre de 2020, que es el final del ciclo de cinco años. Sólo después del 24 de octubre México se consideraría endeudado con cualquier remanente que no haya sido entregado al Río Bravo a nombre de los Estados Unidos. México ha manifestado repetidamente su intención de cumplir con el plazo.

He escuchado que esta es la mayor cantidad de agua jamás adeudada por México en el Río Bravo. Es una gran cantidad de agua para moverse en las últimas semanas del ciclo. Sin embargo, incluso si México no hiciera entregas entre ahora y el 24 de octubre al final del ciclo, estaría lejos de ser la mayor deuda de agua que México haya debido al final de un ciclo. El ciclo 1992-1997 terminó con una deuda de 1.024.000 acres-pies (1263 mcm). Al final del siguiente ciclo, había crecido a más de 1,3 millones de acres-pies (1603 mcm).

He oído de las partes interesadas mexicanas que México puede terminar este ciclo en una deuda porque pagaron la deuda del último ciclo en 2016. La opinión del USIBWC sobre el Tratado del Aguas de 1944 es que, si un ciclo termina en deuda, termina en deuda. Punto. Más importante aún, de acuerdo con otros acuerdos del USIBWC que se extienden al Tratado de Aguas de 1944, México no puede terminar dos ciclos consecutivos en una deuda. Las autoridades federales mexicanas lo entienden, pero algunos funcionarios estatales y locales mexicanos pueden no hacerlo.

over the Conchos River Basin and other tributaries in Mexico, but September brought significant rain for several days.

Mexico has made the offer to allow the U.S. users to take San Juan River water. There are several claims I have had to research in learning about this source of water. The first is that the water provided to the United States will just flow to the Gulf of Mexico, and Mexico will get credit. This is not true. In the past, when the United States has agreed to take San Juan River water, the only water credited to Mexico's delivery was the amount of water the United States could take and beneficially use. It takes a bit more work on the accounting side, but it can be done.

The second item I have heard is that the San Juan River water is of poor quality. I have heard this for a year and have repeatedly asked for the data that shows it is of bad quality. The USIBWC data that was put together for the 2015 event, the last time the United States accepted San Juan River water as a delivery from Mexico, shows it was of good quality. I recognize that each flow event and release of water may be different, and the 2015 event may not be the same as any other event. For me, the main concern about San Juan River water is not unproven claims about poor water quality, but the challenge of storing water downstream of the major international dams.

I have heard that Mexico isn't trying hard enough to release water from their interior reservoirs. Mexico has attempted to make dam releases since December of last year. They have not been able to execute their plans due to opposition and civil unrest within their country. Mexico deployed its National Guard to protect the federal workers and the dam infrastructure from the protesters. This has resulted in the protestors taking over a major interior reservoir in Chihuahua, Mexico and the death of a protester. At this point, Mexico cannot make deliveries to their own irrigators to finish off Chihuahua's irrigation season. In this cycle, Mexico has consistently stated its intention to end the cycle without a debt and has made great efforts to do so.

I know there are no explicit consequences written into the 1944 Water Treaty or other international agreements between the United States and Mexico if Mexico ends the cycle in debt, but the United States is exerting strong diplomatic pressure on Mexico to avoid it doing so.

I also know that hoping for a hurricane is a poor water management strategy for a river basin. More to come.

Pray for rain. Stay safe.

He escuchado que se necesitaría un huracán para eliminar la cantidad adeudada entre ahora y el 24 de octubre. No. No es verdad. La precipitación media proporcionará escorrentía en el Río Bravo y ayudaría significativamente a proporcionar agua del río Conchos y otros afluentes. La precipitación ha estado con tendencia seca sobre la cuenca del río Conchos y otros afluentes en México, pero septiembre trajo lluvia significativa durante varios días.

México ha hecho la oferta de permitir que los usuarios estadounidenses tomen agua del río San Juan. Existen varias afirmaciones que he tenido que investigar para entender esta fuente alternativa de agua. La primera afirmación es que el agua proporcionada a los Estados Unidos simplemente fluiría hacia el Golfo de México, y México obtendría crédito. Esto no es cierto. En el pasado, cuando los Estados Unidos aceptaron tomar agua del río San Juan, la única agua acreditada a la entrega de México era la cantidad de agua que los Estados Unidos podían tomar y usar productivamente. Se necesita un poco más de trabajo en el lado de la contabilidad, pero se puede hacer.

La segunda afirmación es que el agua del río San Juan es de mala calidad. He escuchado esto durante un año y he pedido repetidamente los datos que demuestren que es de mala calidad. Los datos de USIBWC que se reunieron para el evento de 2015, la última vez que los Estados Unidos aceptaron el agua del río San Juan como entrega desde México, muestran que fue de buena calidad. Reconozco que cada evento de flujo y liberación de agua puede ser diferente, y el evento de 2015 puede no ser el mismo que cualquier otro evento. Para mí, la principal preocupación por el agua del río San Juan no son las afirmaciones no probadas sobre la mala calidad del agua, sino el desafío que representa su almacenamiento aguas abajo de las principales presas internacionales.

He oído que México no se esfuerza lo suficiente para liberar agua de sus embalses interiores. México ha intentado hacer liberaciones de agua de las presas desde diciembre del año pasado. No han podido ejecutar sus planes debido a la oposición y a los disturbios civiles dentro de su país. México desplegó su Guardia Nacional para proteger a los trabajadores federales y la infraestructura de las presas de los manifestantes. Esto ha dado lugar a que los manifestantes se apoderen de un importante embalse al interior de Chihuahua, México y la muerte de un manifestante. Al día de hoy, México no puede hacer entregas de agua a sus propios agricultores para terminar la temporada de riego de Chihuahua. En este ciclo, México ha declarado constantemente su intención de terminar el ciclo sin deudas y ha hecho grandes esfuerzos para hacerlo.

Sé que no hay consecuencias explícitas escritas en el Tratado del Agua de 1944 u otros acuerdos internacionales entre los Estados Unidos y México en el caso de que México terminara el ciclo con endeudamiento, pero Estados Unidos está ejerciendo una fuerte presión diplomática sobre México para evitarlo.

También sé que la esperanza de un huracán es una estrategia de manejo deficiente del agua para una cuenca fluvial. Más por venir.

A rezar por la lluvia. Cuídense.

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Internet of Texas Water: Use Cases for Flood, Drought, and Surface Water–Groundwater Interactions

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Abstract: Experts representative of Texas' water sectors identified critical water data needs and described the design of a comprehensive open access data system that facilitates use of public water data in Texas at the April 2018 Connecting Texas Water Data Workshop as reported in the *Texas Water Journal.* Participants described potential use cases to initiate work on the most critical data hubs for connecting Texas water data. This note is an update to work on the Internet of Texas Water Data initiative that describes progress on a flood dashboard by the Texas Water Development Board and development of use cases by workgroups of stakeholders with expertise in water data for drought and for surface water–groundwater interactions.

Keywords: public water data, Texas water, internet of water, water management use case, water data management

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Terms used in paper

Acronym/Initialism	Descriptive Name
FAIR	Findable, Accessible, Interoperable, and Reusable
NASA	National Aeronautics and Space Administration
NRCS	Natural Resources Conservation Service
SCAN	Soil Climate Analysis Network
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
USDA	United States Department of Agriculture
USGS	United States Geological Survey

INTRODUCTION

The April 2018 Connecting Texas Water Data Workshop reported in the Texas Water Journal by Rosen et al. (2019) brought together experts representative of Texas' water sectors to engage in the identification of critical water data needs and discuss the design of a comprehensive, open access data system that facilitates the use of public water data in Texas. Workshop participants identified topics for use cases,[5] including data gaps, needs, and uses for water data in each scenario. They also answered questions on who needs data, what data they need, in what form they need the data, and the purposes for which data are most needed. Comprehensive information about the workshop and a full description of the purpose, development, and use of use cases as well as examples of their application can be found in Rosen and Roberts (2018). Review of the synthesis document by Rosen et al. (2019) will help the reader understand the general basis for the current work described in this update. However, for a full understanding of the expert stakeholder recommendations and recommendations for future work please refer to the full report by Rosen and Roberts (2018) covering the 2018 workshop. That workshop brought together 90 invited experts representative of Texas' government and water agencies, utilities, academia, businesses, industries, research institutes, water associations, and advocacy organizations. The recommendations of those stakeholders included having next steps guided by a small advisory group, with work on use cases conducted by small groups of water data experts relevant to each use case as it is formed. The full report further defines the goals of a Texas water data initiative or data hub(s), develops a model for the structure of data hubs, characterizes several use cases, and supports the development of the use cases to demonstrate the value of connected public water data for improved decision making (Rosen and Roberts 2018).

This program review summarizes the results of work by data experts meeting as advisory and use-case-specific work groups to define the goals of a Texas internet of water data initiative and to characterizes its first use cases. A full description of this work can be found in Rosen and Mace (2019), which should be referred to for comprehensive details.

[5] A use case is a short summary organizing, in a concise and consistent format, the data gaps, needs, uses, users, regulatory requirements, and workflow for a particular objective. Use cases serve as a tool for organizing and assessing stakeholder data needs and for communicating those needs to decision makers. Use cases are presented in Tables 1 and 2.

WATER DATA INITIATIVE ADVISORY COMMITTEE RECOMMENDATIONS

A Water Data Initiative Advisory Committee (hereafter referred to as Committee) was formed and selected three topics to focus on as use cases for beginning work on a Texas water data initiative: (1) flood data, (2) drought data, and (3) surface water–groundwater interactions. Members agreed that each use case should exhibit seven attributes: (1) be valuable, (2) involve known users, (3) be achievable, (4) be scalable/replicable, (5) be non-controversial,[6] (6) provide an opportunity for quick implementation, and (7) result in a viable product for users.[7] For greater detail on the process for use case selection and actions leading up to use case development workshops, please refer to the full report by Rosen and Mace (2019).

Flood data dashboard use case

The Texas Water Development Board (TWDB) received funding from the 86th Texas Legislature in 2019 to develop a water data hub with a flood data dashboard as the first area of focus. The Committee intends to provide comments or suggested guidance as appropriate to the TWDB as the water data hub project progresses. The TWDB's work on the flood dashboard reported herein describes initial and important steps forward for Texas to make important water data more accessible and usable.

Goals under consideration for the flood dashboard and water data hub include aggregating information housed across multiple platforms; providing access to data using an index with data sets identified by multiple factors, including frequency of use and key words; generating an index of authoritative, named data sources; and enabling output of data layers and statistics through a viewer that is customizable by the user.

Initial ideas discussed for design of the flood dashboard and water data hub include collaborating with holders of critical water data sets to coordinate efforts and providing users with the ability to link to data resources and viewers maintained by others. Committee members generally suggested data hub designers consider means to support uninterrupted access to all data hub services and use cloud infrastructure to ensure scalability over time to reduce the need for local servers and better ensure the continuation of service during heavy use.

Drought data dashboard use case

The Committee agreed that a drought data dashboard will be of great value to decision makers. The dashboard should be a forward-looking tool designed to use relevant public, accessible, and usable data (i.e., already collected). The Committee advised that the utility of a dashboard will be increased by identifying existing data sets lacking interoperability and making them usable and accessible and identifying, collecting, and adding relevant new data sets over time. The Committee formed a subcommittee of subject matter experts to initiate work on a use case for a drought data dashboard.

The use case developed by the subcommittee describes a collaborative effort between the TWDB and the Committee (Table 1). The use case details sharing resources, providing expertise, and— where feasible—supporting the TWDB in the design and development of a drought dashboard.

The Committee, as informed by the drought use case, will seek to provide support to the TWDB by delivering expert input and advice and by soliciting stakeholder input on the drought data dashboard design, development, and use through surveys and hands-on testing.

Surface water–groundwater interaction use case

The Committee believes that a system offering access to surface water–groundwater interaction data will provide information of great overall value to decision makers, including regional water planning groups, groundwater conservation districts, and elected officials. The Committee also recognizes that interaction data may be more difficult to assemble than flood and drought data, because far fewer interaction data sets exist (Table 2), and they may be difficult to locate, with some data residing in non-digital formats that must be converted to make them accessible. Despite these limitations, Committee members believe the assembly of these data to be critically important for use by Texas water managers. The Committee formed a subcommittee of subject matter experts to initiate work on a use case for surface water–groundwater interactions.

The Committee received the recommendations of the subcommittee and agreed to a use case that focused on adding available data sets to a data repository with a strong search function (Table 2). The interaction data repository is envisioned as evolving over time into a more robust data dashboard as interaction data sets are compiled and added, and as user needs become better defined.

[6] What is controversial also may vary by region and user (stakeholder group). As a result, what constitutes "controversy" may vary by use case topic, geographic coverage, and user (stakeholder).

[7] Users may be defined as all self-described or potential stakeholders, not just data management experts and water professionals.

Table 1. Texas drought dashboard use case details.

Title	Texas Drought Dashboard: An initiative to define and develop a drought data dashboard for Texas
Objective(s)	To initiate and complete development of a drought data dashboard collaboratively with the Texas Water Development Board (TWDB), to include support assembling and providing drought data expert stakeholder input in the design and build of the dashboard, and to include support assembling key end-user stakeholder group opinion and advice on dashboard design, needs for drought response decision support, and best use input, with design to include support for use by the general public.

Description	This use case is anticipated as a collaborative project with the TWDB to make a drought data dashboard for Texas by providing support to obtain expert advice and assembling key stakeholder group input to aid in the design and build of a data dashboard that may include the following characteristics:
	• Statewide and hyper-local applicability
	• Decision support tool for local decision makers and different levels of users, including decision support for the following as examples:
	  • Local and personal water conservation measures for use in the home and landscaping
	  • Media/public announcements and recommendations
	  • Business and industry water emergency planning
	  • Farming and ranching decisions
	• Scalable, multi-scale
	• Real-time data and historic trends
	• Means to verify and maintain data sets
	• Geographic or map-based interface
	• Robust visualization and graphic presentation capability
	• Functionality built in a sequence for different level users and advanced over time:
	1. Initial Development for the basic user: Entry level capabilities for basic functionality of dashboard:
	a) Basic level of decision support
	b) Accessible front-end site for viewing but no access to back end
	c) Easy to understand visuals and user experience/user interface (e.g., defined with specific user needs in mind)
	d) Built with accessible interoperable data
	e) Webpage for viewing/presentation/information sharing
	f) Data must be up to date
	2. Next Stage Development for the super user: Advanced level capabilities to meet greater level of functionality and robust decision support
	a) Simple back end for administrative and direct access by users
	b) Stable host/site where either the application lives and/or the digital objects are stored
	c) End user customizable interface
	d) Authentication standards
	e) Portable across regions and scales
	f) Modular for data entry-transformation-loading
	g) Model-based
	3. Future Development and capabilities
	a) Strategic problem solving and decision support
	b) Composable and reproducible
	c) Artificial intelligence assistance, recommendation support
	d) Facilitator and user support tools
	e) User-driven decision problem framing and diagnosis tools

<table>
<tr><td>Participants</td><td>• TWDB, along with collaborating Texas state and federal agencies
• Key statewide stakeholders: major local and statewide water stakeholder groups in Texas
• A representative group of the general public</td></tr>
<tr><td>Regulatory Context</td><td>There are no regulatory matters involved in development of an information dashboard. Development of public information portals is not subject to regulatory or statutory oversight. However, there will be interest by elected officials at all levels of Texas government and agency regulators in having drought status data and predictive data about water availability made more widely accessible and understandable to local and statewide decision makers and elected officials, water managers, water utility operators, regulated water users and permit holders, and the general public.</td></tr>
<tr><td>Workflow</td><td>Develop a proposal for funding (a quick operational plan of action linked to a realistic budget) and seek funding.

