Potential Economic Impacts of Environmental Flows for Central Texas Freshwater Mussels

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EXECUTIVE SUMMARY

Problem and Objective

Water management issues are taking on greater importance in Texas. Population growth of 80 percent (from 25 to 46 million people) is expected in the state between 2010 and 2060. This growth will further stress water supplies that are already taxed by climate variability and drought. Agricultural losses totaled $7.6 billion during the 2011 drought.

The U.S. Fish and Wildlife Service (USFWS) has identified five freshwater unionid mussel species (Texas fatmucket, Texas pimpleback, golden orb, Texas fawnsfoot, and smooth pimpleback) and is considering them for possible inclusion on the Federal list of endangered wildlife. These mussel species are not currently listed, but if they were, the Endangered Species Act (ESA) would require preservation of their aquatic habitat. Preserving habitat may necessitate the guarantee of environmental flows (EF) in certain streams and rivers, especially in Central Texas, where the highest diversity of mussels is found. Reserving this water for habitat preservation may further constrain the supply of water for human usage.

Of concern to this study are potential economic impacts caused by reductions or reallocations of water following a possible ESA listing. Critical habitat designation and/or changes in other activities following a listing could have other important economic impacts, but those are outside the scope of this study. The objective of this study was to (1) characterize the hydrology of Central Texas streams where mussels are found, focusing on the Brazos, Colorado, and Guadalupe-San Marcos River basins (36% of Texas, ~95,000 square miles); (2) estimate possible EF requirements to maintain mussel habitats; (3) evaluate where potential water supply reductions caused by EFs may occur; and (4) assess potential economic impacts of EFs in order to allow the state to plan and mitigate impacts.

Methods

In consultation with biologists, 10 mussel locations in the Brazos, Colorado, and Guadalupe-San Antonio River basins were identified that coincide with zones of high economic activity (near San Antonio, Austin, and Waco). Hydrologic conditions in Central Texas streams were characterized by identifying those streams that are maintained by groundwater inflows during drought. These streams were identified using (1) hydrographs of long-term stream discharge data, groundwater-fed base flow, and precipitation; (2) flow-duration curves (FDC); (3) base flow index (BFI; i.e., ratio of base flow to streamflow); (4) streamflow indices derived from FDC; and (5) an assessment of spring distribution. Because biologists are still determining exact mussel habitat needs, plausible EFs were calculated using historic stream-gauge records at mussel sites for low EFs (i.e., EF represented by a stream discharge with a 95% probability of exceedance) and high EFs (i.e., stream discharge with a 75% probability of exceedance).

Water supply reductions caused by maintaining an instream flow as a senior water right at mussel sites were simulated using the Water Availability Model (WAM) by comparing target

diversions with actual diversions for each water right in the three basins for: (1) baseline conditions with no EFs and (2) conditions with EFs to isolate the effect of EFs on surface-water supply. Water diversions were aggregated by county and water rights types were organized into four categories to facilitate economics modeling: (1) steam electric, (2) commercial and industrial, (3) municipal, and (4) agriculture.

County-level water supply-and-demand data were obtained from 2010 regional water plans. Supplies were classified as firm if they did not change (i.e., groundwater and re-use) or not firm (i.e., a surface-water supply that can be reduced during drought or by policy drivers). Counties with surface-water supply deficits (i.e., no surface-water supply buffer) were identified and, within those counties (i.e., Bexar County), the percentage of time that a power plant cooling reservoir was below the minimum operating level was calculated.

Potential one-year economic impacts of EF-induced water shortages (the cost to replace water lost to EFs) were calculated for two groups of water users: (1) commercial and industrial, municipal, and agriculture—users for which the impacts are driven by surface-water supply shortages, and (2) steam-electric generation, for which impacts were handled separately because they are driven by reservoir-level changes (calculated based on shortages). Two scenarios were considered for the economic analyses: (1) an “integrated market,” in which water transfers are allowed between users and counties, and (2) a “segmented market,” in which water cannot be transferred between each of the four water-user types in the same county or from county to county.

Results of Hydrologic Analysis

The hydrologic analysis reveals that many Central Texas streams where mussels are found, particularly in the Colorado and Guadalupe-San Antonio River basins, rely on groundwater inflows. For example, base flow index (BFI; percent of stream discharge from groundwater) is approximately 50% at the San Saba River and 60–80% in the Upper Guadalupe River above Canyon Lake Dam. These streams are hydrologically connected to adjacent aquifers that maintain streamflow during droughts. Therefore, groundwater pumping should be managed to minimize stream depletion near mussel habitats.

Results of Surface-Water Availability Analysis

Values of EFs are generally lower in upstream, tributary locations than at downstream sites. Low EFs represent 3–33% of non-EF baseline flows. High EFs comprise 13–67% of baseline streamflow. Surprisingly, few counties were impacted by EFs for Central Texas mussels and areas with EF-reduced water supplies already had supply issues.

No EF-induced shortages are projected to occur in the Brazos River basin because mussels there are generally restricted to small tributary streams. Colorado River basin worst-case (i.e., higher EF and drought conditions) shortages include Tom Green County (55,000 acre-feet/year [af/yr]; already-low San Angelo municipal supplies) and Wharton County (82,000 af/yr; junior, interruptible irrigation rights). Guadalupe-San Antonio River basin EF shortages occur in Bexar County (74,000 af/yr) and Medina County (4,000 af/yr), but shortages are reduced in both counties to 8,000 af/yr when groundwater can be imported (as is currently the case) from Uvalde County.

Results of Economic Impact Analysis

Economic losses under EFs for Central Texas freshwater mussels would occur in many counties that already have existing water supply issues. One-year economic impacts are much greater under a segmented market because of missed opportunities to transfer water from areas of relative abundance to areas of relative scarcity. For example, during non-EF, baseline conditions conveying groundwater from Uvalde and Medina counties to Bexar County nets approximately $97 million (M) annually in avoided costs under normal hydrologic conditions (i.e., water rights diversions that occur 50% of the time) and $154M during drought (water rights diversions with a 90% probability of exceedance).

Economic impacts to commercial and industrial, municipal, and agricultural sectors can be almost entirely mitigated if water transfers are allowed among sectors and between counties. Water transfers would reduce total one-year commercial and industrial, municipal, and agricultural losses in Bexar, Medina, Tom Green, and Wharton Counties from $37M to $1.6M in a drought and with low EFs. In a drought with high EFs (i.e., a worst-case scenario), water transfers reduce one-year losses from $80M to $11M. Under normal hydrologic conditions, no economic losses would occur with low EFs. Economic losses are nominal (i.e., less than $1M) with high EFs and normal hydrologic conditions.

Evaluation of steam-electric power generation shows that two San Antonio-area power plant cooling reservoirs (Braunig and Calaveras Lakes) could have supply reductions causing one-year economic impacts up to $36M with low EFs and up to $107M with high EFs for a segmented market (assuming that water is not transferred). However, Water availability modeling explores the boundaries of changes in surface water availability but do not necessarily mean that power generation would stop during modeled water shortages. Revenue projections are market calculations using publically available data and do not necessarily reflect actual revenue forecasts. In addition, during the 2011 drought, power plants were granted water use priority and continued operation.