Note: The following steps refer to anticipated potential operational and funded steps to be taken toward completion of the drought data dashboard use case project.

The use case project may identify major key statewide and local stakeholder groups from which to solicit input and may identify a statewide or series of local (across the state) groups that can serve to represent general water-interest stakeholders.

Work with the TWDB to help clearly define roles and responsibilities in a collaborative arrangement. In general, the use case project may serve as a community of experts to provide advice to the TWDB as requested and may manage multi-stakeholder input and review of the dashboard during the design-build phase of work. In general, any final decisions would have to be made by the TWDB. This would cover matters involving data sets and dashboard function, build of the dashboard interface, and populating the dashboard with data or real-time data feeds.

The use case project is anticipated to convene stakeholder input sessions online and in workshops (perhaps at stakeholder conferences). These sessions may be aimed at identifying and managing the diversity or needs and complexity of the many different dashboard user groups. In addition to typical efforts to solicit stakeholder input based on the general concept of a drought dashboard, the use case project may use innovative means to solicit information on decision support needs desired by stakeholders and will seek input on innovative dashboard tools:

1. The use case project may seek to focus stakeholder learning about dashboards and enhance the usefulness of their response by developing and having stakeholders test-use simulated drought dashboards. Test dashboards should have realistic functionality that can provide stakeholders with high-level hands-on understanding of how a dashboard works and its use to support decision making. This can provide context for the stakeholders to understand the value of a dashboard as a decision support tool and make suggestions for improvement. Through input received during an iterative involvement process as the dashboard is built, stakeholders may help guide the design and functionality of the dashboard sequentially over time based on what they need, want, and are found to use, in part as a result of using the dashboard simulation.

2. The TWDB may choose to use information received through the use case project to help design the dashboard to accommodate the needs of multiple users. Users may range in level of technical training from expert to general public users. Users may range in the scope of decision support from decision making that affects water use by large populations to water use at an individual user’s home. Users may also vary in geographic area of concern from statewide to hyper-local.

3. The use case project may help describe or design decision support visualization tools and graphic presentations or interfaces to determine best practices for delivering information to the various stakeholder groups.

4. The use case project can help support stakeholder feedback on potential innovative and enhanced dashboard design, such as use of artificial intelligence in decision support, virtual visualization tools, or 3D representations of data sets. Such innovation in dashboard design could be tested in advance of spending time and money to overbuild or add advanced functionality that may not be used or needed. This could help allow public funding to be focused on the best and most useful dashboard design.</td></tr>
<tr><td></td><td></td></tr>
</table>

Table 1 (Continued). Data Sources.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Weather, river stage	Real-time temperature, precipitation, wind chill, heat index, humidity, wind, soil moisture, soil temperature, river flow, and river stage	Accessible	TexMesonet	https://www.texmesonet.org/	Also used by watermaster programs to determine surplus water for requested diversions and may impact environmental flow determinations both during low and high flow periods. Should also determine other real-time monitoring systems that are relied upon by the Texas Commission on Environmental Quality (TCEQ) and others for similar determination, such as International Boundary and Water Commission stream flow stations.
Drought impacts	Quantifiable losses attributable to drought	Variable	• TWDB • TCEQ • The National Drought Resilience Partnership • United States Department of Agriculture (USDA) • Various other sources	• https://www.drought.gov/drought/states/texas • https://www.tceq.texas.gov/response/drought • https://www.waterdatafortexas.org/drought • https://droughtreporter.unl.edu/map/	• Difficult to quantify impacts, but no comprehensive reporting process • Annual agricultural statistics available for commodity crops, but no standardized process to separate drought impacts from other factors affecting the agricultural economy • Harder to justify resources for drought response when impacts are not comprehensively accounted for • The prolonged nature of a drought and its broad geographic distribution make it more difficult to assess impacts than in a discrete event, such as a flood.
Water use data	Real-time surface water and groundwater use	Accessible, but not real-time	• TWDB • TCEQ	• https://www.tceq.texas.gov/permitting/water_rights/wr-permitting/wrwud • https://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/index.asp	TWDB water use data are annual and not available in real time. TCEQ data show monthly values but are only listed through 2014, except for watermaster areas, where near real-time diversion rate and authorizations are available.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Soil moisture	Remotely sensed soil moisture products (e.g., soil moisture active passive products) and modeled soil moisture from the North American Land Data Assimilation System suite of models.	Accessible, variable	• TWDB • Natural Resources Conservation Service (NRCS), Soil Climate Analysis Network (SCAN) • National Aeronautics and Space Administration (NASA)	• www.texmesonet.org • NRCS-SCAN sites	• Soil moisture data are currently available only from a few point measurements. The TexMesonet stations are collecting soil moisture. However, there needs to be a much wider spatial coverage of in-situ observations. • Remotely sensed soil moisture products (e.g., soil moisture active passive products) and modeled soil moisture from the North American Land Data Assimilation System suite of models. These are available from NASA's Distributed Active Archive Center and from Mirador, but it would be nice to collate the data and have it accessible as soil moisture maps and other value-added products (e.g., soil moisture anomalies for a given month or season). While these datasets are replacements for in-situ data, they can be used in tandem with in-situ data. The plus point for the remotely sensed or modeled products is that they provide continuous surfaces and may provide useful information on soil moisture variability across Texas.
Planning group boundaries	Regional water planning group boundaries	Accessible	TWDB	http://www.twdb.texas.gov/waterplanning/rwp/index.asp	
Population data (census or state water plan)	Population data from the census or state water plan	Accessible	TWDB	http://www.twdb.texas.gov/waterplanning/swp/index.asp	
Groundwater and reservoir level	Real-time groundwater, reservoir level	Accessible	TWDB	https://waterdatafortexas.org/reservoirs/statewide	
Groundwater extraction rates	Water extracted monthly for each aquifer	Variable	TWDB		
Topographic information	Digital elevation models and/or Lidar datasets	Accessible	Texas Natural Resources Information System	https://data.tnris.org/	The refined Lidar datasets are important for connecting various impact and vulnerability concerns.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Instream flow requirements	Adopted ecological flow standards for stream segments where values have been set	Accessible	TCEQ	https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/rulemaking	
Water discharge per day	Real-time water discharge rate per day	Variable	TCEQ	Public Information Request or direct request form to TCEQ and regional offices	If return flows from wastewater treatment plants, then utilities are required to measure and report this data to TCEQ.
U.S. Drought Monitor	Drought monitor (national, by state)	Accessible	• USDA • National Oceanic and Atmospheric Administration	https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?TX	
Drought calculator for ranch/farm production	Predictive tool for assessing potential drought impacts on forage production	Accessible	NRCS	https://www.nrcs.usda.gov/wps/portal/nrcs/detail/nd/technical/landuse/pasture/?cid=nrcs141p2_001670	
United States Geological Survey (USGS) dashboard for Texas	Stream gage data	Accessible	USGS	https://txpub.usgs.gov/txwaterdashboard/	
Streamflow	River streamflow statewide	Accessible	USGS	https://waterdata.usgs.gov/tx/nwis/current/?type=flow	

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Groundwater level monitoring	Static groundwater level measurements from different times of year, with data on impact of drought on those levels and groundwater availability	Accessible, variable	Groundwater conservation districts	Groundwater conservation districts	These data sets are variable, difficult to access in real time, and may not be readily interoperable.
Groundwater availability	Groundwater availability: How much water is available to be permitted and how much water has already been permitted	Accessible, variable	Groundwater conservation districts	Groundwater conservation districts	
Lithology-geological data	Drilling reports, electrical reports, seismic	Accessible, variable	• TWDB • Railroad Commission of Texas	Request	

Table 2. Surface water–groundwater interaction data use case details.

Title	Surface Water–Groundwater Interaction Data Repository and Dashboard for Texas: A use case to build a repository of existing surface water–groundwater interaction data and make the data available to users through a robust indexing system and by working to make the data available to users in a FAIR,[1] georeferenced data hub for interaction data to which data sets and new data can be added over time; there are means provided to hub users through a dashboard or viewer to access, view, and work with these data, along with user-added data to demonstrate interactions or other desired analysis; and means to allow users to add data or data sets where contributors' data are subject to review and verification. [1] FAIR: F=Findable, A=Accessible, I=Interoperable, and R=Reusable
Objective(s)	To design and build a surface water–groundwater interaction data repository, hub, and a dashboard viewer for Texas that thoroughly considers key stakeholder input in the design, build, and uses of the hub and dashboard, including input from the general public to aid in making the hub/dashboard universally valuable in enabling users to make better decisions about managing their water resources.
Description	• The use case may collect, index, and enable access to all available groundwater and surface water interaction data stratified by river basin, water planning region, groundwater management area, and groundwater conservation district. • The data may be housed first in a user-accessible repository or data hub that may contain all available interaction data sets, indexed at a minimum as described immediately above. • In a next step, an interaction data dashboard and viewer can build on a repository or hub using FAIR data. Over time, the dashboard may add the capacity for users to conduct basic data comparison work and view interaction display functions. The dashboard may allow for the addition of more water data over time that may enable display of more and better interaction information and help identify future data needs. • The dashboard may be initially populated with data sets that focus on high-priority areas (for conservation or public benefit purposes) or high-profile river basins or locations, such as San Felipe Springs, Devils River, Blanco River, Brazos River, Colorado River near San Saba, or Balmorhea/San Solomon Springs. • Initial work may define who is expected to use the dashboard. These stakeholders or stakeholder groups may be identified and asked to provide input on what they need and how they would use the dashboard. The project may also develop an example dashboard, or mock-up, to start the discussion with stakeholders and help define and test needs and desires. This can help in the development of multiple entry points to data sets for different levels of users or users with different needs, including delivery of information synthesized for public use.
Participants	• Groundwater conservation districts and other groundwater managers • River authorities and other surface water managers • Regional water planners • Water rights holders/owners • Counties and major cities government and elected officials • Water providers • Texas Water Development Board (TWDB) and collaborating Texas state and federal agencies • Texas Commission on Environmental Quality (TCEQ) • A representative group of the general public
Regulatory Context	There are no regulatory matters involved in development of a data repository or dashboard. The development of public information portals is not subject to regulatory or statutory oversight. However, there is likely to be interest by elected officials at all levels of Texas government and agency regulators in having surface water and groundwater interaction information and predictive data about interactions affecting water availability made more widely accessible and understandable to local and statewide decision makers, elected officials, water managers, water utility operators, regulated water users and permit holders, and the general public.

<table>
<tr><td>Suggested Workflow</td><td>Identify potential funders and make initial contact where possible and appropriate.

Develop a framework work plan and budget for the use case. This plan may include items such as a detailed listing of sequential actions to be taken to develop the data repository and dashboard and to add data sets and tools that will turn these data sets into information displays about interactions and water availability described as useful and needed for decision making by water managers and stakeholders. Then, use the plan and budget as a guide to develop a proposal for funding by potential funders.

Develop the technical work plan to design and build the repository and dashboard, including architecture, function, tools, interface, and back end.

Develop a mock-up dashboard to provide a working example for stakeholder education, testing, and input.

Identify initial examples to serve as initial subjects for populating the dashboard with FAIR data. Focus the following efforts on each basin or location as work proceeds. Repeat as new basins or locations area added, with data fit for each new specific purpose adding to the evolution and iterative building of a comprehensive dashboard.
Create and use a local stakeholder network or advisory group for project review and input on development of locally desired features and functionality of the dashboard by area, as opposed to relying only on technical experts and programmers.
Gather and add data sets relevant to each location, gradually building a comprehensive dashboard with capacity to display decision support information about surface water and groundwater interactions and availability.
Develop/adapt a mock-up dashboard for each new area to provide a working example for stakeholder education, testing, and input.
Develop a marketing plan to describe the benefits/results of better water management by users of the decision support tools available on the dashboard.</td></tr>
</table>

Table 2 (Continued). Data Sources.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Weather, river stage	Real-time temperature, precipitation, wind chill, heat index, humidity, wind, soil moisture, soil temperature, river flow, river stage	Accessible	• TWDB • TexMesonet	https://www.texmesonet.org/	
Groundwater levels	Daily water level (feet below ground surface) for 234 wells across the state	Accessible	TWDB	www.waterdatafortexas.org/groundwater/	Few, if any, of these wells are in alluvial aquifers. Priority could be placed on instrumenting at least some wells in alluvial aquifers in the future.
Field studies of Colorado River and Carrizo-Wilcox Aquifer in Central Texas	Report prepared to support the update of the groundwater availability model of the central portion of the Carrizo-Wilcox Aquifer	Accessible, data may not be readily interoperable	TWDB	http://www.twdb.texas.gov/groundwater/models/gam/czwx_c/Final_BBASC_083117.pdf?d=1566575514973	
Surface water and aquifer relationships in the Brazos River Alluvium Aquifer	Report prepared to document the conceptual model of the groundwater availability model of the Brazos River Alluvium Aquifer	Accessible	TWDB	http://www.twdb.texas.gov/groundwater/models/gam/bzrv/BRAA_AQUIFER_GAM_REPORT_ALL.PDF	