While water markets are an attractive way to meet water demands from environmental regulations without expensive new water supply projects, implementation of basin-scale water markets across the state faces some roadblocks that may require time to address. For example, adverse economic impacts to source regions (particularly declines in agricultural regions where water is typically sourced) present an impediment to water transfers. Such water markets could include mechanisms (such as adding a levy to water transfers) to provide suitable compensation to areas and sectors that relinquish water. The revenue generated could be used to invest in the source region. Other hurdles common to water markets that could delay implementation in Texas include (but are not limited to): a lack of federally-subsidized infrastructure to transport water from water-rich to water-poor areas (as is the case in California), inconsistent water rights enforcement (except for the Rio Grande), holding of large water volumes by a few owners (river authorities), low water prices, and/or invasive species (such as the zebra mussel). More work is needed for water markets to become an effective means to mitigate EF-induce water supply shortages in Texas.

Conclusions and Implications

Water supply reductions caused by EFs are lower than expected, given that mussels are found throughout Central Texas. Those economic impacts to the state economy caused by EFs could be mitigated by the transfer of water between economic sectors and between counties, as was done during the 2011 drought and is common in the western United States. In such scenarios, the transfer of water is typically from agricultural to municipal users. In Texas, the Edwards Aquifer Recovery Implementation Plan allows leasing of irrigation water during droughts. The Rio Grande basin also has a relatively active water market. However, barriers to implementation need to be addressed before water markets can become an effective way to mitigate EF-induced water supply shortages.

In light of Texas' expanding population and growing demand for water, it would be prudent to also develop water supply buffers, such as aquifer storage and recovery, conjunctive use of groundwater and surface water (with caution, so as not to exhaust streams that rely on groundwater inflows), interbasin transfers, and improved system-wide water-use efficiency to further mitigate the effects of EFs, as well as reduced supplies during droughts. As stakeholders confront Texas' water supply challenges, there is an urgent need to develop approaches for EFs, and also to have a broad range of strategies to quantify economic impacts of EF requirements and mitigate those impacts as much as possible.

(KEY TERMS: Central Texas, drought, economic impacts, endangered and threatened species, environmental flow, ESA, freshwater unionid mussels, industrial water demand, instream flow, irrigation, municipal water demand, power water demand, water allocation, water demand, water markets, water policy, water resource economics, water scarcity, water supply, water transfers.)

1.0 INTRODUCTION

1.1.1 Increasing Texas Population and Water Demand

Water management issues are taking on greater importance in Texas as the population continues to grow. Population is projected to grow 80%, from 25 to 46 million people, in the state between 2010 and 2060 (TWDB, 2012a). As a result, water demand is expected to grow by 22%. At the same time, the overall water supply may decrease by up to 10% because of aquifer depletion. Texas water storage is also stressed. Texas now has 188 reservoirs with a per capita storage of 1.5 acre-feet (TWDB, 2012a). By 2060, per capita storage could be reduced to less than one acre-foot, a level not seen since the “drought of record” in the 1950’s.

In light of Texas’ water supply needs, the state projects that 8.3 million acre-feet (maf) of new water resources need to be developed by 2060 to provide drought buffers and avoid economic impacts. Understanding supply and demand is critical for effective water-resource planning. Texas has a five-year water-planning cycle, which culminates in publication of the State Water Plan (TWDB, 2012a). This document includes reports of current and projected supply-and-demand information for municipal, commercial and industrial, steam-electric, and agricultural sectors for 16 water-planning regions.

1.1.2 Climate Variability and Drought in Texas

Climate variability and drought may further compound the problem of meeting the state’s growing water needs. The State Water Plan identifies these factors as sources of uncertainty in planning. The drought of the 1950’s is generally considered the drought of record upon which drought plans are based. However, tree-ring records show that this drought was exceeded in intensity twice in the 1700’s (Cleaveland, 2006). Another recent tree-ring study extending back to the 800’s shows that Texas has been subject to four 15- to 30-year-long megadroughts that were longer and more intense than the 1950’s drought (Cleaveland et al., 2011). Such megadroughts should be considered when planning Texas’s water needs. Surface-water supplies are more vulnerable to droughts than are groundwater. Therefore, groundwater can provide a buffer during supply shortages caused by climatic variability. However, many streams in Texas are linked to groundwater, and during drought groundwater inflows provide important subsistence flows for streams and springs (Slade et al., 2002). Thus, groundwater development projects should evaluate whether groundwater pumping would deplete or reduce flows in nearby streams, exacerbating flow reductions caused by drought. Streamflow depletion from groundwater pumping is understood to be a problem in the American West (Butler et al., 2001; Zektser et al., 2005).

1.1.3 Environmental Flow Process in Texas

In addition to population growth, climate variability, and drought, water reserved for aquatic habitat preservation—the focus of this study—may also exacerbate water-supply issues in Texas.

In the State of Texas, three agencies are primarily responsible for water resource management. The Texas Commission on Environmental Quality (TCEQ) grants water use permits based upon assessments of water availability. The Texas Parks and Wildlife Department (TPWD) makes recommendations to avoid impacts to fish and wildlife as a result of water management decisions. The Texas Water Development Board (TWDB) administers a state-wide planning process to meet human needs for water in the future.

Senate Bill 2, passed during the 2001 Texas Legislative session, instructed the TWDB, TPWD, and TCEQ to develop methodologies to evaluate EFs (Brown, 2001). In 2003, the Texas Legislature passed Senate Bill 1639, which created a Study Commission on Water for Environmental Flows charged with making recommendations to the legislature on how to balance human and environmental needs for water in the water rights allocation process (Staples, 2003). A review of the Texas EF program was completed in 2005 (National Research Council, 2005). Also in 2005, the Texas Legislature passed Senate Bill 3 (SB3) which created a process to evaluate and set standards for EFs in the state (Armbrister, 2005). The SB 3 EF process is an accelerated, stakeholder-driven, scientific and consensus-based process to establish EF recommendations from which TCEQ sets standards. Work plans that describe additional data and detailed studies which are needed as part of an adaptive management component to refine recommendations and standards are another important output from the SB 3 EF process. The process utilizes input from regional stakeholders and the best available science to make recommendations that balance human and EF needs. In the legislation, EFs are defined as "adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats."

Now, EF recommendations submitted as part of the ongoing stakeholder-based process are being finalized into standards by TCEQ. The EF recommendations made by Basin and Bay Area Stakeholder Committees (BBASCs) and standards adopted by TCEQ have considered the results of water supply modeling. This process starts with the Basin and Bay Expert Science Team (BBEST), a panel of scientific experts who make EF recommendations based only upon the best available scientific information. The BBEST recommendations are considered by BBASC in conjunction with other factors, including human water needs at present and in the future. As of December 2012, EF standards have been set for the Colorado and Guadalupe-San Antonio River basins (TCEQ 2012a, TCEQ 2012b). The TCEQ is in the process of developing final EF standards for the Brazos River basin. These standards will be finalized in 2013 and (along with previously adopted EF standards) incorporated into the 2017 State Water Plan (TWDB, 2012a). These EFs will contain standards for base flows (i.e., average or normal flows in the absence of precipitation needed to maintain aquatic habitat), pulse flows (i.e., short-duration, high-magnitude, in-channel flows), and overbank flows (i.e., infrequent, high-magnitude flows that overtop the channel and enter the floodplain). Base flows may be specified for dry, normal, or wet periods. Pulse flows will be seasonal to attempt to replicate the natural river flow pattern.

Subsistence flows, minimum flows to prevent aquatic organism losses, will also be specified. This report focuses on low flows, which are critical for analysis of economic impacts.