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Texas aquifers	Both major (9) and minor (22) aquifers as defined by the TWDB	Accessible	TWDB	http://www.twdb.texas.gov/mapping/gisdata.asp	Available shapefiles; website includes many other pertinent GIS data (e.g., river basins, rivers, reservoirs)
Summary report of surface water–groundwater interactions in Texas	Estimated groundwater flow to surface water based on historical baseflow data from nearly 600 USGS stream gauging stations.	Accessible	• TWDB • USGS	http://www.twdb.texas.gov/groundwater/docs/studies/TexasAquifersStudy_2016.pdf?d=1566575164951	• Base flow is from USGS stream gauges, TWDB aquifer properties and map. • Report prepared by the TWDB at the direction of the 84th Texas Legislature (House Bill 1232)
Spring discharge	Stage/discharge relationships and time series groundwater elevation and spring discharge records	Limited availability	Limited; some springs included in TWDB groundwater database	https://www.twdb.texas.gov/groundwater/data/index.asp	• Few spring discharge values are available. • Spring rating curves linking stage and discharge are generally not available.
Groundwater pumping data	Time series volume of water pumped by well (spatially explicit), covering all well types (including exempt wells)	Limited availability	• TWDB • Groundwater conservation districts • Others		• Pumping data are scarce • Estimates by different agencies are mixed and use a number of assumptions to estimate.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Soil moisture	Remotely sensed soil moisture products (e.g., soil moisture active passive products) and modeled soil moisture from the North American Land Data Assimilation System suite of models	Accessible	• TWDB • Natural Resources Conservation Service, Soil Climate Analysis Network (NRCS-SCAN)	• www.texmesonet.org • NRCS-SCAN sites	• Soil moisture data are currently available only from a few point measurements. The TexMesonet stations are collecting soil moisture. However, there needs to be a much wider spatial coverage of in-situ observations. • Remotely sensed soil moisture products (e.g., soil moisture active passive products products) and modeled soil moisture from the North American Land Data Assimilation System suite of models. These are available from National Aeronautics and Space Administration's Distributed Active Archive Center and from Mirador, but it would be nice to collate the data and have it accessible as soil moisture maps and other value-added products (e.g., soil moisture anomalies for a given month or season). While these datasets are replacements for in-situ data, they can be used in tandem with in-situ data. The plus point for the remotely sensed or modeled products is that they provide continuous surfaces and may provide useful information on soil moisture variability across the state.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Potential areas with surface water–groundwater interactions	Surface water–groundwater interaction evaluation for 22 Texas river basins	Accessible but generally not in a database; many numbers/ studies in published papers and reports	Texas Natural Resource Conservation Commission	https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/Surface-Groundwater_Interaction.pdf	• Assessment of surface water–groundwater interactions for river segments. Points out areas of the state where interaction is expected to occur (and relative degree of interaction). • Data is dated (circa 1999) and more qualitative than quantitative.
Streamflow gain/ loss	Streamflow measurements along a reach to define interaction between surface water and groundwater	Accessible, usability variable	USGS	https://pubs.usgs.gov/of/2002/ofr02-068/	• There are 366 streamflow gain-loss studies in 249 unique reaches. • Highly variable results • Snapshot in time measurements don't reflect groundwater dynamics. • Data does not address bank storage; existing methods are difficult and expensive; new methodologies needed. • Data doesn't include results from studies completed after 2000.
Stream and spring discharge	Real-time stream and spring discharge	Accessible	USGS	https://waterdata.usgs.gov/tx/nwis/current/?type=flow	• Stream flow at 640+ sites. Spring flows for 10 springs including Chalk Ridge Falls, Felps, Barton, San Marcos, Comal, Hueco, Jacobs Well, Giffin, San Solomon, and Las Moras. • Data does not exist for many springs in Texas.
Groundwater levels	Real-time groundwater elevations	Accessible	USGS	https://waterdata.usgs.gov/tx/nwis/current/?type=gw	• 15-minute data for water level for 35 wells across the state; few, in any, of these wells are in alluvial aquifers • Priority could be placed on instrumenting at least some wells in alluvial aquifers in the future.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Geodatabase	Geologic and hydrogeologic information for a geodatabase for the Brazos River Alluvium Aquifer	Accessible	USGS	• https://pubs.usgs.gov/of/2007/1031/ • https://pubs.usgs.gov/sim/2989/	• Data were compiled primarily from drillers and borehole geophysical logs from government agencies and universities, hydrogeologic sections and maps from published reports, and agency files. • Provides estimate of alluvial aquifer extent and thickness for one alluvial aquifer in Texas. Much less data available for other alluvial aquifers in the state.
Streamflow gain/ loss	Gain/loss study for Colorado River in Burnett and San Saba counties	Accessible	USGS	https://pubs.er.usgs.gov/publication/sir20155098	• Traditional gain/loss study on about 10 miles of the Colorado River • Typical gain/loss study with use of an acoustic Doppler current profiler to make flow measurements. Example of study completed after #3 and #10 above.
Streamflow gain/ loss	Gain/loss study for Guadalupe River in Gonzales County	Accessible	USGS	https://pubs.er.usgs.gov/publication/fs20183057	• Gaining and losing sections of river determined using floating geophysical methods • Methods provide an indication of gaining or losing, but don't quantify the amount. Map the length of segment (not just individual points)
Streamflow gain/ loss	Gain/loss study for the Brazos River from McLennan County to Fort Bend County	Accessible	USGS	https://pubs.er.usgs.gov/publication/sir20075286	Base flow (1966–2005) and streamflow gain and loss (2006) of the Brazos River, McLennan County to Fort Bend County, Texas
Streamflow gain/ loss	Gain/loss study for the Brazos River from New Mexico–Texas state line to Waco, Texas	Accessible	USGS	https://pdfs.semanticscholar.org/92e0/bbbaf13ceb477442ac9d9a2f966714151776.pdf?_ga=2.107396166.51329	Base flow (1966–2009) and streamflow gain and loss (2010) of the Brazos River from the New Mexico–Texas state line to Waco, Texas

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Spring locations	USGS database of Texas springs	Accessible	USGS	https://doi.org/10.3133/ofr03315	
Surface water–groundwater relationship	Estimate of groundwater outflow versus Medina Lake stage	Accessible, unknown usability	USGS	https://pubs.er.usgs.gov/publication/fs20173008	• Regression equations for groundwater outflow vs. stage based on measurements from 1955–1964, 1995–1996, and 2001–2002. • Example of the type of data that needs to be collected to estimate groundwater recharge from surface water bodies
Surface Water quantity/quality	Data related to surface water quality and quantity at field and watershed scales	Accessible	Texas Institute for Applied Environmental Research, Tarleton State University	Contact at Saleh@tarleton.edu	• Over 25 years of water quality and quantity data collected from number of watersheds in Texas for data analysis and modeling • Data related to interaction of surface and ground water quality and quantity; surface water quality and quantity data for many locations are of limited use
Overview of the impacts of surface water–groundwater interactions on water quality and quantity	Surface water–groundwater interactions in Texas	Accessible, use limited by location	Bureau of Economic Geology, University of Texas	http://www.beg.utexas.edu/files/publications/cr/CR2005-Scanlon-3_QAe6975.pdf	Data are limited to certain locations in state.
Streamflow/river Forecasts	Times series of river stage forecasts and streamflow at certain USGS gaging stations during certain conditions	Accessible, use limited	West Gulf River Forecast Center	https://www.weather.gov/wgrfc/obsfcst#	• Depending on conditions, forecasts of river stages, associated streamflow, and various USGS gaging stations • Currently, streamflow forecasts are not typically available for "normal" and "dry" conditions.

Data Category	Description	Availability	Data source	Access Method	Added Characteristics
Spring flow	Spring flow targets where already specified	Accessible, where specified as desired future conditions			May be policy-oriented target value, not collected data
Streamflow	Environmental flow targets	Available but not in a publicly accessible database	TCEQ	Database in development with Texas Parks and Wildlife Department	May be policy-oriented target values, not collected data
Groundwater management	Desired future conditions	Available but not in a publicly accessible database	TWDB	https://www.twdb.texas.gov/groundwater/management_areas/index.asp	May be policy-oriented target values, not collected data
Baseflow separation	Base flow separation using water chemistry and other tracers. Better data than simple flow-based separation.	Isolated case studies	e.g., Rhodes KA et al. Rhodes. 2017. The Importance of Bank Storage in Supplying Baseflow to Rivers Flowing Through Compartmentalized, Alluvial Aquifers. Water Resources Research. 53(12):10539-10557. Available from: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017WR021619		• Data not now generally available • More intensive monitoring required • A data need
Groundwater	Groundwater availability and water availability models outputs as well as inputs	Available but not wholly FAIR	• TWDB • TCEQ	https://www.twdb.texas.gov/groundwater/models/gam/index.asp	
Evapotranspiration rates	Remote sensing evapotranspiration data over a period of time	Not generally available	OpenET is developing a platform for remote-sensed evapotranspiration for the western United States	https://etdata.org/	• Data not now generally available • A data need • OpenET data products scheduled for release in 2021

NEXT STEPS

Committee members acknowledge and strongly support the TWDB's current work to develop a data hub and dashboards for flood and drought. They committed to assisting the agency when possible. The TWDB's work on data dashboards has the potential to serve as use cases that demonstrate the value of integrated Texas water data visualization tools to decision makers. A surface water–groundwater interaction data repository will add to this value demonstration. Future steps may be to link these efforts via a data hub, enabling an even more complete picture of Texas water data.

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REFERENCES

Rosen RA, Roberts SV. 2018. Connecting Texas water data workshop. San Antonio (Texas): Institute for Water Resources Science and Technology, Texas A&M University-San Antonio. 87 p. Available from: https://digitalcommons.tamusa.edu/water_books/2/.

Rosen RA, Hermitte SM, Pierce S, Richards S, Roberts SV. 2019. An internet for water: connecting Texas water data. Texas Water Journal. 10(1):22-29. Available from: https://doi.org/10.21423/twj.v10i1.7086.

Rosen RA, Mace RE. 2019. Internet of Texas water data: Use cases for flood, drought, and surface water–groundwater interactions. San Marcos (Texas): The Meadows Center for the Environment, Texas State University. 51 p. Report No. 2019-10. Available from: https://digitalcommons.tamusa.edu/water_books/1/.

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Exploring Groundwater Recoverability in Texas: Maximum Economically Recoverable Storage

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Abstract: The 2017 Texas state water plan projects total supply deficits of 4.8 and 8.9 million acre-feet under drought-of-record conditions by the year 2020 and 2070, respectively, driven by a growing population concurrent with declining available water supplies. Reductions in groundwater supply account for 95% of anticipated declines in total water supply. Meanwhile, restrictive groundwater management plans may be creating a regulation-induced shortage of groundwater in Texas, given the significant groundwater storage volumes that are unutilized under many management plans. However, these estimates do not account for many of the physical and none of the economic constraints to groundwater recoverability. We report an analysis of groundwater extraction feasibility and simulate maximum economically recoverable storage for conditions representative of the central section of the Carrizo-Wilcox Aquifer under economic constraints associated with agricultural uses. Two key limitations are applied to simulate recoverability: (1) the value of water pumped relative to pumping costs and (2) the capacity of the aquifer and well to meet demand. Our results indicate that these constraints may limit certain uses to as little as 1% of current groundwater availability estimates. We suggest that Texas groundwater managers, stakeholders, and policymakers assessing groundwater availability need an alternate approach for estimating recoverability.

Keywords: groundwater availability, groundwater recoverability, pumping costs, total estimated recoverable storage, TERS, maximum economically recoverable storage, MERS

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Terms used in paper

Acronym / Initialism	Descriptive Name
DFC	Desired Future Conditions
GCD	Groundwater Conservation District
GMA	Groundwater Management Area
MAG	Modeled Available Groundwater
MERS	Maximum Economically Recoverable Storage
TERS	Total Estimated Recoverable Storage
TWC	Texas Water Code
TWDB	Texas Water Development Board

INTRODUCTION

Is Texas running out of groundwater, blessed with abundance, or somewhere in the middle? This question, historically shrouded in scientific uncertainty and political controversy, represents a complex nexus of hydrogeology, economics, and policy with many relevant and potentially conflicting considerations. Hydrogeologic conditions and management objectives vary significantly across the state, and as a consequence there is no universal yield solution.

Nonetheless, one key element common to all human groundwater demand is *recoverability*, defined as the relative ease or difficulty of extraction. Recoverability is constrained by aquifer characteristics, well design, and economics. While recoverability data is crucial to groundwater planning and management, particularly with respect to availability assessments, Texas' best estimates of recoverable groundwater volumes reflect only the volume in storage and take no account of well design or economic constraints. This study therefore addresses the question: What are the economic and physical limits to recoverability? By establishing these limits, we can better estimate potentially available groundwater for given uses and infrastructure.

Goals and objectives

We seek here to (a) develop improved methods for quantifying groundwater recoverability by integrating aquifer and well dynamics with economics and (b) contextualize our results within existing policy frameworks and discussions. The key purpose of this study is to facilitate the exploration of planned and potential changes in groundwater recoverability by developing methods for analytically calculating the physical and economic constraints and limitations to pumping associated with changes in depth-to-water over time.

This study does not seek to establish a yield prescription for groundwater management, but it does estimate a reference limit we term maximum economically recoverable storage (MERS). While not designed to be economically efficient, MERS is intended to establish clear and rational limits to groundwater recoverability for the purpose of evaluating groundwater availability under variable uses and infrastructure. Moreover, because MERS is, in part, a function of depth-to-water, its limits are directly comparable to existing or proposed depth-to-water based groundwater management goals.

For any pumping groundwater well, the maximum volume of recoverable water is a subset of total aquifer storage, which may be numerically simulated using simplified hydrogeologic and economic constraints. The maximum yield a well can physically produce is limited by the relationship between the aquifer, well, and pumping rate. We anticipate that aquifer and pumping characteristics introduce capacity constraints where demand is constant. We further expect some percentage of saturated thickness to be unavailable for production (a groundwater "dead pool") at any given pumping rate, and a relationship to exist between the pumping rate and the saturated thickness available for production. In terms of economics, increasing depth-to-water increases pumping costs where other factors are held constant. We expect these changes can be significant to agricultural and other uses. Therefore, we address two hypotheses in this study:

- H1: In shallow and unconfined settings, physical constraints related to the capacity of the aquifer and well to meet demand, not economic constraints, will limit groundwater recoverability.
- H2: In deep and confined settings, economic constraints, not physical constraints, will limit groundwater recoverability for some uses, restricting them to producing from confined, pressurized storage.

Groundwater management in Texas

Groundwater in Texas is managed at the local level by approximately 100 groundwater conservation districts (GCD(s)). However, in 2005, the 79th Texas Legislature enacted House Bill 1763, which amended the Texas Water Code (TWC) to regionalize groundwater availability decision making under groundwater management areas (GMA(s)).

House Bill 1763 further instructs GCDs within a GMA on how they should cooperate with each other and the Texas Water Development Board (TWDB) to determine groundwater volumes available for permitting. Chapter 36 §108 of the TWC states that "[GCDs] shall propose for adoption desired future conditions for the relevant aquifers within the [GMA]." Desired future conditions (DFC(s)) are further defined by Title 31, Part 10, §356.10(6) of the Texas Administrative Code to be "the desired, quantified condition of groundwater resources (such as water levels, spring flows, or volumes) within a [GMA] at one or more specified future times as defined by participating [GCDs] within a [GMA] as part of the joint planning process." Our evaluation of currently adopted DFCs shows that, while spring flow and saturated thickness metrics are common, groundwater in Texas is most commonly managed as a function of depth-to-water over time (i.e., x feet of drawdown over y years).

Once DFCs are adopted, Chapter 36 §108(b) of the TWC requires the TWDB to calculate values for the volume of modeled available groundwater (MAG) that comply with the adopted DFC given the hydrologic properties of the aquifer in question. Finally, Chapter 16 §053(e)(3) of the TWC requires that GCDs honor MAG volumes in their groundwater management plans. In this way, the DFCs adopted by GCDs create a regulatory target or cap for groundwater extraction in the form of the derived MAG volumes provided by the TWDB (Mace et al. 2008).

2017 State Water Plan: Water for Texas

The latest iteration of the Texas state water plan, 2017's "Water for Texas," predicts a deficit of total water supplies under drought-of-record conditions in the amount of 4.8 and 8.9 million acre-feet by the year 2020 and 2070, respectively, resulting from an anticipated 70% increase in the population concurrent with an 11% projected decline in total water supplies (TWDB 2016). The plan further estimates that, if left unresolved into 2070, these deficits would result in approximately $151 billion of annual economic losses and roughly a third of the projected population having less than half the projected municipal water demand (TWDB 2016). The plan considers drought-of-record conditions. Under unprecedented drought driven by climate change (Nielsen-Gammon et al. 2020), supply deficits and economic losses may be even higher. Even without this consideration, the plan findings establish a central theme: demonstrating the necessity of responsive water development financing while sounding a call to action for policymakers.

But how were these conclusions reached? What key assumptions were made?

First, an important distinction should be noted between water resource *availability* and water resource *supply* as those terms are defined by the plan. Section 6.1 of the plan clarifies:

> "Water availability refers to the maximum volume of raw water that could be withdrawn annually from each source (such as a reservoir or aquifer) during a repeat of the drought of record. **Availability does not account for whether the supply is connected to or legally authorized for use by a specific water user group**. Water availability is analyzed from the perspective of the source and answers the question: **How much water from this source could be delivered to water users as either an existing water supply or, in the future, as part of a water management strategy?** [...] [Then], planning groups evaluate the subset of the water availability volume that is already connected to water user groups. **This subset is defined as existing supply**." (TWDB 2016, p. 61 [**emphasis** added])

Recognizing this distinction, the plan reveals a projected 20% decline in available groundwater (from 12.3 million to 9.8 million acre-feet) and a 24% decline in groundwater supply (from 7.2 million to 5.5 million acre-feet) over the planning period (2020 through 2070) "… due primarily to reduced availability from the Ogallala Aquifer, based on its managed depletion, and the Gulf Coast Aquifer, based on regulatory limits aimed at reducing long-term groundwater pumping to limit land surface subsidence" (TWDB 2016, p. 70).

Indeed, reductions in groundwater supply considered by the plan account for 95% of the anticipated 11% decline in total water supply (TWDB 2016). If the impacts of population growth are assumed valid and held constant (i.e., only the decline in total supply is considered), the total water resource

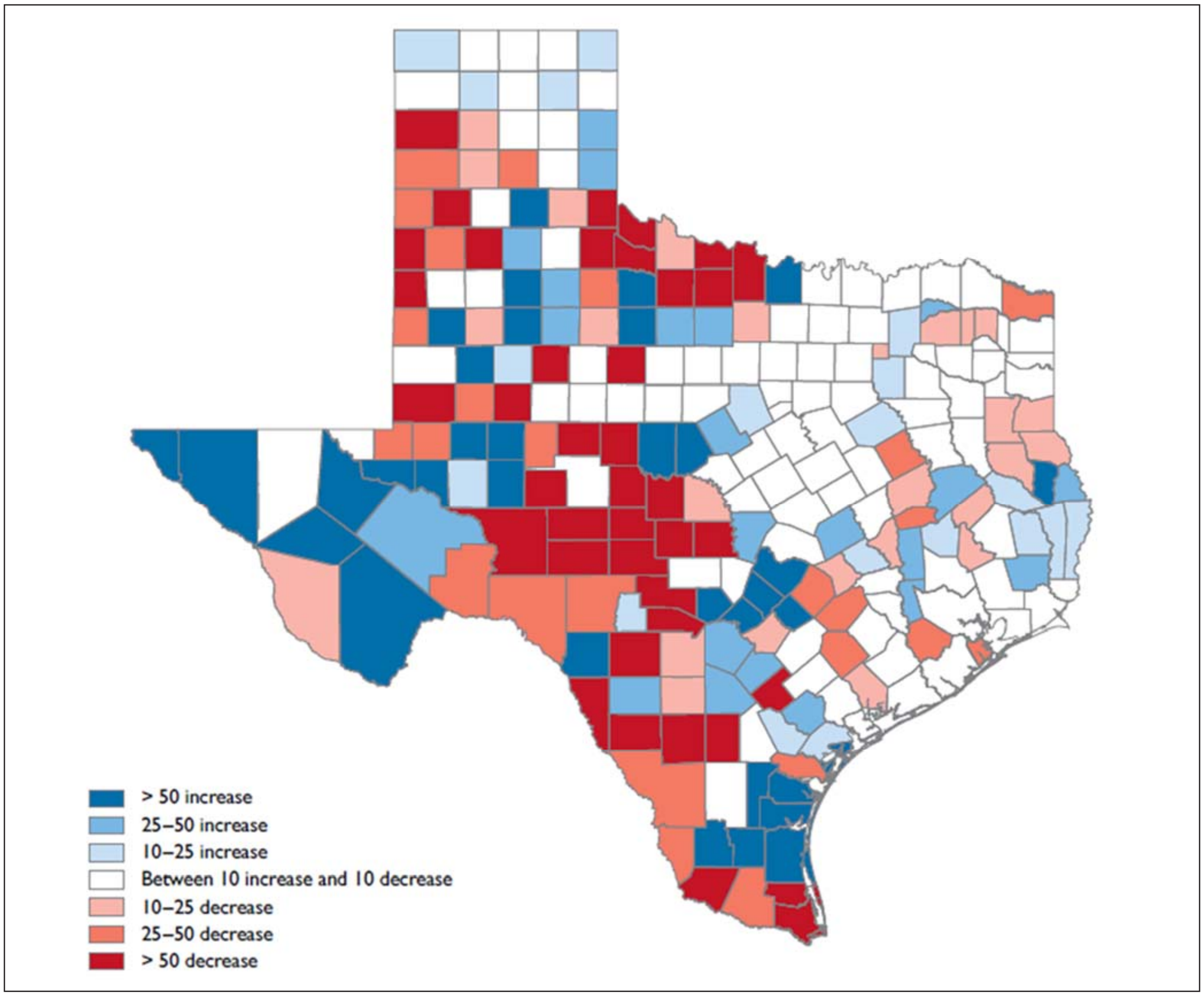

Figure 1. Change in groundwater availability by county from the state water plan in 2012 to 2017 (TWDB 2016).

deficits portended by the plan are driven almost entirely by anticipated declines in groundwater availability.

Second, we note that this water plan determines, for the first time, groundwater availability volumes as the sum of the MAG volumes provided by the TWDB in accordance with the DFCs adopted by GCDs (TWDB 2016). This change in accounting methodology from the previous state water plan (2012) to the current plan (2017) has produced significant changes in regional groundwater availability estimates, in many jurisdictions increasing or decreasing volume by 50% or more (TWDB 2016) (Figure 1).

However, MAG volumes derived from DFCs do not strictly adhere to the definition of availability given by the plan. Specifically, MAG volumes from DFCs are the total volume of groundwater that is "legally authorized for use" (TWDB 2016, p. 61).

TOTAL ESTIMATED RECOVERABLE STORAGE

Prior to adopting a DFC, Chapter 36 §108(d)(3) of the TWC requires GCDs to consider, among nine potentially conflicting issues, the total estimated recoverable storage (TERS) volumes provided by the TWDB for each area aquifer. TERS is defined by Rule §356.10.23 of the Texas Administrative Code as "the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25% and 75% of the porosity-adjusted aquifer volume."

Given the statutory definition of TERS and the statutory definition of total storage provided in Chapter 36 §001(24) of the TWC as "the total calculated volume of groundwater that an aquifer is capable of producing," the TWDB has developed a working definition of TERS as a two-step calculation.

In the first step, the hydrologic properties and geometries of the aquifer (such as transmissivity, water levels, and storage coefficients) are established according to the relevant TWDB groundwater availability model (where available). Those values are then used to derive total storage (Bradley 2016). The calculation differs among confined and unconfined aquifers and is provided by the TWDB (Bradley 2016) as:

$$\textit{total unconfined storage} = \textit{area} \times (\textit{water level} - \textit{bottom}) \times Sy \tag{1}$$

$$\textit{total confined storage} = (\textit{area} \times (\textit{water level} - \textit{top}) \times St) + (\textit{area} \times (\textit{top} - \textit{bottom}) \times Sy) \tag{2}$$

where *total unconfined storage* is the storage volume of water released due to water draining from an unconfined setting (i.e., dewatering); *area* is the land surface area of the aquifer; *water level* is the depth of potentiometric head; *bottom* is the depth of the bottom of the aquifer; *Sy* is the specific yield storage coefficient; *total confined storage* is the storage volume of water released due to the elastic properties of the aquifer, plus the volume of water released due to dewatering; *top* is the depth of the top of the aquifer; and *St* is the confined storativity storage coefficient.

In the second step, the calculated total storage is multiplied by 25% and 75% to "account for recovery scenarios that range between 25% and 75% of the porosity-adjusted aquifer volume" (Wade and Shi 2014b., p. 4) and thereby arrive at final TERS volumes.

We are unaware of any rationale provided in the public record for why 25% and 75% were chosen to represent the limits of potentially recoverable groundwater in TERS. We therefore assume these bounds are arbitrary reference points and that none of the potential physical and economic constraints and limitations associated with the recoverability of groundwater extraction are captured by TERS.

The total storage component of TERS is the state's closest approximation of groundwater availability, or "the maximum volume of raw water that could be withdrawn" (TWDB 2016, p. 61), as it incorporates depth-to-water and spatially variable aquifer characteristics. Thus, we compile total storage volumes (Tables 1 and 2), published by the TWDB as of April 2018 for the nine major aquifers of the state within each GMA (Figure 2). Note that total storage data are not available for the Hueco-Mesilla Bolsons Aquifer and GMA 5 because no GCDs administer this area. The Carrizo-Wilcox Aquifer and the Gulf Coast Aquifer reported the largest total storage volumes at 5.227 and 4.163 billion acre-feet (respectively) and together constitute 81% of the sum total volume of water in storage for all nine major aquifers, calculated at 11.575 billion acre-feet. By contrast, the Seymour, Edwards (Balcones Fault Zone), and Edwards-Trinity (Plateau) Aquifers reported the smallest total storage volumes at 5.128, 24.951, and 45.491 million acre-feet, respectively. The total storage volume for the Ogallala Aquifer is reported to be 380.544 million acre-feet, representing only 3% of the total volume of water in storage for all nine major aquifers.

Even at the 25% TERS metric, the TERS volume reported for the Carrizo-Wilcox Aquifer alone (1.306 billion acre-feet) is far more than sufficient to satisfy the 2070 deficits projected by the 2017 state water plan (8.9 million acre-feet by 2070). The difference between these volumes could mean that, while the state is projecting water supply deficits, it is ignoring significant reserves of recoverable groundwater.

We are not the first to acknowledge TERS volumes in light of potential future deficits. A 2016 report by Brady et al. (2016), addressed to the Texas Comptroller of Public Accounts, criticized the current groundwater management approach as reverse-engineered and politicized, resulting in a "regulation-induced [groundwater] shortage" (Brady et al. 2016, p. 2). They recommended that the approach be revised in favor of more objective, economic constraints and presumably greater volumes of groundwater available for production. The report "assumes that prudent aquifer management would allow the TERS in each GCD to be drawn down by 5% over a 50-year period—or .1% of TERS annually" (Brady et al. 2016, p. 9) and proposes that such a metric replace the MAG from DFC volume regulations mandated by the current form of the TWC. TERS estimates report significant volumes of groundwater in storage that could potentially be available to meet the deficits projected by the state water plan. However, this critique disregards the apparently arbitrary recoverability constraints of TERS (25% and 75% of total storage).

SIMULATING RECOVERABILITY

To test H1 and H2 and quantitatively evaluate the physical and economic impacts to groundwater recoverability associated with changes in depth-to-water, we develop a simplified, single-cell pumping simulation using numerical processors to generate MERS. This is done through a linear convex optimization constrained by hydrogeology, pumping dynamics from given well specifications and pumping demand, and the given agricultural value of the water pumped over derived pumping costs. The MERS model is applied to a variety of user inputs and hydrogeologic conditions but was conceptualized for a single well pumping for agricultural uses.

Table 1. Total storage and total estimated recoverable storage (25% and 75%) of the nine major aquifers of Texas in GMA 1-8. Source: Boghici et al. 2014, Jones et al. 2013a., Jones et al. 2013b., Kohlrenken et al. 2013a., Kohlrenken et al. 2013b., Kohlrenken 2015, Shi et al. 2014.

TWDB major aquifers		Aquifer (million acre-feet)	Groundwater management area (million acre-feet)						
			1 (Kohlrenken 2015)	2 (Kohlrenken et al. 2013a.)	3 (Jones et al. 2013a.)	4 (Boghici et al. 2014)	6 (Kohlrenken et al. 2013b.)	7 (Jones et al. 2013b.)	8 (Shi et al. 2014)
Carrizo - Wilcox	Total storage	5,227.077							
	25%	1,306.769							
	75%	3,920.308							
Gulf Coast	Total storage	4,163.507							
	25%	1,040.877							
	75%	3,122.630							
Trinity	Total storage	1,405.166					0.471	0.523	1,359.625
	25%	351.292					0.118	0.131	339.906
	75%	1,053.875					0.353	0.392	1,019.719
Ogallala	Total storage	380.545	232.700	139.210	0.010		2.285	6.340	
	25%	95.136	58.175	34.803	0.002		0.571	1.585	
	75%	285.408	174.525	104.408	0.007		1.714	4.755	
Pecos Valley	Total storage	323.860		2.000	309.000	1.490		11.370	
	25%	80.965		0.500	77.250	0.373		2.843	
	75%	242.895		1.500	231.750	1.118		8.528	
Edwards - Trinity (Plateau)	Total storage	45.491		0.142	0.390	3.780		38.821	
	25%	11.373		0.036	0.098	0.945		9.705	
	75%	34.118		0.107	0.293	2.835		29.116	
Edwards (BFZ)	Total storage	24.952							0.095
	25%	6.238							0.024
	75%	18.714							0.071
Seymour	Total storage	5.128	0.001	0.057			5.070	0.001	
	25%	1.282	0.000	0.014			1.268	0.000	
	75%	3.846	0.001	0.043			3.803	0.000	
	Gross storage	11,575.726	232.701	141.409	309.400	5.270	7.826	57.055	1,359.625
	25% Gross storage	2,893.932	58.175	35.352	77.350	1.318	1.957	14.264	339.906
	75% Gross storage	8,681.795	174.526	106.057	232.050	3.953	5.870	42.791	1,019.719

Table 2. Total storage and total estimated recoverable storage (25% and 75%) of the nine major aquifers of Texas in GMA 9-16. Source: Jigmund and Wade 2013, Jones and Bradley 2013, Jones et al. 2013c., Wade and Anaya 2014, Wade and Bradley 2013, Wade et al. 2014, Wade and Shi 2014a., Wade and Shi 2014b.