The ongoing SB3 EF process is occurring within the context of two prior approaches to determine EFs in Texas: (1) Consensus Criteria of Environmental Flow Needs (CCEFN; TWDB, 2012b), and (2) the Lyons Method (Bounds and Lyons, 1979). The CCEFN are used by regional planning groups to evaluate if surface-water supplies are sufficient to meet the needs of planned projects. The CCEFN are based upon modeled pre-development streamflow. The Lyons Method is used by TCEQ to evaluate if enough surface water is available for a new water permit diversion (typically smaller permits; TRG, 2008) and uses historic streamflow data. As a result, CCEFN and the Lyons Method generate different EF requirements for the same stream. Typically, CCEFN EFs are larger than EFs found with the Lyons Method (National Research Council, 2005, Box 6-3). For example, at one location on the Trinity River (Oakwood) for the month of July, CCEFN reserves 20% of streamflow for EF, while the EF provided by the Lyons Method is 17% of streamflow (Opdyke, 2010). In contrast, at that location SB3 BBEST recommendations for July were split between 5% and 16% of streamflow for EFs, with the EF standard adopted by TCEQ being between these two values (TCEQ, 2011). Thus, any project proposed by regional planning groups that is feasible under CCEFN EF requirements should be able to meet EF standards adopted by TCEQ as part of the SB3 process.

1.1.4 Texas Endangered and Threatened Aquatic Species

Texas already has several endangered and threatened aquatic species that may drive future EF needs, including approximately 30 fish, 16 mollusks, and eight salamanders (TPWD, 2012). These aquatic species are found throughout Texas (CPA, 2012). The most notable case in which aquatic species have driven flow requirements for aquatic habitat was when the Sierra Club sued USFWS and the Secretary of the Interior for violating the ESA in 1991 by not implementing plans to protect endangered species in San Marcos and Comal Springs (*Sierra Club et al. v. Babbitt et al.*, 1993). As a result, USFWS was ordered to provide minimum spring flow requirements to avoid an ESA-listed species take (**Table 1**). Takings would occur between 86% and >99% probability of exceedance of long-term spring discharge. As a result of this case, the Edwards Aquifer Authority (EAA) was created and groundwater pumping was restricted to 572,000 af/yr (Armbrister, 2005). A plan for drought leasing of irrigation water to preserve spring flows was also recently implemented via the Edwards Aquifer Recovery Implementation Program (EARIP) (RECON, 2011).

1.1.5 Possible Environmental Flows for Whooping Crane Habitat

The Aransas Project filed a lawsuit against many defendants in March 2010 seeking to assure mandated flows to the Guadalupe River estuary as a result of suspected endangered whooping crane deaths and a poor fishing season in 2008–09 (*TAP v. Shaw et al.*, 2010). Currently, no freshwater inflow EFs are required for the Guadalupe River estuary. The Aransas Project estimated that 1.3 maf/yr would be required to flow to the estuary as the most senior water right in the basin. The Defendant-Intervenor Guadalupe-Blanco River Authority (GBRA) sponsored a hydrologic and economic evaluation of requiring estuary inflow requirements. Monthly inflows were required to evaluate changes in surface-water availability; therefore, a monthly breakdown of 1.147 maf/yr from TPWD (Warren et al., 1998) was used for modeling. Water-availability modeling was done assuming all existing water rights would be used, no water-rights return flows would occur, and wastewater discharge would occur and continue to provide streamflow (Perkins, 2011). The modeling analysis showed that this environmental flow (EF) would require most of the run-of-the-river rights to flow to the estuary, drain approximately half of Canyon Lake, and reduce power generator water supplies during droughts. The total economic impact from this EF from 2010 to 2060 was estimated at $6.7B (Sunding, 2011).

1.1.6 "Megalawsuits" for Listing Many Endangered Species at Once

Additional endangered species issues that may affect Texas water management include "megalawsuits" (also referred to as consolidated multi-district litigation) that include dozens of species (CBD, 2011a; CBD, 2011b; Guardians, 2011).

For example, in a court-approved settlement (CBD, 2011b; Guardians, 2011) outlined in the ESA Listing Workplan (USFWS, 2013), USFWS committed to publish in fiscal years 2013 to 2018 ESA listing actions (petition findings, listing determinations, critical habitat designations) on multiple candidate species (USFWS, 2010a). The possible Central Texas aquatic candidate species included are two Brazos River fish (sharpnose Shiner, smalleye Shiner), four salamanders (Austin blind, Georgetown, Salado, Jollyville Plateau), and three Comal Springs invertebrates (Comal Springs Dryopid Beetle, Comal Springs Riffle Beetle, Peck's Cave Amphipod). While not located in Central Texas, several other aquatic species with possible management implications are six West Texas aquatic invertebrates (Pecos Amphipod, diminutive Amphipod, Diamond Y Spring Snail, Phantom cave Snail, Phantom Springsnail, Gonzales springsnail) and one freshwater mussel found in the Pecos River and Rio Grande (Texas hornshell).

A second "megalawsuit" was filed by the Center for Biological Diversity and Pesticide Action Network for approximately 200 endangered species threatened by pesticides (CBD, 2011). Included in this lawsuit were several Central Texas aquatic species (Texas blind salamander, San Marcos Salamander, Devils River Minnow, and Fountain Darter, among others). Thus, impetus for this study comes partly these lawsuits.

1.1.7 Texas Freshwater Mussels and Aquatic Habitat

USFWS has not listed Texas freshwater mussels as threatened or endangered and TCEQ has not yet finalized EF requirements for mussels. Freshwater mussels are considered indicator species of aquatic ecosystem health (Williams et al., 1993) and studies evaluating aquatic habitat needs of mussels are ongoing, making it difficult to predict what EFs might be mandated. In light of this uncertainty, it is plausible that flows may eventually be similar to the percentage of stream discharge reserved for endangered species associated with the San Marcos and Comal Springs (*Sierra Club et al. v. Babbitt et al.*, 1993).

Globally, freshwater mussel species are in decline. As of 2003, there were a total of 708 freshwater mollusk species on the IUCN (International Union for Conservation of Nature) Red List of Threatened Species (IUCN, 2012). Mussels are affected by changes in hydrologic regime resulting in aquatic habitat degradation and/or fragmentation (Richter et al., 1997). Suitable mussel habitat can be degraded by a variety of human activities, including construction of water impoundments (e.g., dams and weirs), erosion and sedimentation from agriculture or urban areas (Bogan, 1993; Box and Mossa, 1999), and scouring (from reservoir release or natural floods) (Bogan, 1993). However, scouring flood flows may not historically have been a problem because these areas could be repopulated by fish hosts that are an essential part of mussel reproduction. Currently, movement of fish hosts up and down a river may be blocked by dams and other stream impoundments. Changes in temperature (Vaugh and Taylor, 1999), impacts to host fish needed for mussel reproduction (Bogan, 1993; Williams et al., 1993), water pollution (Ford et al., 2010), as well as reduced water availability are additional threats to mussels.