TWDB major aquifers		**Aquifer (million acre-feet)**	**Groundwater management area (million acre-feet)**							
			9 (Jones and Bradley 2013)	10 (Jones et al. 2013c.)	11 (Wade and Shi 2014a.)	12 (Wade and Shi 2014b.)	13 (Wade and Bradley 2013)	14 (Wade et al. 2014)	15 (Wade and Anaya 2014)	16 (Jigmund and Wade 2013)
Carrizo - Wilcox	Total storage	5,227.077			2,061.633	1,019.320	1,951.720	19.804	69.900	104.700
	25%	1,306.769			515.408	254.830	487.930	4.951	17.475	26.175
	75%	3,920.308			1,546.225	764.490	1,463.790	14.853	52.425	78.525
Gulf Coast	Total storage	4,163.507			1.447	0.450	2.460	2,776.000	368.800	1,014.350
	25%	1,040.877			0.362	0.113	0.615	694.000	92.200	253.588
	75%	3,122.630			1.085	0.338	1.845	2,082.000	276.600	760.763
Trinity	Total storage	1,405.166	5.280	23.057	0.500	11.100	4.705			
	25%	351.292	1.320	5.764	0.125	2.775	1.176			
	75%	1,053.875	3.960	17.293	0.375	8.325	3.529			
Ogallala	Total storage	380.545								
	25%	95.136								
	75%	285.408								
Pecos Valley	Total storage	323.860								
	25%	80.965								
	75%	242.895								
Edwards - Trinity (Plateau)	Total storage	45.491	2.358							
	25%	11.373	0.590							
	75%	34.118	1.769							
Edwards (BFZ)	Total storage	24.952	0.261	22.878			1.718			
	25%	6.238	0.065	5.719			0.430			
	75%	18.714	0.196	17.158			1.289			
Seymour	Total storage	5.128								
	25%	1.282								
	75%	3.846								
	Gross storage	11,575.726	7.899	45.935	2,063.580	1,030.870	1,960.603	2,795.804	438.700	1,119.050
	25% Gross storage	2,893.932	1.975	11.484	515.895	257.718	490.151	698.951	109.675	279.763
	75% Gross storage	8,681.795	5.924	34.451	1,547.685	773.153	1,470.453	2,096.853	329.025	839.288

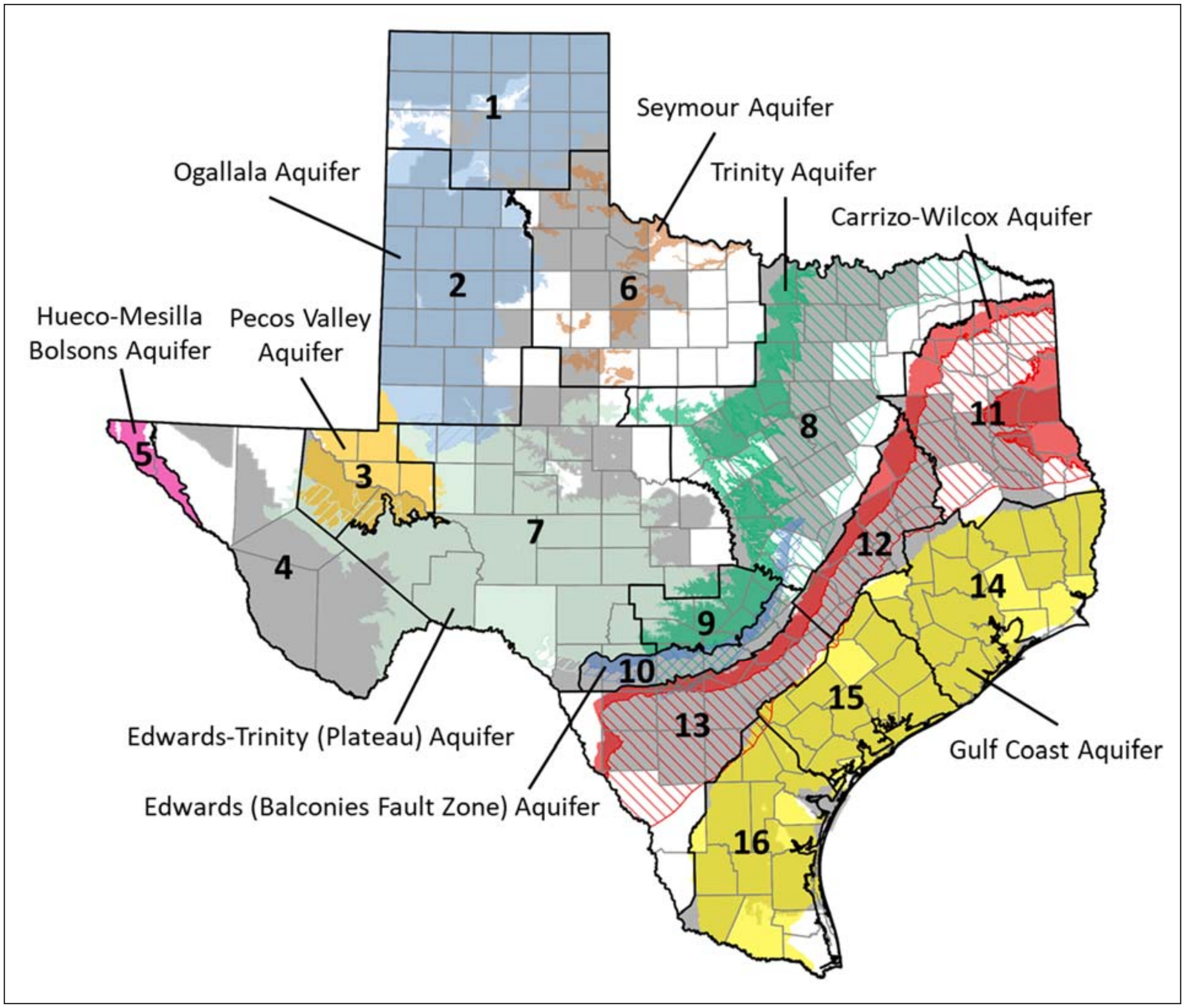

Figure 2. Map of the state's 16 Groundwater Management Areas (numbered) and nine major aquifers (colored). Solid aquifer colors indicate outcrop areas (the part of an aquifer that lies at the land surface) and hatched aquifer colors indicate sub-crop areas (the part of an aquifer that lies or dips below other formations). Gray areas indicate areas regulated by groundwater conservation and subsidence districts. Gray outlines indicate Texas counties. Map generated by ArcGIS with data available from the TWDB at: https://www.twdb.texas.gov/mapping/gisdata.asp.

Methods

To test and develop the MERS model we simulate hydrogeologic characteristics and approximate conditions in the central section of the Carrizo-Wilcox Aquifer under confined and unconfined conditions. This area was selected in part because the Carrizo-Wilcox Aquifer, with the largest total storage in the state, is in close proximity to development corridors and population centers, and in part because much of its water is stored at significant depths under confined conditions. Similarly, hypothetical well characteristics (presumably available to stakeholders and managers applying these methods but estimated here) were derived from representative agricultural demand and approximated aquifer characteristics.

Carrizo-Wilcox Aquifer characteristics were estimated from the literature to represent a simplified version of the generalized conditions present in Bastrop, Burleson, Caldwell, Gonzales, Guadalupe, Lee, Milam, and Wilson counties located within GMA 12 (four counties) and GMA 13 (four counties). Due to limitations in the scope of this study, we assume that the Carrizo-Wilcox Aquifer is both homogenous and isotropic within the study area and this construction is characterized by

Table 3. Hydrogeologic properties assumed for the study area simulation.

Property	Setting	Value	Source
Depth to aquifer bottom	Unconfined	350 feet	(Dutton et al. 2003)
Depth to aquifer bottom	Confined	2,000 feet	
Depth to aquifer top	Confined	1,650 feet	
Initial saturated thickness	All	350 feet	
Specific yield	All	0.15	
Storativity	Confined	$10^{(-3.52)}$	(Mace et al. 2000)
Hydraulic conductivity	All	7 feet per day	(Dutton et al. 2003)

the above idealized and simplified hydrogeological properties (Table 3).

Key assumptions

The limitations of this MERS analysis are akin to those applied to TERS; no consideration is given to subsidence, surface water interaction, or water quality. These are all clearly important issues for groundwater managers and must be considered when adopting DFCs pursuant to Chapter 36 §108(d) of the TWC.

We simulate agricultural uses because this economic sector generally returns the smallest monetized benefit per volumetric unit of water consumed. When compared to industrial or municipal/domestic uses, the volumes demanded are comparatively high and the economic value of the product (crops) is comparatively low (Aylward et al. 2010; Young and Loomis 2014). We therefore assume agricultural users may be considered the most sensitive of all users to prospective changes in recoverability driven by increasing depth-to-water. Additionally, we assume that agricultural users represent a substantial proportion of groundwater ownership under Texas law (which links groundwater ownership to the area of owned overlying land and historical use—see *Edwards Aquifer Authority v. Day-McDaniel*) and therefore those users have significant agency in DFC adoption.

We also assume that agricultural daily water demand is constant, cannot be deferred during the growing season, and cannot be satisfied by alternative sources. We calculate constant daily demand as a function of the irrigated area and the requisite irrigation depth as follows:

$$demand = \left(\left(\frac{irdepth}{12}\right) \times irarea \times 325851\right) \div t \qquad (3)$$

where *demand* is in units of gallons per minute, *irdepth* is the target daily irrigation depth in units of inches (simulated here as 0.5 unless otherwise noted), *irarea* is the area to be irrigated in units of acres (simulated here as 100), 325,851 is the conversion constant from acre-feet to gallons, and *t* is the time of pumping in units of minutes (assumed here to be 1440 minutes, or one day, in all cases).

Reference agricultural harvest values in units of dollars per acre per year are assumed in this simulation to be inclusive of any relevant subsidies and net of all costs external to pumping (such as fertilizer, labor, machinery). Reference harvest values are given by Shaw (2005) as: alfalfa = $440, onions = $778, tomatoes = $1,018, grains = $1,153, and potatoes = $2,792. These values are likely overestimates of the actual net value of all costs unrelated to pumping, but such crop-specific data are difficult to obtain. Thus, we assume that groundwater managers and agricultural users will input this key variable to the MERS model with more precise values for local uses.

Well efficiency, or the energy loss of the well due to friction, is given as a user input to the model and held constant. As most modern pumps have an efficiency of between 50% and 85% (Stringman 2013),depending upon the age of the system, the type of construction, accumulated well screen fouling, the type of power plant, and other factors, we hold operational well efficiency constant at 75% for all calculations.

Finally, we assume that where hypothetical depth-to-water in the confined setting falls below the depth of the top of the aquifer, the groundwater system fully transitions to the unconfined setting. In this way, the same demand-capacity constraints that are applied to the unconfined setting also apply to the confined setting but occur at greater depth. Furthermore, the depth of the bottom of the aquifer in the confined setting is assumed to be the depth of the base of potable water, approximately 2,000 feet in our study area (Dutton et al. 2003).

Aquifer and well performance

Here we use specific capacity to capture the hydrogeologic limitations to production at a given well. Specific capacity has units of length squared per time but is frequently reported in units of volume per time per length of drawdown. For example, a specific capacity of 5 square feet per minute may be reported as 37.4 gallons per minute per foot of drawdown, where the conversion from one form to the other is accomplished by multiplying square feet per minute by the constant 7.48052 gallons per cubic foot. A relationship between specific capacity and pumping dynamics was developed from the Theis (1935) non-equilibrium solution by Theis (1963) and is presented in this form in Mace et al. (2000):

$$\textit{specific capacity} = (4 \times \pi \times T) \div [\ln((2.25 \times T \times t) \div (r^2 \times S))] \quad (4)$$

where *specific capacity* is in units of length squared per time (such as feet squared per minute), T is the transmissivity of the aquifer in units of length squared per time (also equal to the product of hydraulic conductivity and saturated thickness), t is the time of pumping (one day or 1440 minutes), r is the well radius (simulated here as 1 foot to include the gravel pack), and S is the dimensionless storativity of the aquifer (Sy in the unconfined setting and St in the confined setting).

As we are interested in increasing depth-to-water over time (as might occur under DFCs), we iteratively calculate specific capacity by applying transmissivities that decrease as a function of declining saturated thickness (in single foot increments here) to simulate planned and potential changes in depth-to-water.

A representative depth of the top of the well screen (the depth of the bottom of the aquifer minus the length of the well screen interval) is calculated for this MERS simulation from demand and the well screen intake capacity. A representative well screen intake capacity is estimated from the maximum well entry velocity (assumed here at 0.1 feet per second) and the well screen open area (i.e. slot size) derived from grain size distribution of the Carrizo-Wilcox Aquifer which is estimated from hydraulic conductivity using the Hazen (1893) approximation. Here we simulate the smallest well screen interval capable of supporting demand in order to minimize the well screen dead pool.

We then iteratively calculate the maximum pumping rate supported by the hydrogeologic and well characteristics (at all possible depths-to-water) as a function of the specific capacity and the available saturated thickness as:

$$\textit{maximum pumping rate} = \textit{specific capacity} \times s\_max \quad (5)$$

where *maximum pumping rate* is in units of volume per time (such as gallons per minute), *specific capacity* is in units of volume per time per unit of drawdown (such as gallons per minute per foot) as converted from Equation 4, and *s_max* is the maximum possible drawdown given available saturated thickness, simulated here as the difference, in length, between the iterated depth-to-water and the top of the well screen.

Note that where maximum pumping rate values are significantly greater than demand the results may not be plausible with the given well screen (due to well entry velocity and other factors) and are provided for reference only. The maximum pumping rate declines with declining transmissivity and available *s_max* associated with hypothetical dewatering (decreasing saturated thickness) occurring in the unconfined or transitioned setting over time. To avoid pumping air, a certain amount of saturated thickness must be reserved from production to support the well screen interval dead pool and the pumping period drawdown (*s*, which is assumed here equivalent to *s_max* where the maximum pumping rate equals demand). Thus, where the maximum pumping rate equals demand a binding constraint is applied to the MERS model; beyond this depth-to-water, defined here as *h_max*, the aquifer and well can no longer satisfy demand (Figure 3).

While it is possible to pump beyond *h_max* (i.e., where the top of the well screen is exposed), the MERS model does not allow such over pumping as we assume the introduction of air to the system has significant impacts to efficiency and may damage the well. The difference between the initial depth-to-water and *h_max* is defined here as the production range (Figure 3). Within the production range, the aquifer and the well have the physical capacity to satisfy demand. Similarly, we dub the saturated thickness required to support pumping period drawdown which is variable with pumping rate and well characteristics the pumping range (Figure 3). Importantly, the production range and pumping range vary significantly with demand.

Pumping costs

Pumping costs at the well head (or marginal extraction costs) are identified here as the hypothesized binding constraint for agricultural users in deep and confined settings. These are defined as the energy costs required to pump water to the surface at the given hydrogeologic, well and demand conditions. Fixed costs are not considered in this study.

Water horsepower, or the amount of horsepower required to do the work of lifting the given output of water to the discharge point if the well was 100% efficient (Fipps 2015), is defined as:

$$\textit{water horsepower} = (h \times \textit{demand}) \div 3960 \quad (6)$$

where h is the iterated hypothetical depth-to-water in feet and 3,960 is the conversion constant to horsepower.