Historically, the United States, particularly the eastern half, had high freshwater mussel abundance (Williams, Warren et al., 1993). However, mussel populations have declined since 1900, with 35 of 297 species going extinct (Turgeon et al., 1998). Population declines are associated with river habitat degradation and the effects of invasive species (Ricciardi and Rasmussen, 1999). As a result of these declines and the previously mentioned "megalawsuit," USFWS has proposed listing several species of freshwater mussels found in the Southeast and Midwest United States (USFWS, 2012b; USFWS, 2012c). The USFWS (2012b) designated 1,494 stream miles in Alabama and Florida as critical habitat for eight freshwater mussels. Elsewhere in the Southeast, mussel deaths were reported during the 2006 drought, perhaps caused by low upstream reservoir releases (Meruelo, 2007). More than 80 percent of this habitat is situated on private land. In a separate decision regarding the mussels of the United States Midwest, the USFWS (2012c) is proposing designating as critical habitat 2,138 miles along waterways in 12 states (cumulative river length that is nearly two-and-half-times the distance from El Paso to the Louisiana border; over 80 percent of the habitat in this listing is also on private lands) for two types of freshwater mussels (the Neosho mucket and rabbitsfoot).

As with mussel listings in the Southeast and Midwest, potential economic impacts (as well as benefits) of specifying an area as critical habitat are considered (USFWS, 2012d). If the economic analysis (often contracted to Industrial Economics, Incorporated; Allan, 2012) finds that the benefits of excluding an area outweigh the costs of including it, the area may not be designated at critical habitat. The exception to this rule is if excluding the area would result in species extinction. The U.S. Office of Management and Budget (OMB) provides guidelines for economic analyses to measure the impacts of a regulation against a baseline without the proposed action (OMB, 2013). This analysis includes both a benefit-cost analysis (BCA) and cost-effectiveness analysis (CEA). The BCA is used to measure benefits and costs of successively increased regulatory alternatives to find the best option using a variety of methods. The CEA is used to identify the best options for most effective use of available resources. For the southeastern United States mussel listing, economic impacts of critical-habitat listing over a 20-year period are approximately $1.7 million (M) (costs primarily associated with bridge and road replacement and maintenance; USFWS, 2012b). The economic analysis for the Midwest mussels is not yet complete but will be used when making a final decision on critical habitat (USFWS, 2012c). Economic impacts calculated for other eastern U.S. freshwater mussel listings include approximately $0.5M in the Apalachicola-Chattahoochee-Flint Rivers (hydropower and logging impacts; USFWS, 2007), $9M in the Mobile River basin (primarily hydropower impacts; USFWS, 2010b), and complete loss of construction costs when work on the Duck River Colombia Dam was halted in 1983 and the dam subsequently demolished (TVA, 2001).

Whereas freshwater mussels are most abundant in the eastern half of the United States, they are also found in many rivers of Central Texas. These Central Texas species have suffered population declines as well (Howells, 2010). The TPWD has listed 15 species of freshwater mussels that are threatened in the state of Texas (TPWD, 2009). In Texas, mussel declines have likely resulted from the same combination of climatic, hydrologic, and land-use factors that have reduced mussel populations elsewhere (Burlakova and Karatayev, 2007; Ford et al., 2010; Howells, 2010; Randklev et al., 2010b).

Listing of five of the state-threatened freshwater mussel species has been found to be warranted by USFWS (USFWS, 2011b); however, they are precluded by higher priority species, such as the lesser prairie chicken, Oregon spotted frog, and Gunnison sage-grouse (USFWS, 2012a). The Texas fatmucket, Texas pimpleback, golden orb, Texas fawnsfoot, and smooth pimpleback are on the candidate list, and USFWS is developing a proposal to list them and determine critical habitat. None of these Central Texas mussels is currently listed or has yet had critical habitat designated. Studies are ongoing to collect additional data on habitat requirements and population distribution in order to provide the USFWS with adequate information to protect these species (USFWS, 2011b). The proposed listing of five Central Texas mussels does not include a designation of critical habitat, but such economic analyses would be required if critical habitat were to be designated (USFWS, 2011b).

For a state-level comparison of Federal critical habitat economic assessments, the Texas Department of Transportation (TxDOT) does not actually do economic impact assessments of environmental regulations for endangered or threatened species (Fisher, 2012). Instead, TxDOT seeks to minimize impacts of ESA listings on transportation infrastructure projects. As such, TxDOT often requests that critical habitat not be designated within TxDOT rights of way during ESA listing comment periods.

1.1.8 Water Markets: Accommodating Demand By Transferring Water

1.1.8.1 What Are Water Markets?

In light of increased water demands caused by increased population growth, climate variability, and environmental regulations in water-scarce areas like the western United States, water markets have been proposed as a means to effectively and equitably satisfy demand while reducing investment in expensive new water supply projects by using existing water more efficiently (Characklis et al., 2006; Easter et al., 1999). Within a water market, water permit holders are legally allowed to forego water use and transfer water to another user in exchange for compensation (Hanak, 2005). Transfers can be on a temporary or long-term lease basis or as a permanent sale (Hanak, 2005). For example, 80% of transfers in California were for short terms to meet dry-period needs (Hanak, 2005). Most commonly, water transfers occur from agricultural to municipal users—particularly from marginally productive agricultural areas (such transfers comprise up to 90% of transfer volumes in California in most years; Griffin and Characklis, 2002; Hanak, 2005; Howe, 2000).

1.1.8.2 Where are Water Markets in the Western United States?

Well-developed water markets can be found throughout the western United States. From the mid-1970s to the mid-1980s, Utah, New Mexico, and Colorado lead in the number of trades, although Wyoming, Arizona, California and other states had water transfers (Howe, 1997). California water markets expanded in the 1990s. There, one-third of new purchases since 1995 were allocated to meet state and federal environmental regulations instead of municipal demands (Hanak, 2005). The effect of these regulations reduced diversions bound for Southern California from the Sacramento-San Joaquin Delta in order to restore aquatic habitat for ESA-threatened delta smelt and other species (Lund et al., 2007).

1.1.8.3 Water Markets in Texas

In Texas, water markets are found along Rio Grande (surface water), the Edwards aquifer (groundwater), and, to a limited extent, in other rivers and aquifers across the state (a summary of Texas water markets presented here is provided in Griffin and Characklis, 2002; available on TWDB’s website, “A Texan’s Guide to Water and Water Rights Marketing” also provides background on Texas water markets).

First, the Rio Grande has the most active Texas water market (in leases and sales; Griffin and Characklis, 2002). There, irrigators absorb most dry-period shortages in order to maintain municipal supplies. Annual sales are typically 10,000 af/yr at $1,200 to $1,400/acre-foot from agricultural to urban uses. Leasing within sectors (i.e., farm-to-farm or city-to-city) is generally 20,000 to 80,000 af/yr.

Second, an EAA-administered water market has been established in the Edwards Aquifer to manage groundwater pumping to maintain ESA-mandated spring flow in Comal and San Marcos springs. Here, up to 50% of an irrigators' water can be sold to urban use with transfer via the Edwards aquifer, which acts as a natural water transfer project. Sold or leased groundwater flows in the aquifer under gravity from irrigated areas west of San Antonio towards that city, where it can be pumped.

Active surface water markets are uncommon in Texas other than along the Rio Grande, despite water policy favoring water transfers (rights severed from land, transferable rights, and shortages allocated between senior and junior rights within a prior appropriation system). Nevertheless, a few large transfers have occurred, including: (1) a 35,000 acre-feet purchase by Corpus Christi from the Garwood Irrigation Company in 1997, (2) a 101,000 acre-feet in firm yield gain by the Lower Colorado River Authority (LCRA) by purchasing Garwood Irrigation Company for $75M in 1998, and (3) a transfer of up to 50,000 acre-feet in firm yield when LCRA signed agreements for groundwater and surface-water rights on the Pierce Ranch for $17M in 2000.