However, because no well is 100% efficient, the wire-to-water efficiency of the pumping system must adjust water horsepower to calculate the true horsepower applied to run the pump at the observed pumping rate. The pumping rate demand, as adjusted for well efficiency losses, is then directly relatable to dollar costs per unit of pumping time to meet the given demand volume by introducing an applicable power cost rate for the study area to calculate a pumping cost rate at depth-to-water as:

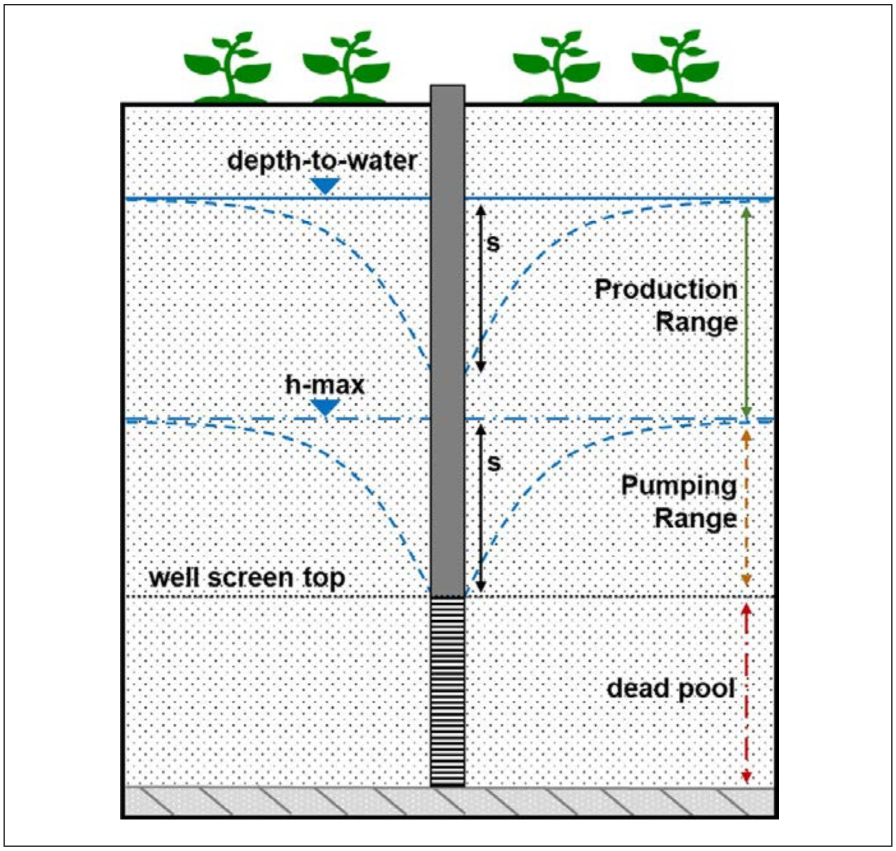

Figure 3. Representation of the aquifer and well constraints associated with pumping applied to the simulation in order to generate demand-capacity constraints.

$$pumping\ cost\ rate = \left(\frac{water\ horsepower}{well\ efficiency}\right) \times 745.7 \times power\ cost\ rate \tag{7}$$

where *pumping cost rate* is in units of dollars per minute, 745.7 is the conversion constant from horsepower to watts, and power cost rate is the applicable *power cost rate* in dollars per watt-minute (assumed $0.07 per kilowatt-hour here).

We can then simplify the pumping cost rate at depth-to-water and demand to dollars per gallon, a form we refer to here as recoverability:

$$recoverability = pumping\ cost\ rate \div demand \tag{8}$$

Pumping costs in the MERS model is then expressed in dollars per pumping period as a function of demand and recoverability as:

$$pumping\ costs = (demand \times t) \times recoverability \tag{9}$$

While we choose to express depth-to-water as all possibilities between the land surface and the aquifer bottom for this study, the range of *h* may be adjusted by the user to evaluate any relevant range of potential depth-to-water changes (such as existing or proposed DFCs).

Depth maximization

Given that most of the simplified relationships evaluated by this simulation are functionally linear, we modify an analytical solution (originally developed by Domenico 1972) for linear optimization of groundwater yields to implement the limitations associated with an aquifer bottom and declines in transmissivity associated with increasing depth-to-water over time. We define *value* as the estimated daily dollar value of irrigation as:

$$value = (harvest\ value \times irarea) \div irrigation\ days \tag{10}$$

where *harvest value* is in units of dollars per area of agricultural production per year (such as dollars per acre per year, a common metric), *irarea* is the user defined area to be irrigated (100 acres simulated here), and *irrigation days* is the number of days in the annual growing season to be irrigated (simulated here as

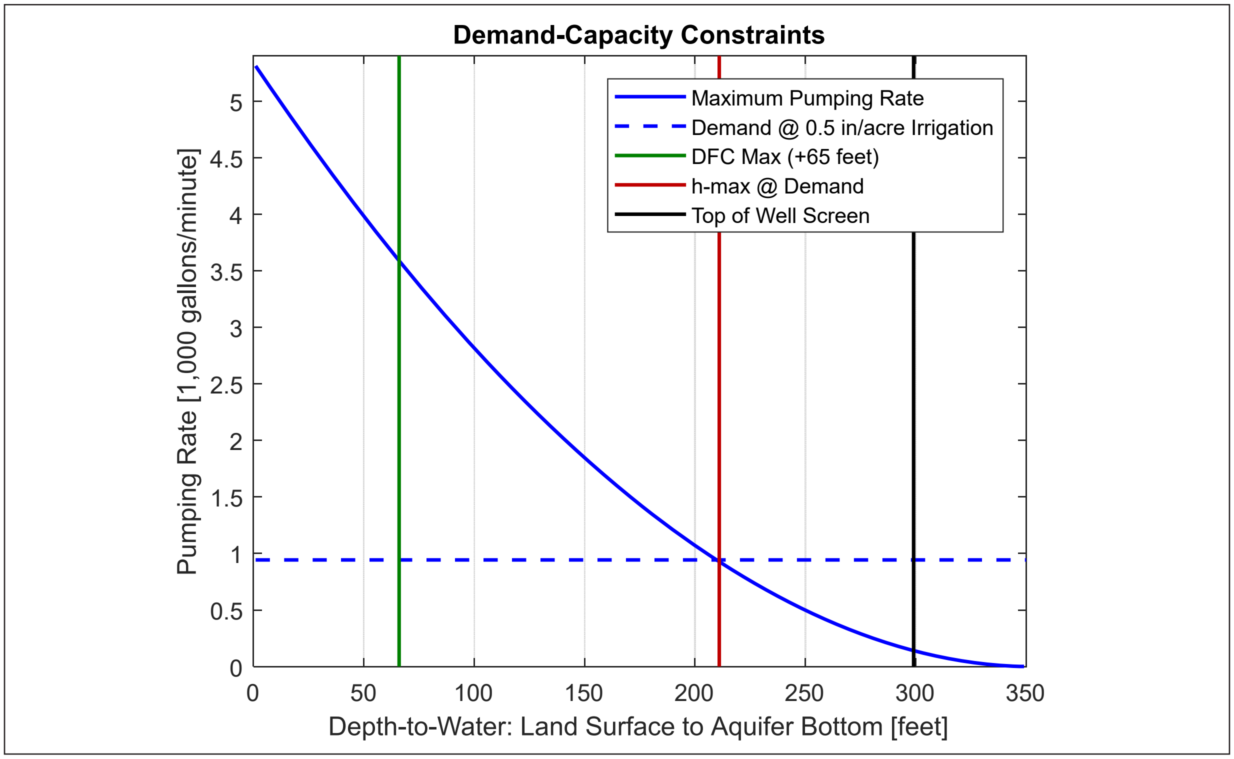

Figure 4. Relationship between maximum pumping rate, demand, and depth-to-water in the unconfined setting given input aquifer, well, and use parameters. The (solid blue) curve is the maximum pumping rate. The only horizontal line (dashed blue) is demand at the given irrigation rate. From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the second vertical line (solid red) represents *h_max*, the third vertical line (solid black) indicates the top of the well screen. Note that where maximum pumping rate values are significantly greater than demand the results may not be plausible with the depicted well screen interval due to well entry velocity and other factors. Simulation generated by MATLAB.

111 days per year = 37 growing season weeks per year multiplied by 3 irrigation days per week).

With pumping costs and value determined we are able to generate a simple profit function in terms of dollars per irrigation day:

$$profit = value - pumping\ costs \tag{11}$$

Because *value* is constant here and *pumping costs* increase linearly with increasing depth-to-water, *profit* falls linearly to zero where *pumping costs* are equivalent to *value*. Beyond this point the irrigator is theoretically losing money if pumping continues and, if no other constraint is limiting, this constraint is binding on the MERS model. This ensures a global solution to the optimization problem and creates an objective limit to economic recoverability.

Altogether, the MERS simulation applies three key limitations as constraints upon recoverability: (1) saturated thickness screened by the well, (2) the saturated thickness necessary to accommodate drawdown at demand, and (3) the depth-to-water at which value is equivalent to pumping costs. The smallest depth-to-water value (i.e., the most constraining limitation) is then applied to derive the maximum recoverable depth-to-water.

Results

Shallow and unconfined storage (addressing H1)

Two factors limit physical yield capacity: (1) dewatering (increasing depth-to-water which reduces saturated thickness), and (2) variability in pumping rates. In effect, the well screen dead pool and the pumping range together serve to simulate an effective aquifer bottom and thereby introduce physical constraints on yields in the form of production capacity.

As the saturated thickness of the aquifer decreases, the maximum pumping rate supported by the well and aquifer decreases non-linearly (Figure 4). The DFC with the largest increase

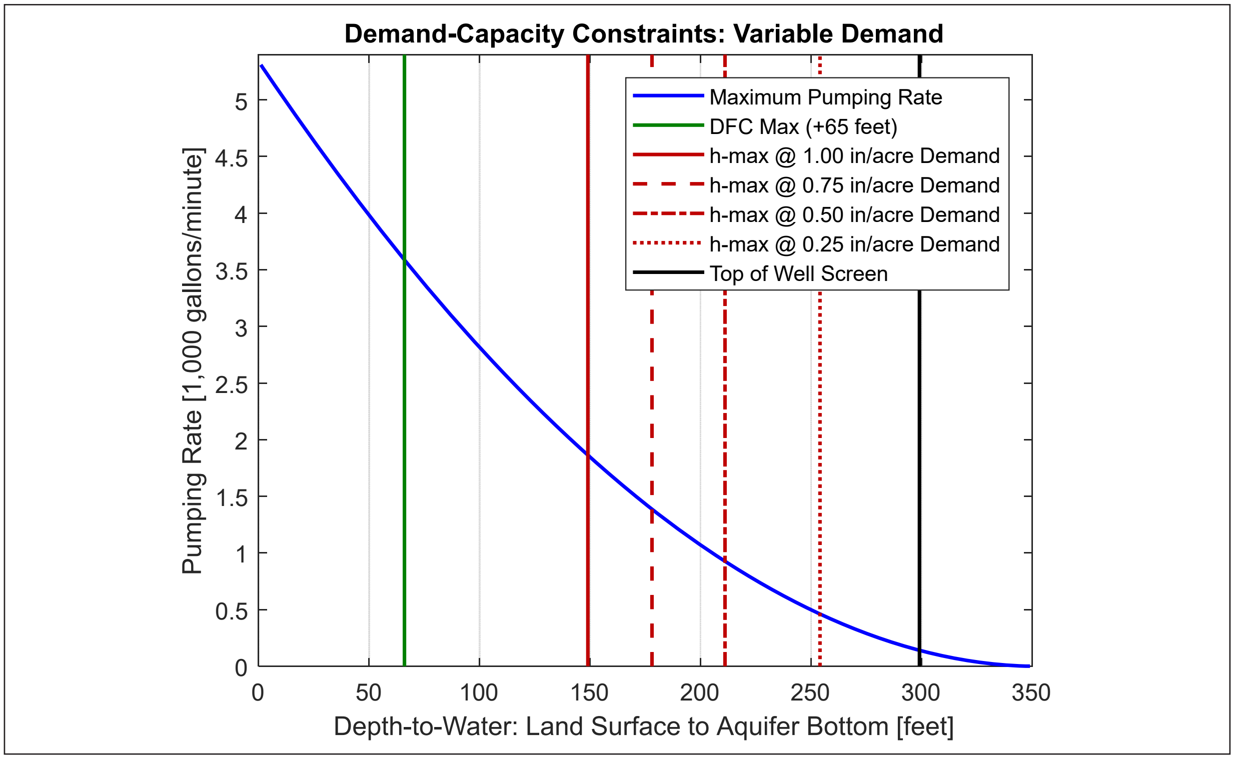

Figure 5. Relationship between maximum pumping rate, varying demand, and depth-to-water in the unconfined setting given input aquifer, well, and use parameters. The (solid blue) curve is the maximum pumping rate. From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the four red vertical lines indicate *h_max* at irrigation demand of 1.00 inches per acre per day (solid), 0.75 inches (dashed), 0.50 inches (dash-dot), and 0.25 inches (dotted), and the fifth vertical line (solid black) indicates the top of the well screen (generated for demand at 0.5in/acre irrigation). Simulation generated by MATLAB.

in depth-to-water within the simulated study area is 65 feet of drawdown over 50 years (in Burleson and Milam counties, GCD #71) and provided for reference. Specific capacity, the first component of the maximum pumping rate, falls with declines in transmissivity (Equation 3), which in turn falls with declining saturated thickness. Similarly, the maximum distance between the initial depth-to-water and the top of the well screen (i.e., *s_max*), the second component of maximum pumping rate, falls linearly with declining saturated thickness. Thus, at some depth-to-water, the transmissivity and available pumping range are insufficient to support the demanded pumping rate and resultant drawdown under pumping. Here a binding constraint is applied to the model: beyond this depth (*h_max*) the aquifer and well do not have sufficient capacity to meet irrigation demand.

The higher the pumping rate demanded is, the greater the drawdown under pumping and resultant pumping range are. Naturally, where the pumping range increases, the production range decreases as additional saturated thickness is reserved from production to accommodate the increased drawdown. Importantly, our results indicate that impacts to the pumping and production ranges are significant within the potential range of irrigation demand for various crops. Here we simulate irrigation depths (which drive demand) from 0.25 inches per acre per day to 1.00 inch per acre per day to evaluate the changes in the pumping range (Figure 5). When irrigation demand is 0.25 inches, *h_max* is over 250 feet (over 80% of the unscreened saturated thickness is physically recoverable); but when the irrigation demand is 1.00 inch, *h_max* is less than 150 feet (approximately 50% of the unscreened saturated thickness is physically recoverable). Thus, smaller pumping rates may extract from greater depths than larger pumping rates before reaching the demand-capacity constraints of the well and aquifer.

Simulated pumping costs increase linearly with depth-to-water to a maximum of $33.41 per acre-foot at the aquifer bot-

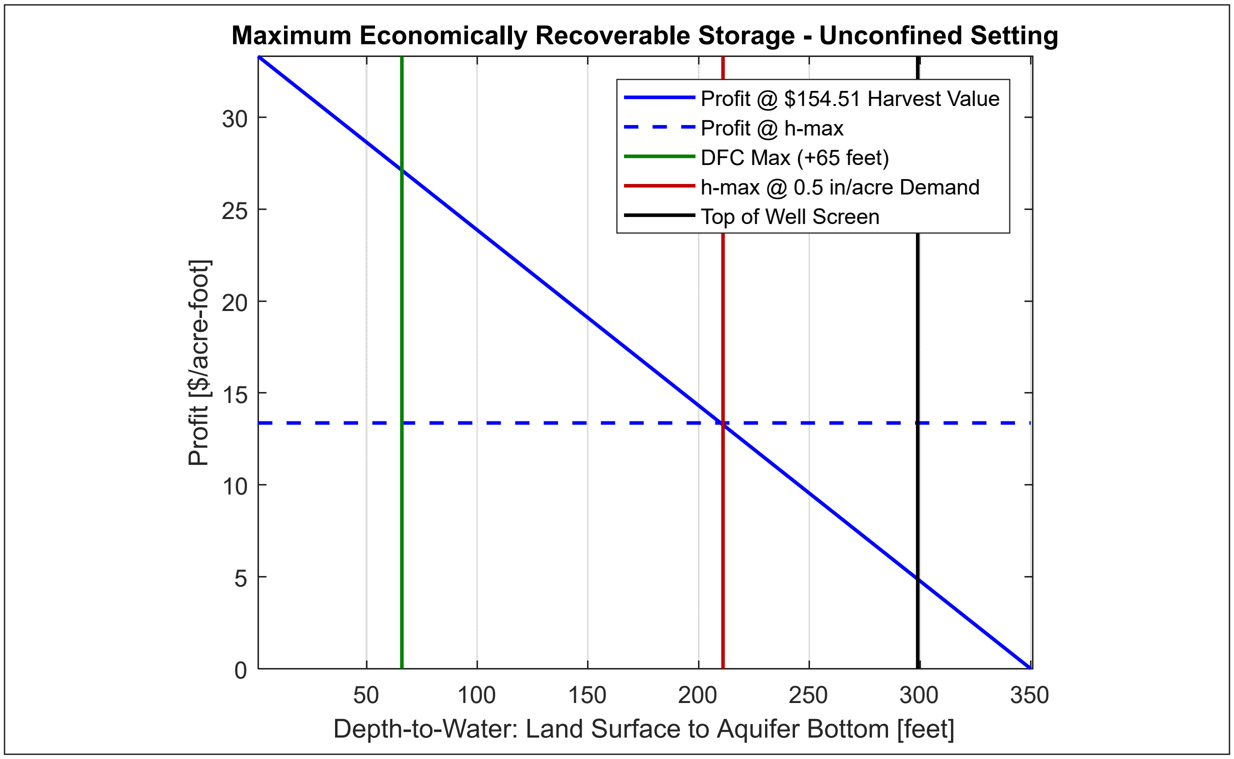

Figure 6. Maximum economically recoverable storage where harvest value is $154.51 per acre per year and irrigation demand is 0.5 inches per acre per day in the unconfined setting. The (solid blue) diagonal line reflects the linear change in profit as pumping costs increase with depth-to-water. The only horizontal line (dashed blue) is profit at the binding demand-capacity constraint (*h_max*). From left to right: The first vertical line (solid green) is the deepest depth-to-water based DFC found in the representative study area of the Carrizo-Wilcox Aquifer (+65 feet), the second vertical line (solid red) represents *h_max* (binding here), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

tom (a depth of 350 feet) while profit falls linearly with increasing depth-to-water. The harvest value point at which profit is equivalent to pumping costs at the depth of the bottom of the aquifer (350 feet) is found to be $154.51 per acre per year. At this harvest value, profit is $13.27 per acre-foot of groundwater pumped at the above *h_max* depth of 211 feet—less than 40% of the initial value.

Importantly, a $154.51 harvest value falls well below even the lowest reference harvest value considered here, which is alfalfa at the price of $440 per acre per year. This suggests that many or all harvest values may be sufficient to dewater the full production range before profit falls to zero in shallow and unconfined settings.

Thus, where irrigation demand is 0.50 inches per acre per day, the irrigated area is 100 acres, and the harvest value is $154.51 per acre per year, the binding MERS constraint in the unconfined setting is the demand-capacity constraint (*h_max*), simulated at a maximum depth of 211 feet or 71% of the unscreened saturated thickness (Figure 6). The demand-capacity constraint (*h_max*) simulated here in the unconfined setting exceeds this maximum DFC depth by over 140 feet.

These results confirm H1: simulated recoverability is constrained by demand-capacity limitations in shallow and unconfined settings for all irrigation demand rates and harvest values. However, the reference harvest values noted here are estimates and may not represent true agricultural values net of all costs beyond those explicitly considered here. Moreover, pumping costs are not insignificant to agricultural users. Determining what reduction in profit irrigators are willing to accept as pumping costs rise is another matter not considered here beyond the economically inefficient limit of profit = 0.

Deep and confined storage (addressing H2)

The methods for calculating MERS in the confined setting have several important distinctions from the methods used in

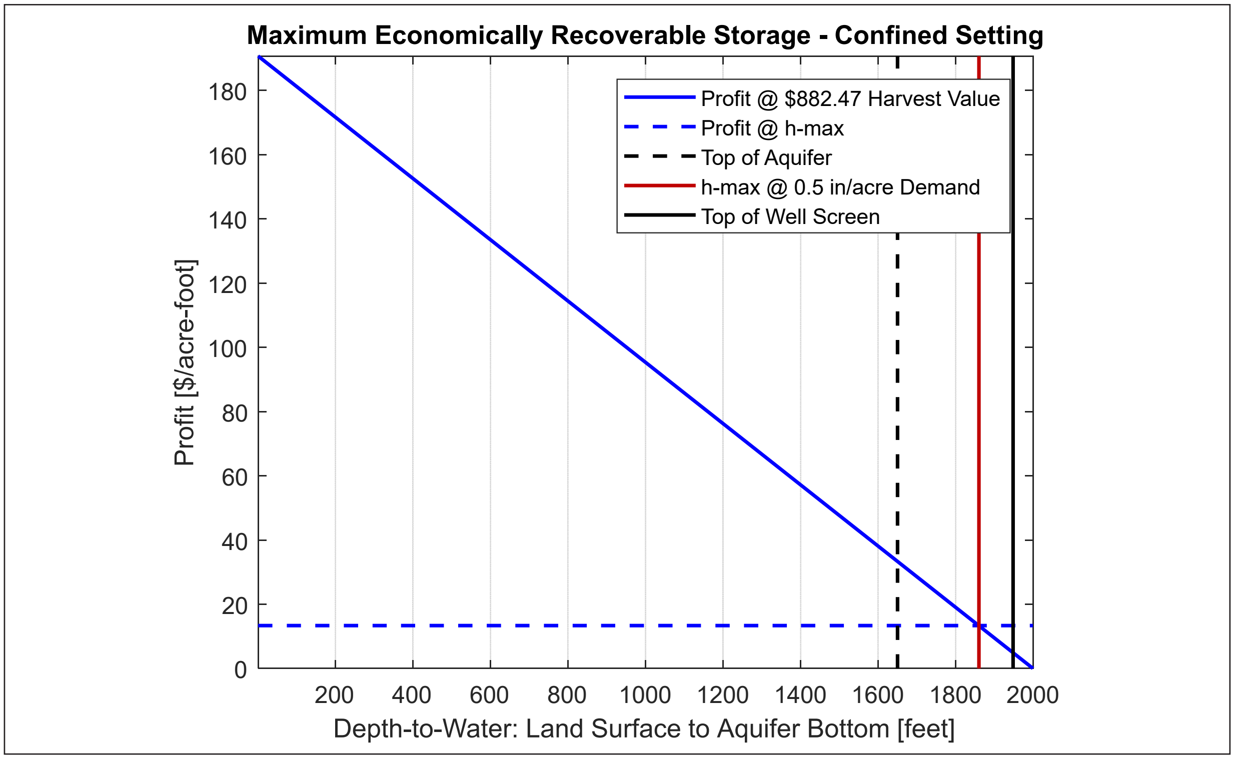

Figure 7. Maximum economically recoverable storage where harvest value is $882.47 per acre per year and irrigation demand is 0.5 inches per acre per day in the confined setting. The (solid blue) diagonal line reflects the linear change in profit as pumping costs increase with depth-to-water. The only horizontal line (dashed blue) is profit at the binding demand-capacity constraint (*h_max,* binding here). From left to right: The first vertical line (dashed black) is the depth of the top of the aquifer, the second vertical line (solid red) represents *h_max* (binding here), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

the unconfined setting. In this construct of the Carrizo-Wilcox Aquifer the simulated depth to the bottom of the aquifer is much deeper in the confined setting (2,000 feet) than the unconfined setting (350 feet). The depth to the top of the aquifer (1,650 feet) is introduced as a new variable to create a distinction between the pressurized storage of the aquifer and pore space storage. Accordingly, the well screen and pumping range occur at significant depth (within the saturated thickness of the aquifer). Thus, the demand-capacity constraint considered by the MERS model is also at great depth (Figure 7) and, while present, may not be binding in light of economic impacts.

Pumping cost impacts to recoverability within the production range are significant in deep and confined settings. Pumping costs at the depth of the bottom of the aquifer (2,000 feet) reflect the increased depth and are found to be $190.90 per acre-foot, or roughly 5.71 times the $33.41 pumping costs at the aquifer bottom in the shallower, unconfined case (350 feet). Similarly, the harvest value point where profit = 0 at the depth of the bottom of the aquifer (2,000 feet) is found to be $882.47 per acre per year; again, this is 5.71 times the comparable $154.51 harvest value above as changes in pumping costs are linear (5.71 is equivalent to the change in depth, 2,000 feet / 350 feet). Where harvest value is $882.47 per acre per year, profit is $13.27 per acre-foot of groundwater pumped at the *h_max* depth of 1,860 feet—less than 7% of the initial value.

Agricultural users experience much greater changes in pumping costs over the full production range in the confined setting because the range of depths is greater, and those changes are sufficient to make a clear difference in recoverability among crop types (Figure 8). For example, alfalfa harvest values are insufficient to allow positive profit long before depth-to-water reaches the top of the aquifer (and transitions it from the confined to the unconfined state), but tomato harvest values are sufficient to reach the demand-capacity constraint (Figure 8). Note that demand is constant at an irrigation rate of 0.5 inches per acre per day for all simulated harvest values shown here (Figure 8), but higher value crops may require greater irrigation demand than lower value crops. Additionally, simulated harvest values are likely overestimates of the actual net value of all costs unrelated to pumping (see key assumptions).

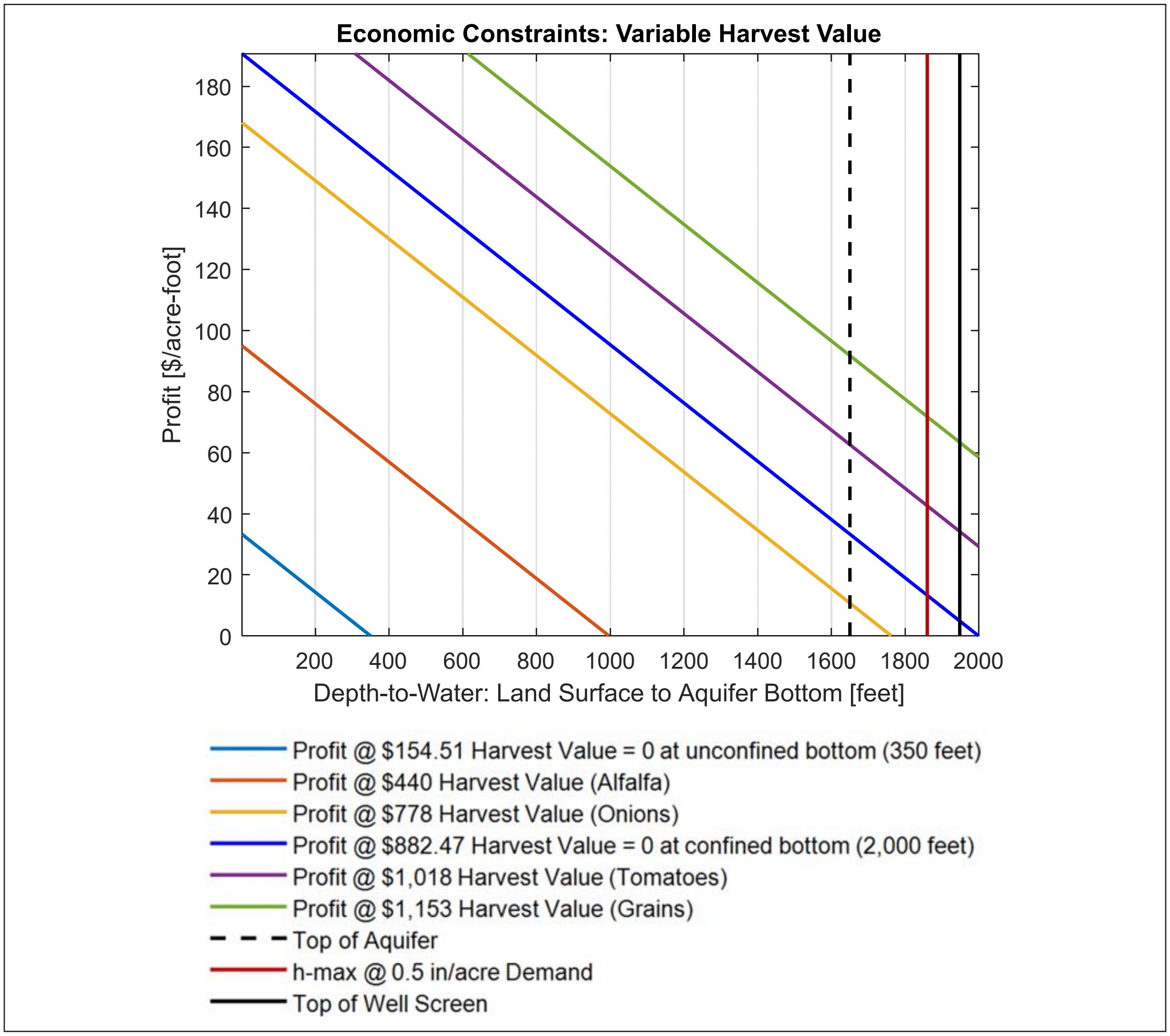

Figure 8. Profit function over increasing depth-to-water in the confined setting for a range of reference and representative harvest values. The diagonal lines reflect the linear changes in profit as pumping cost increases with depth-to-water for given harvest values. From left to right: The first vertical line (dashed black) is the depth of the top of the aquifer, the second vertical line (solid red) represents *h_max* (where irrigation demand is 0.5 inches per acre), and the third vertical line (solid black) indicates the top of the well screen. Simulation generated by MATLAB.

These results confirm H2, that simulated recoverability in deep and confined settings is constrained by economic limitations for some uses (harvest values) at all irrigation (demand) rates, restricting them to producing from pressurized storage.

DISCUSSION

Whether Texas is running out of groundwater or experiencing a regulation-induced shortage depends upon how one assesses groundwater availability. At the same time, there is no universal groundwater availability assessment method for the state as availability is a function of many, potentially conflicting management objectives. The methods developed here define MERS as a simplified simulation of the physical and economic limitations to groundwater recoverability; key elements of availability common to all human groundwater demand absent from total storage and TERS.

Our results indicate that recoverability is a function of use, aquifer characteristics, and well infrastructure. Here we show the capacity of an aquifer to meet demand is a function of transmissivity where transmissivity declines with increasing depth-to-water. Together with well screen limitations and drawdown under pumping, a maximum depth-to-water with the capacity to satisfy the demanded pumping rate is established as a binding constraint. While simple in concept, these constraints are absent from many publications in the literature that assume a bottomless aquifer of infinite areal extent. This demand-capacity constraint is found to be binding in shallow and unconfined settings simulated here and exceeds maximum established DFCs for all agricultural uses. Changes in pumping costs are shown to be significant to agricultural users and directly associated with changes in depth-to-water in both the confined and unconfined settings. Indeed, while the capacity of deep and confined aquifers to meet demand is high, the costs associated with reaching the depth-to-water necessary to extract much of that storage may be economically prohibitive for some uses. In all cases, users are economically incentivized to minimize pumping costs (and thereby depth-to-water) irrespective of confined or unconfined setting.

Critically, our results further suggest that storage-based estimates that do not incorporate the physical and economic constraints of pumping (such as TERS, at either percentile benchmark) may overestimate groundwater availability in deep and confined settings by orders of magnitude due to the change in storage coefficient assumed when an aquifer transitions from confined to unconfined state (Equation 2). This manifests for uses where pumping from depth-to-water at or below the top of the confined aquifer is infeasible.