In addition to these large surface water transfers between river authorities, the Texas Water Bank was established by the 73rd Legislature in 1993 to allow for and assist with temporary or permanent water transfers between buyers and sellers (following permit modification from the TCEQ). Despite this policy mechanism facilitating water transfers, water bank deposits posted by sellers as of December 2012 seeking buyers amounted to a little over 500 acre-feet (Texas Water Bank, 2012). Most of the water deposits (approximately 470 acre-feet) were water rights located in Lower Colorado River tributaries (San Saba River and South Llano River drainages) with proposed lease prices from $30 to $50/af/yr. In the Rio Grande basin, 47 acre-feet were available. No water permit owners in other parts of the state were currently seeking transfers.

Groundwater markets in Texas, apart from the Edwards aquifer, are in development. Amarillo purchased 70,000 acre-feet of groundwater from Roberts County ranchers for $275/acre-foot (Griffin and Characklis, 2002). Numerous other groundwater transfer projects have been proposed and/or are in development, including (but not limited to): approximately 17,000 acre-feet/year of Edwards-Trinity aquifer groundwater from Pecos County near Fort Stockton to Midland (currently in litigation; Butcher, 2011), approximately 30,000 acre-fee/year of Pecos Valley Alluvium groundwater to be piped 76 miles from the T-Bar Ranch in Winkler County to Midland (Petty, 2012), and up to 45,000 af/yr from the Carrizo-Wilcox aquifer on Alcoa property in Milam, Lee, Bastrop, and Williamson counties to the LCRA service area (Mashood, 2012a).

1.1.8.4 Water Market Barriers and Solutions to Implementation

Why are so few water transactions currently occurring in Texas, despite favorable policies? Four primary reasons are cited by Griffin and Characklis (2002): (1) East Texas water shortages are not yet severe enough in most years to drive transfers, (2) Texas, unlike California and Arizona, lacks federally-subsidized infrastructure (canals, pipelines, and pumps) to move water from water-rich to water-poor areas, (3) water rights enforcement, with the exception of the Rio Grande basin, is inconsistent and limited to droughts, and (4) river authorities may have near-monopoly water rights holdings, hindering water market formation and function.

Other hurdles can make establishing effective water markets difficult. First, third-party effects (impacts to parties not involved in the water transfer) can cause declining economic activity in the region where the water transfer originates (Easter et al., 1999). More specifically, transfers involving irrigation water can retire irrigated land (Colby, 1988) and cause "secondary economic impacts" such as reduced sales of agriculture inputs (seeds, fertilizers, equipment) (Howe, 2000). Especially in the case of a large water transfer, highly-visible secondary impacts in agricultural areas can attract public opposition (Howe, 2000) because some residents in the selling region suffer economic losses, despite the transaction increasing overall water use efficiency (especially in the region receiving the transfer; Hanak, 2005). One solution to mitigate potential impacts to the source area includes review and approval of the proposed water transfer by a public agency (Easter et al., 1999). For example, California has a "no-injury" law (which only applies to surface water trades) to prevent unmitigated source-region impacts (Hanak, 2005). Another solution is to redistribute "gains-from-trade" by compensating the source region with revenue from levies on water transactions or by requiring the buyer to pay a fee for the costs imposed on the irrigation system from which water is transferred (Easter et al., 1999). For example, the Gonzales County Underground Water Conservation District is proposing an approximately $300,000 fund to monitor and mitigate the effects of possible groundwater transfers from the Carrizo-Wilcox aquifer to Hays County (O'Rourke and Price, 2012). Additional policies to protect water transfer source-areas include limiting trades as a percentage of water rights in a source area (Easter et al, 1999). For example, Edwards aquifer permit holders can transfer up to 50% of their adjudicated pumping limit (Griffin and Characklis, 2002).

A second possible hurdle to establishing a water market for groundwater (outside of that in the Edwards aquifer) is the risk of groundwater overdraft (Easter et al., 1999). As in the Edwards aquifer, transfers can be limited to a percent of water rights. Trading can also be limited in areas with groundwater declines, with taxes imposed on groundwater sales where groundwater is especially scarce. All of this depends on water rights adjudication (Easter et al., 1999).

Third, (as previously mentioned) monopoly control over water has been identified as an impediment to effective water markets (particularly if a river agency holds a majority of water rights [Easter et al., 1999; Griffin and Characklis, 2002]). Some solutions to preventing monopoly control over water include limiting trades to a percentage of the source area (as also with the case of groundwater markets), requiring public agency approval (as with California's "no-injury" law), regulating monopolies, and providing financial and legal assistance to small rights holders (Easter et al., 1999).

Fourth, a water market that does not deal with surface-water and groundwater in an integrated manner can cause conflicts (Matthews, 2004). For example, surface-water in many Texas streams is connected to groundwater (Slade et al., 2002). Thus, groundwater pumping near such stream can reduce surface-water flows (impacting surface-water rights holders; Butler, 2001). Thus, a water market should be supported by policies that take into account surface-water-groundwater connections (Griffin and Characklis, 2002).

Fifth, operational rules of water permits must be certain, transparent, and enforced (Matthews, 2004). For example, for a water transfer to occur smoothly, a potential buyer needs to know clearly how, where, when, and how much water can be used (and possibly also returned to the stream). The Texas Water Bank effectively shows where and how much water is available for purchase or lease. The Bank could be improved by also including all operational rule details which a potential buyer might wish to know. Furthermore, in order to create certainty in a water market, operational rules must be enforced. However, Texas water permit enforcement is light and generally limited to droughts (with the exception of the Rio Grande; Griffin and Characklis, 2002). Enforcement can be especially difficult for groundwater (Easter et al., 1999)—even without including uncertainties added by the EAA v. Day & McDaniel findings. Some possible solutions to improving enforcement include improving enforcement budgets funded by a levy on water transfers and/or clarifying permit definitions (Matthews, 2004).

Sixth, a low water price in Texas (and elsewhere) has been recognized as a barrier to water markets (Matthews, 2004). For example $30 to $50/af/yr surface-water lease prices (Texas Water Bank, 2012) may not be incentivizing trades. Groundwater sales in the Edwards aquifer appear to range from $750 to $800/acre-foot, although the lack of price transparency further hinders trades (Griffin and Characklis, 2002). In the Carrizo-Wilcox aquifer, the Hays Caldwell Public Utility Agency typically pays landowners $100/af/yr to lease groundwater (O'Rourke and Price, 2012).

Finally, the presence of invasive species in source water supplies could present a further barrier to water transfers. For example, zebra mussels, which can clog water intake pipes and displace native species, are found in Lake Texoma and Lake Ray Roberts (TWDB, 2012c) and could spread elsewhere in the state when water is transferred.

Water markets are a promising mechanism to provide water to meet possible future environmental regulation requirements without constructing new water supply projects. However, more work is needed for water markets to be implemented at a basin-wide scale throughout the state.

1.2 Objectives

Of concern are potential economic impacts caused by reductions or reallocations of water following a possible ESA listing of Texas freshwater mussels. Such a listing, if it occurred, could be followed by federally mandated EFs for rivers where mussels are found. (Designation of critical habitat and/or changes in other activities following a listing could have additional important economic impacts, but those other potential impacts are outside the scope of this study.) During years of drought of severity comparable to the recent 2011 drought, mandates to keep a certain level of flow in a river to preserve aquatic habitat might limit the water available to existing water-rights holders. This study (1) determines whether water supplies would be reduced from EFs, and then (2) estimates potential economic impacts of such changes in water supply. Solutions to mitigate economic impacts of a mussel listing are also presented. Because the highest diversity of freshwater mussels is in Central Texas, this study focused on the Brazos, Colorado, and Guadalupe-San Antonio River basins. Zebra mussels are an invasive species and present an issue separate from native freshwater mussels. The threat posed by zebra mussels may change how water is managed in Texas, but this factor not considered in detail in this study.

2.0 MATERIALS AND METHODS

2.1 Study area

This aim of this study was to determine whether water supply reductions caused by EFs following ESA listing of five Texas freshwater mussel species are likely to occur and if so, in what locations. Flows were assessed in the Brazos, Colorado, and Guadalupe-San Antonio River basins, where mussels have been found. These rivers are also associated with intensive economic activities (in San Antonio, Austin, and Waco) that could be affected by a reduction in available water (**Figure 1**). These Central Texas rivers harbor the highest freshwater mussel abundance in Texas (USFWS, 2011a). The study area comprises 36% of the total area of Texas (~95,000 square miles).

Currently, USFWS is working through a multi-species petition to determine if ESA listing is warranted. Included are twelve state-threatened freshwater mussel species found in rivers throughout Texas. Of these, USFWS found that five Central Texas species (golden orb, smooth pimpleback, Texas fatmucket, Texas fawnsfoot, and Texas pimpleback) warrant listing, but higher priority species, including the lesser prairie chicken, Oregon spotted frog, and Gunnison sage-grouse (USFWS, 2012a), must first be evaluated before the mussels can be considered (USFWS, 2011b). Locations where freshwater mussels are found or are likely to be found were determined using input from biologists, including Neil Ford, Robert Howells, and Charles Randklev (**Figure 2**). Freshwater mussels are located using surveys (**Figure 3**) and exhibit a variety of shapes and sizes (**Figures 4, 5, 6, and 7**).

2.2 Methods

2.2.1 Hydrology of Central Texas Streams

Hydrologic conditions in Central Texas streams were characterized using hydrographs with base flow (i.e., groundwater contribution to streamflow) and precipitation, flow-duration curves (FDC), base flow index (BFI; i.e., ratio of base flow to streamflow), streamflow indices derived from FDC, and an assessment of spring distribution. To prepare for the mussels being listed as endangered, these analyses identified ephemeral streams that go dry during droughts. The analysis also shows which streams are maintained by groundwater inflows during droughts and are at risk of drying up as a result of nearby groundwater pumping.

Hydrographs were generated for the ten gauges located near mussel sites with long-term U.S. Geologic Survey (USGS) stream-gauge data for the entire period of continuous record available (USGS, 2012). The response of streams to rainfall was examined using precipitation data from nearby gauges (NCDC, 2012). Groundwater/surface-water interactions (i.e., whether a stream reach is losing or gaining) were evaluated using a BFI-analysis approach that estimates the percentage of streamflow that originates from inflows of groundwater (Rutledge, 1998). BFI at a particular location can increase over time during droughts if groundwater drained from aquifers comprises an increased percentage of streamflow. Thus, streams with high BFI values are at greatest risk of reduced streamflow from nearby groundwater pumping. Streams with low BFI values are often flashy and ephemeral.

Flow-duration curves (FDC) were generated using long-term stream-gauge data (USGS, 2012) as described by Smakhtin (2001). These FDCs show probabilities of stream discharge exceedance referred to as QX, where X is the percentage probability of exceedance of a certain flow rate. Streamflow indices derived from FDCs were used to understand streamflow variability and relative groundwater inflows. The ratio Q20/Q90 is an index of streamflow variability (Smakhtin, 2001). Q50/Q90 shows low-flow variability (Smakhtin, 2001). Q90/Q50 shows relative proportion of surface water from groundwater (Smakhtin, 2001). A high slope between Q34 and Q77 indicates highly variable flow rates in streams (i.e., large flood flows and also low flows during dry periods), whereas low slopes indicate that groundwater inflows are important for the maintenance of streamflow (Sawicz et al., 2011). Ephemeral streams were identified using FDCs and are at risk of being dry a greater percentage of the time if nearby groundwater pumping reduces base flow.

Loss or gain of stream segments was also assessed qualitatively by identifying those springs which may provide groundwater inflows during droughts. Maintaining groundwater-fed streams that flow during extended droughts is critical for the maintenance of mussel habitat. Spring distribution (Heitmuller and Reece, 2003) is compared to mussel sightings.

2.2.2 Determining Environmental Flows

At mussel locations (**Figure 2**), EFs were calculated using a stream discharge probability of exceedance based on long-term USGS stream-gauge data (USGS, 2012), an approach similar to that used by Hughes and Hannart (2003). Because the ultimate EF volumes for mussels cannot be predicted with certainty, we considered a range of possible EFs with a 95% probability of stream discharge exceedance for a low-EF scenario and 75% probability of exceedance for a conservatively high-EF scenario. Only minimum EFs were calculated. This approach may be less desirable than incorporating seasonal flow variability (Arthington et al., 2006), but the complexity of modeling seasonal flows precluded such inclusion.

2.2.3 Changes in Surface-Water Availability as a Result of Environmental Flows

Surface-water supply reductions caused by maintaining an EF as a senior water right at mussel sites were modeled using the Water Rights Analysis Package (WRAP) (Wurbs, 2005b), which was adopted by TCEQ for water availability modeling (WAM) for every river basin in Texas (Wurbs, 2005a; Wurbs, 2011). WRAP uses a prior-appropriation water permitting system to simulate water availability at a monthly time step on a basin-wide scale to assess if a new water-right permit request or EF will create water shortages for existing permit holders. Two WRAP input file versions are available were considered: WAM Run3 and WAM Run8. Run3 assumes that existing water rights divert the full permitted amount with no return flows and that reservoir storage exists at built capacity. (Because reservoirs lose capacity over time as they fill with sediments, reservoir storage-area relationships may not reflect current conditions; therefore, Run3 may overestimate reservoir storage [Alexander, 2012; Yang, 2012].) Run3 is more conservative and is used by TCEQ to assess state-wide surface-water availability. Run8 reflects current conditions of self-reported data on actual permit holder diversions, includes return flows, and reflects current reservoir holdings (Alexander, 2012).

WRAP input files provided by TCEQ were modified by adding EF requirements as senior rights at known or likely mussel locations (**Figure 2**). Thus, senior EFs are satisfied before junior water rights can divert. This approach is similar to that of Perkins (2011), who evaluated changes in surface-water availability in response to a required EF to the Guadalupe River estuary at the Gulf of Mexico to maintain habitat for whooping cranes. Target diversions were compared with actual diversions for each water right in the three basins using WAM Run3 for: (1) baseline (no EF), and (2) with low and high EFs to isolate the effect of EFs on surface-water supply.

Changes in annual regulated flows were assessed by plotting time series of stream discharge for baseline and EF conditions. Regulated flows are defined as modeled stream discharge after diversions have occurred to satisfy water rights, fill reservoirs, and maintain EFs (if required) (Wurbs, 2005a). Regulations related to EFs can increase regulated flows, particularly during droughts, by keeping water in a stream to meet aquatic habitat needs.

Water availability changes caused by drought were assessed by calculating probabilities of exceedance for each water right diversion over the period of record where: (1) a 90% probability of exceedance represented drought conditions (i.e., during low-flow, drought conditions, stream discharge is exceeded 90% of the time), and (2) a 50% probability of exceedance represents normal hydrologic conditions (i.e., when stream discharge is exceeded 50% of the time). Shortages caused by EFs were calculated by comparing baseline water availability with both EF scenarios during drought and normal hydrologic conditions.