For example, the local total storage volume for a 100-acre farm pumping in deep and confined settings, where the initial depth-to-water is 350 feet above land surface (artesian), would be 5,313.25 acre-feet (Equation 2 and Table 3). Related TERS volumes would be 3,984.93 acre-feet (at 75% of local total storage) and 1,328.31 acre-feet (at 25% of local total storage). However, if we apply the above conditions and assumptions to an alfalfa farm, we see that the MERS model constrains the maximum recoverable depth-to-water to the depth where profit = 0 at approximately 1,000 feet (Figure 8). We can then calculate the local MERS volume by integrating this simulated depth-to-water recoverability limit with the relevant elements of the total storage calculation (Equation 2). The MERS model would thus estimate that only 42.69 acre-feet is recoverable for this use, about 0.8% of the local total storage or 1.1% and 3.2% of comparable TERS estimates.

Thus, while the Carrizo-Wilcox Aquifer stores 5.227 billion acre-feet of water, or 45% of the total 11.575 billion acre-feet stored by all major aquifers of the state (Tables 1 and 2), the overwhelming majority of that storage may be unrecoverable, by these standards, for some uses and locations due to the change in depth necessary to transition the aquifer from the confined to unconfined state.

Importantly, while we choose to simulate agricultural uses operating in the central section of the Carrizo-Wilcox Aquifer, the MERS model may be applied to any aquifer and any use to estimate groundwater recoverability where demand and the economic value generated by pumped groundwater are known and effectively constant. Moreover, the MERS model is deliberately designed to be calculable with commonly held data (such as specific capacity) without the need for advanced computing and mathematics, perhaps increasing accessibility.

We suggest that groundwater policymakers, managers, and producers consider including MERS (or a similar metric) along with TERS and the other considerations of Chapter 36 §108(d)(3) of the TWC, especially in jurisdictions operating under a depth-to-water based DFC. Even a simple estimate of how groundwater recoverability changes with depth-to-water for variable uses, such as when certain pumping demands become infeasible for various crop or other use values, may prove useful. Failure to account for demand-capacity constraints and the economic impact to pumping costs arising from prospective changes in depth-to-water may result in overestimates of groundwater availability.

CONCLUSION

We conclude that Texas groundwater managers, stakeholders, and policymakers assessing groundwater availability need an alternate approach for estimating recoverability. The current metrics employed by the state for estimating groundwater storage and recoverability, total storage and TERS, are highly limited in scope and function. Irrespective of the name, TERS values do not scientifically account for many of the physical and none of the economic constraints upon groundwater recoverability, as noted by the TWDB (Bradley 2016).

The system of equations described above, which constitute the MERS model, represents one method for estimating the limits of groundwater recoverability that accounts for some of the physical and economic constraints upon yields. These constraints can be significant and may limit recoverability to as little as 1% of local storage (or 1.1% and 3.2% of comparable TERS estimates) in deep and confined settings. This suggests that the majority of water stored in the Carrizo-Wilcox Aquifer (45% of major aquifer storage in Texas) may not be economically recoverable for some agricultural uses. Conversely, recoverability of water stored in shallow and unconfined settings may be limited only by the capacity of the well and aquifer to meet demanded pumping rates.

Future studies expanding on these methods may refine drawdown estimates by replacing specific capacity estimates with drawdown solutions that account for partial well penetration, though the analyses would become more complex. These or similar methods could also be integrated with the TWDB groundwater availability model and groundwater database data to estimate local recoverability for any use and aquifer.

Ultimately, what is recoverable for a microchip manufacturer may not be the same as what is recoverable for a farmer, and what is recoverable for an alfalfa farmer may not be the same as what is recoverable for a tomato farmer. Moreover, the limits to what is economically recoverable for any user are not economically efficient and pumping costs increase for all users in all cases where depth-to-water increases. Nonetheless, quantifying planned and potential changes to groundwater recoverability using scientific methods with known assumptions, conditions, and infrastructure provides important information for Texas policymakers and stakeholders looking to the future.

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REFERENCES

Aylward B, Seely H, Hartwell R, Dengel J. 2010. United Nations Food and Agriculture Organization. The economic value of water for agricultural, domestic and industrial uses: a global compilation of economic studies and market prices. Prepared by Ecosystem Economics LLC. Available from: https://www.researchgate.net/publication/284848775_The_economic_value_of_water_for_agricultural_domestic_and_industrial_uses_a_global_compilation_of_economic_studies_and_market_prices.

Boghici R, Jones IC, Bradley RG, Shi J, Goswami RR, Thorkildsen D, Backhouse S. 2014. GAM Task 13-028: total estimated recoverable storage for aquifers in groundwater management area 4. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-028.pdf.

Bradley R. 2016. Aquifer assessment 16-01: supplemental report of total estimated recoverable storage for groundwater management area 10. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/AA/AA16-01_TERS.pdf.

Brady R, Beckerman W, Capps A, Kennedy B, McGee P, Northcut K, Parish M, Qadeer A, Shan A, Griffin J. 2016. Reorganizing groundwater regulation in Texas. Bush School of Government and Public Service. College Station (Texas): Texas A&M University. Available from: https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/187041/2016%20Final%20Report%20Reorganizing%20Groundwater%20Regulation%20in%20Texas%20%283%29.pdf?sequence=1&isAllowed=y.

Domenico P. 1972. Concepts and models in groundwater hydrology. New York (New York): McGraw-Hill. 395 p. ISBN 07-017535-7.

Dutton A, Harden B, Nicot JP, O'Rourke D. 2003. Groundwater Availability Model for the Central Part of the Carrizo-Wilcox Aquifer in Texas. Prepared for the Texas Water Development Board under contract no. 2001-483-378. Austin (Texas): Bureau of Economic Geology, the University of Texas at Austin. 405 p. Available from: http://www.twdb.texas.gov/groundwater/models/gam/czwx_c/czwx_c_full_report.pdf.

Edwards Aquifer Authority v. Day-McDaniel. Supreme Court of Texas. Case Number 08-0964. Decided February 24, 2012. Available from: https://caselaw.findlaw.com/tx-supreme-court/1595644.html.

Fipps G. 2015. Calculating horsepower requirements and sizing irrigation supply pipelines. Texas Agricultural Extension Service. College Station (Texas): Texas A&M University. 11 p. Available from: http://faculty.missouri.edu/~schumacherl/Fipps,%20G.%20(n.d.)%20Calculating%20Horsepower%20Requirements%20and%20Sizing%20Irrigation%20Supply%20Pipelines.%20Texas%20Agricultural%20Extension%20Service,%20Texas%20A&M%20University%20System..pdf.

Hazen A. 1893. Some physical properties of sands and gravels. Massachusetts Board of Health. 24th Annual Report. 539–556.

Jigmund M, Wade S. 2013. GAM Task 13-025: total estimated recoverable storage for aquifers in groundwater management area 16. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/GR12-025.pdf.

Jones IC, Boghici R, Kohlrenken W, Shi J. 2013a. GAM Task 13-027: total estimated recoverable storage for aquifers in groundwater management area 3. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-027.pdf.

Jones IC, Bradley RG. 2013. GAM Task 13-032: total estimated recoverable storage for aquifers in groundwater management area 9. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-032.pdf.

Jones IC, Bradley RG, Boghici R, Kohlrenken W, Shi J. 2013b. GAM Task 13-030: total estimated recoverable storage for aquifers in groundwater management area 7. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-030.pdf.

Jones IC, Shi J, Bradley R. 2013c. GAM Task 13-033: total estimated recoverable storage for aquifers in groundwater management area 10. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-033.pdf.

Kohlrenken W. 2015. GAM Task 15-006: total estimated recoverable storage for aquifers in groundwater management area 1. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: https://www.twdb.texas.gov/groundwater/docs/GAMruns/Task15-006.pdf

Kohlrenken W, Boghici R, Jones I. 2013a. GAM Task 13-026: total estimated recoverable storage for aquifers in groundwater management area 2. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-026.pdf.

Kohlrenken W, Boghici R, Shi J. 2013b. GAM Task 13-029: total estimated recoverable storage for aquifers in groundwater management area 6. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-029.pdf.

Mace R, Petrossian R, Bradley R, Mullican WF, Christian L. Texas Water Development Board. 2008. A streetcar named desired future conditions: the new groundwater availability for Texas (revised). In: Proceedings of The Changing Face of Water Rights in Texas; 2008 May 8–9; Bastrop (Texas): State Bar of Texas; 21 p. Available from: http://www.twdb.texas.gov/groundwater/docs/Streetcar.pdf.

Mace R, Smyth R, Xu L, Liang J. 2000. Transmissivity, hydraulic conductivity, and storativity of the Carrizo-Wilcox Aquifer in Texas. Prepared for the Texas Water Development Board under contract no. 99-483-279, Part 1. Austin (Texas): Bureau of Economic Geology, University of Texas Austin. Available from: http://www.beg.utexas.edu/files/publications/contract-reports/CR2000-Mace-1.pdf.

Nielsen-Gammon JW, Banner JL, Cook BI, Tremaine DM, Wong CI, Mace R, Gao H, Yang ZL, Gonzalez MF, Hoffpauir R, Gooch T, Kloesel K. 2020. Unprecedented drought challenges for Texas water resources in a changing climate: what do researchers and stakeholders need to know? Earth's Future. 8(8):1-20. Available from: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020EF001552.

Shaw WD. 2005. Water resource economics and policy: an introduction. Cheltenham (United Kingdom): Edward Elgar Publishing. 364 p. ISBN 1-84376-917-4.

Shi J, Bradley RG, Wade S, Jones I, Anaya R, Seiter-Weatherford C. 2014. GAM Task 13-031: total estimated recoverable storage for aquifers in groundwater management area 8. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-031.pdf.

Stringman B. 2013. Understanding horsepower and water horsepower efficiency and fuel consumption costs for irrigation pumps. Las Cruces (New Mexico): New Mexico State University. 2 p. Available from: http://aces.nmsu.edu/pubs/_m/M227.pdf.

Texas Administrative Code Texas, Title 31 – Natural Resources and Conservation, Part 10 – Texas Water Development Board, Chapter 356 – Groundwater Management, Subchapter A – Definitions, Rule § 356.10. Available from: http://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=31&pt=10&ch=356&rl=10.

Texas Water Code, Title 2 – Water Administration, Subtitle C – Water Development, Chapter 16 – Provisions Generally Applicable to Water Development, Subchapter A – General Provisions. Available from: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.16.htm.

Texas Water Code, Title 2 – Water Administration, Subtitle E – Groundwater Management, Chapter 36 – Groundwater Conservation Districts, Subchapter A – General Provisions. Available from: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.36.htm.

[TWDB] Texas Water Development Board. 2016. 2017 state water plan – water for Texas. Austin (Texas): Texas Water Development Board. 150 p. Available from: http://www.twdb.texas.gov/waterplanning/swp/2017/index.asp.

Theis CV. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. American Geophysics Union. 16:519-524. Available from: https://water.usgs.gov/ogw/pubs/Theis-1935.pdf.

Theis CV. 1963. Estimating the transmissivity of a water-table aquifer from specific capacity of a well. Washington (District of Columbia): United States Department of the Interior. U.S. Geological Survey Water-Supply Paper 1536-I. 332-336. https://pubs.usgs.gov/wsp/1536i/report.pdf.

Wade S, Anaya R. 2014. GAM Task 13-038: total estimated recoverable storage for aquifers in groundwater management area 15. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-038.pdf.

Wade S, Bradley R. 2013. GAM Task 13-036: total estimated recoverable storage for aquifers in groundwater management area 13. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-036revised.pdf.

Wade S, Shi J. 2014a. GAM Task 13-034: total estimated recoverable storage for aquifers in groundwater management area 11. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-034.pdf.

Wade S, Shi J. 2014b. GAM Task 13-035: total estimated recoverable storage for aquifers in groundwater management area 12. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-035_v2.pdf.

Wade S, Thorkildsen D, Anaya R. 2014. GAM Task 13-037: total estimated recoverable storage for aquifers in groundwater management area 14. Austin (Texas): Texas Water Development Board, Groundwater Resources Division. Available from: http://www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-037.pdf.

Young RA, Loomis JB. 2014. Determining the economic value of water: concepts and methods. 2nd edition. New York (New York): RFF Press. 337 p. ISBN 978-0-415-83846-7.

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Commentary: Water: A Preventable Disaster

Texas Senator Charles Perry[1]

Editor-in-Chief's Note: The opinion expressed in this commentary is the opinion of the individual author and not the opinion of the Texas Water Journal or the Texas Water Resources Institute.

[1] Texas Senator Charles Perry, Senate District 28, Chair of the Senate Committee on Water and Rural Affairs

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As we enter the 87th Session of the Texas Legislature, we will once again confront disaster just as we did at the beginning of last session. This time, we are not mitigating a catastrophic weather event but recovering from a pandemic that resulted in business shutdowns, high unemployment, and a state budget deficit. This session will be about lessons learned (good and bad) while developing best practices for the next storm to come.

Over 5 million Texans filed for unemployment insurance benefits in 2020 with over 4 million COVID-19 related job losses (Texas Workforce Commission UI Claimant Dashboard n.d.). Throughout the pandemic, Senate District 28 had over 12,000 new unemployment claims from all industry sectors (Texas Workforce Commission UI Claimant Dashboard n.d.). There is no doubt this legislative session will focus on our state's resiliency and road to recovery.

As tragic as COVID-19 is, it cannot be a reason to stop long-term planning. Transportation, education, infrastructure, and principally, water supply development must continue to be a priority. Part of a resilient Texas lies with the focus on our state's natural resources. As I have repeatedly said, the future of our economy is built on a stable and reliable water supply. Businesses have continued to move to Texas, but they will not if Texas does not have the ability to meet their infrastructure needs. By drawing on Texas ingenuity, we can leverage technology, public-private partnerships, and regulations that will encourage the creation of new water sources while expanding existing strategies.

Following the 86th Legislative Session, it was my intention to dive deep into what our state can do for future water supply. The pandemic derailed planned interim hearings with water experts. However, I continued to hold meetings and request information from stakeholders in produced water management, aquifer storage and recovery, water reuse, and more for our interim report.

There are over 34,000 disposal wells in the state according to the Texas Railroad Commission. In 2017, there were 9.8 billion barrels of produced water which is over 1 million acre feet. Nearly 47% of the produced water was used for enhanced oil recovery with the remaining 53% injected into the ground for disposal (16 August 2019 meeting with Leslie Savage, Chief Geologist, Texas Railroad Commission; unreferenced). What if Texas could capture all produced water and turn it into a viable water source? Through our research, we found that many in the oil and gas industry and commercial water recycling groups have the technology. Scalability, distribution, and economic models have not been developed to determine the viability of converting produced water to a potable source. A bill to determine viability will be introduced in this legislative session. Consolidating all the technologies and stakeholder groups into one room to work together is needed. It is my intention to continue to encourage the partnership of science, private industry, and the state to tap into this potential water supply.

As a reminder, Texas entered drought quickly in Fall 2020. COVID-19 caught us by surprise; there is no excuse for a deficient water supply to catch us by surprise. Texas and the nation can prevent water scarcity. Our state is anchored by the Gulf of Mexico, with rivers, aquifers, and reservoirs for water resources and storage capacity. If we have a water supply issue, we must look no further than the mirror. Texas can do this!

REFERENCES

Texas Workforce Commission UI Claimant Dashboard. n.d. Austin (Texas): Texas Workforce Commission. Updated 23 November 2020. Accessed 23 November 2020. https://texasmapsonline.com/portal/apps/MapSeries/index.html?appid=e3e490c4196a45868610f65b72e9f303.