2.2.4 Economic Loss Framework

Economic losses result from inability to meet county-level water demand. In general, the economic loss that results from a water supply disruption is less when the shortage is allocated to market sectors with relatively elastic demand (market sectors in which, if price goes up, demand goes down, i.e., residential water use) and with relatively low “price-cost margins” (industries that generate relatively low levels of profit) between water rates and the marginal cost of the water service. In the western United States, water has typically been transferred from agricultural to municipal areas during supply reductions (Griffin and Characklis, 2002; Hanak, 2005; Howe, 2000). Given the relatively high fixed costs associated with supplying residential and commercial and industrial (C&I) sectors, price-cost margins tend to be higher in these sectors compared to the agricultural sector. Agricultural demand is also relatively more elastic than residential and C&I demand. Accordingly, it would be expected that the outcome that minimizes the economic loss of a supply disruption in the integrated markets scenario involves agricultural users trading water to support residential and C&I demands under shortage conditions.

Several issues are involved in constructing economic loss functions across market sectors in the counties having surface-water supply deficits. First, the end uses of water may be different from the permitted uses. Restrictions for EFs that reduce permitted uses of water do not necessarily result in end-use impacts; examples include cases in which permitted uses exceed current demand for water or when an irrigator with a permit to divert water chooses to use groundwater rather than exercise the permitted use.

Second, the prevailing end uses of water may not maximize production of goods and services. The reason is that there exists no water market to reallocate water to users with the highest willingness to pay (WTP). Without a water market, water allocations are possible in which some sectors experience water surpluses while, at the same time, users in other market sectors experience water shortages.

Third, economic losses due to EF restrictions are sensitive to physical and political constraints that limit water movement between counties and between user groups. Restrictions caused by EFs may impact water supplies based on historical rights of permit-holders rather than on an efficiency criterion that targets shortages towards those for whom water produces the lowest economic return. It is therefore necessary to consider both physical and political constraints that limit water movement across counties and across market sectors.

The three issues noted above were handled as follows in constructing economic losses. First, end uses of water were aligned with permitted uses by constructing residual demand functions for each market sector. Residual demand for each sector is defined as water demand minus firm water supplies. Firm water supplies include groundwater extractions, recycled water, and surface-water diversions from sources other than the affected basins (i.e., interbasin transfers). Firm water supplies reflect water supplies that are not impacted by EF restrictions, whereas impacted supplies refer to all surface-water diversions from the affected basins, and, in the case of the steam-electric sector, withdrawals from reservoirs that store surface water (e.g., Calaveras Lake).

Residual demand for impacted surface water was calculated for each county and each sector by matching firm water supply with demand projections for 2010 presented in TWDB regional water-planning documents (AECOM, 2010a, b; Freese and Nichols, 2011; HDR, 2010a, b, c; TWDB, 2011). TWDB projected demands are provided for each county according to six categories of use: (1) municipal; (2) manufacturing; (3) mining; (4) steam electric; (5) livestock; and (7) irrigation. Municipal demand in each county is assumed to be representative of residential use, and the remaining five categories were aggregated into three market sectors: a commercial and industrial (C&I) sector comprised of manufacturing and mining demand in each county, a steam-electric sector, and an agricultural sector that combines livestock and irrigation users.

The economic loss framework considers economic impacts specifically related to water supply reduction. For each county in the Brazos, Colorado, and Guadalupe-San Antonio river basins, economic losses were calculated based on 2010 water demand and supply conditions provided by regional water-planning documents. Several regions comprise our study area: the Brazos (O, G, H) (AECOM, 2010a; HDR, 2010a, b), Colorado (F, K) (AECOM, 2010b; Freese and Nichols, 2011), and Guadalupe-San Antonio River basins (L) (HDR, 2010c). The hydrologic period of record varies for the different rivers: Brazos (1940–1997), Colorado (1940–1998), and Guadalupe-San Antonio (1934–1989) River basins. More recent hydrologic data have not yet been included by TCEQ in the input files; however, the period of record considers a range of hydrologic conditions. Economic losses by county and by user class were computed for each hydrologic draw as the difference between economic outcomes with and without the EF restrictions. Economic losses differ for each county according to various factors including nature of water demand in the area, current rate structure, availability of alternative water sources, and reliability of water rights with and without EF restrictions.

Economic losses were calculated at the county level in a framework that does not allow water transfers to take place across counties to meet regional shortages. The exception is Bexar, Medina, and Uvalde counties, which have explicit trading rules in place for groundwater transfers across county lines (HDR, 2010c). The implicit assumption of no water trading across counties reduces the scope of the economic analysis to four counties most severely impacted by water supply reductions: (1) Bexar; (2) Medina; (3) Tom Green; and (4) Wharton counties.

For the case of Bexar County losses, steam-electric plants were treated separately from other C&I users due to differences in the way that steam-electric plants utilize water. Steam-electric plants require adequate cooling water to safely operate, and accordingly use permitted water diversions to maintain water levels in cooling reservoirs. Economic losses at steam-electric plants were calculated by taking the difference in average annual operating frequency under baseline water supply conditions and EF restrictions and valuing the commensurate loss of annual power generation at prevailing electricity prices net of the savings in variable input costs. The probability that power plant cooling reservoir levels would drop below minimum operating levels required for power plant cooling was calculated using WAM Run8 monthly end-of-period storage with and without EFs (following the approach of Perkins [2011]). Run8 is more appropriate for this purpose than Run3 (which was used to calculate surface-water shortages), because Run8 includes treated wastewater returns used to fill two San Antonio-area reservoirs, Braunig and Calaveras Lakes; these returns are not included in Run3.

A similar approach was used to evaluate how Canyon Lake reservoir diversions (from Comal County) to senior water-rights holders in Bexar, Comal, Hays, and Kendall counties change from baseline to EF scenarios. Subordinate, downstream Canyon Lake user diversions were increased until Canyon Lake had one month of dead storage (4,140 acre-feet; water in the reservoir that cannot be used for water-rights deliveries because it is below pump intakes).

2.2.5 Estimating Municipal, Commercial & Industrial, and Agricultural Economic Losses

For each county, economic loss to municipal, C&I, and agricultural uses was calculated under two hydrologic draws: (1) normal water supply availability (which is specified as the 50% probability of exceedance, median diversion) and (2) water supply availability under drought conditions (90% probability of exceedance, drought diversion). The assessment of outcomes under drought conditions at the 90% probability of exceedance is important for analyzing extra risks posed by EF requirements under EF restrictions. When agents have any degree of risk aversion, it is important to characterize not just normal outcomes, but also outcomes with reduced water availability under drought conditions because agents may be motivated to avoid these circumstances.

Economic losses were calculated separately for the combined municipal, C&I, and agricultural sector and the steam electric sector (for counties of interest, **Figure 8**). For the combined municipal, C&I, and agricultural sectors, economic losses were calculated under a segmented markets scenario in which surplus water is not traded across market sectors in response to an overall water shortage as well as under an integrated markets scenario in which water is allowed to flow to the highest-valued use. In both cases, the steam-electric sector is segmented from remaining sectors of the regional economy.

Economic losses to municipal, C&I, and agricultural uses in each county depend on the ultimate allocation of the water supply reduction across high- and low-valued uses. The allocation of the water supply reduction is translated from the reduction in individual diversion rights, which depend on the seniority of diversion rights, to an aggregate supply reduction using drought response functions that mimic different abilities of water users to transfer water among uses.

Two types of response to EF-induced shortages are considered. The first represents a segmented markets response, in which the water supply reduction affecting a given economic sector can be shared among water users in the same sector but cannot be shared between different sectors of the regional economy. Under such a segmented-markets response, diversion rights cannot be transferred to the municipal and C&I sectors of the regional economy to minimize the economic loss of an overall water supply reduction. The second response represents an integrated-markets response, in which the total water supply reduction affecting a county can be freely allocated across market sectors to minimize the economic loss in the county. The integrated-markets response mimics the response that would occur in a water market where water prices emerge to allocate water rights from low-value uses to high-value uses. The segmented-markets response and integrated-markets response bookend the institutional response to a water supply reduction in each county, as various counties have instituted policies that facilitate the transfer of water between market sectors; for instance, the Edwards Transfer agreement allows groundwater pumping rights among irrigation uses in Bexar, Medina, and Uvalde counties to be purchased or leased for municipal uses in Bexar County.

Refer to Supporting Information for details on the approach used to calculate economic losses to municipal, commercial & industrial, and agricultural sectors.

2.2.6 Estimating Steam-Electric Economic Losses

The analysis considers economic losses to Bexar County coal- and natural gas-fired plants caused by EF-induced water shortages. These plants include J.K. Spruce and J.T. Deely coal-fired power plants and O.W. Sommers natural gas-powered plants which rely on diversions to Calaveras Lake and to Braunig Lake. The J.T. Deely plant is slated to be closed in 2018 and replaced with a gas plant in Seguin (CPS Energy, 2012; ERCOT, 2012). Thus, the economic loss calculations in this study are a worst-case estimate, reflecting the continued operation of J.T. Deely beyond its anticipated closure.

The expected annual operation frequencies for each plant were modeled directly (i.e., from WRAP water diversions) as the difference in projected operating frequencies under baseline conditions and under EF restrictions. A plant was considered operating during the times Calaveras and Braunig Lake levels were at or above a minimum cooling reservoir operating level. This steam-electric water availability modeling explores the boundaries of changes in surface water availability and does not necessarily mean that power generation would be reduced during modeled water shortages. The economic loss of EF restrictions at steam-electric plants was calculated by taking the difference in expected operating frequency under baseline diversions and EF diversions based on the exceedance probability of meeting the minimum operating level at each lake using monthly data from the hydrologic record over the period 1934–1989. Revenue projections are market calculations using publically available data and do not necessarily reflect actual plant revenue forecasts.

Refer to Supporting Information for details on the approach used to calculate economic losses to the steam-electric sector.

3.0 RESULTS AND DISCUSSION

This section presents the results of the hydrologic evaluation of Central Texas streams and EFs calculated for mussel sites. Changes in surface-water availability as a result of low and high EFs, including potential economic impacts resulting from EFs, are also presented.

3.1 Hydrology of Central Texas Streams

3.1.1 Hydrographs of Streamflow, Base Flow, and Precipitation

Mean daily streamflow, calculated base flow, and precipitation are shown in the representative hydrograph for the Guadalupe River at Cuero (USGS 8175800) (**Figure 9**). Hydrographs for the other nine mussel locations evaluated are shown in Supporting Information. Average Cuero area precipitation is approximately 30 inches per year (for 1942–2012). Increased streamflow is evident during high rains, particularly during 1992–1993. The 2009 drought is also visible in the record as reduced flows and precipitation. Stream discharge varies from approximately 200 to 100,000 cubic feet per second (cfs). During dry periods, base flow is essentially equal to total flow, although because of the gauge's downstream location, the base flow calculation is not accurate and does not truly reflect groundwater contribution because low flows here are comprised primarily of treated wastewater discharge, which appears as groundwater in the base-flow calculation.

3.1.2 Flow-Duration Curves

FDCs for all gauges at mussel sites are shown grouped by river basin (USGS 8175800) (**Figure** 10). FDCs for the 10 mussel locations are also shown in Supporting Information.

In the Brazos River Basin, three of the four gauges are in upstream areas and have highly variable flow (coefficient of variation = 2–8); two of these (Sabana River and Yegua Creek) are ephemeral (**Table 2**). The Leon River has also ephemeral but is dry less than ten percent of the record. The Richmond gauge is downstream and has more stable flows. Thus, the "flashy" and variable nature of Brazos River tributaries streams may explain why relatively few mussels are found there.

The Colorado River has much more stable flows at all three of the streams where mussels are found. Nevertheless, the San Saba River and the Colorado River near San Saba both go dry for a small percentage of the record. The flat slope of the San Saba River indicates that groundwater makes up much of the streamflow. The relatively stable discharge of the Colorado River streams may explain why several mussel locations are found there.

The Guadalupe-San Antonio River basin has even more stable flow profiles, at all three sites, than does the Colorado River. Cuero is a downstream location receiving relatively steady San Antonio wastewater return flows as well as steady Comal and San Marcos River spring flows; as a result, discharge varies little approximately 70% of the time. As with the Colorado River, stable flows in the Guadalupe-San Antonio River basin may contribute to modern mussel populations persisting there.

3.1.3 Streamflow Indices Derived from Flow-Duration Curves

A suite of metrics were calculated from the FDCs to describe quantitatively stream hydrology at each mussel location (**Table 2**). Mean BFI was also calculated at each site. The ten sites considered can be classified in three general groups: (1) ephemeral streams, (2) regulated and/or downstream locations; and (3) highly groundwater-dependent streams.

The first group of streams is composed of the Sabana River near De Leon and Yegua Creek near Somerville. The Sabana River goes dry because it is not regulated by an upstream dam. It has a low mean BFI (9%), reflecting low groundwater inflows that would support streamflow during drought. Yegua Creek is a "flashier" stream and even though it is regulated by a dam, it is still ephemeral. Both gauges have relatively high slopes in the low-flow part of the FDC between Q34 and Q77, indicating highly variable flows (-6 and -11). Mussels in ephemeral streams are at risk if groundwater pumping further reduces inflows to streams or if reservoir operation makes the stream dry more often.

The second stream group contains seven regulated and/or downstream gauges that have relatively steady discharge. Only the Leon River near Belton has relatively high streamflow variability (Q20/Q90 = 135; Q34–Q77 slope = -6.9; **Table 2**). The Brazos River at Richmond and Colorado River near San Saba have relatively low streamflow variability (Q20/Q90 = 14.80; Q34–Q77 slope = -3.78 and Q20/Q90 = 14.63; Q34–Q77 slope = -3.16, respectively). The Colorado River near San Saba, however, has a much lower median flow (208 cfs compared to 22,860 cfs at Richmond) and has gone dry 0.1% of the time. Thus, any changes in upstream water management that increase streamflow variability or the number of days the river runs dry may represent a threat to mussel habitat. The Leon River should also be managed to preserve streamflow. All other locations in the second group should maintain stable mussel habitat.

The third group contains one highly groundwater-dependent stream: the San Saba River at San Saba. This river depends on groundwater inflows to maintain streamflow during droughts (mean BFI = 49%; Q90/Q50 = 0.31), particularly in upstream reaches near Mason. Streamflow depletion caused by groundwater pumping near the San Saba River, as well as surface-water withdrawals for irrigation, both represent risks to mussel habitat.

Streamflow metrics were also calculated for 40 additional gauges throughout the Central Texas study area to create a regional picture of hydrologic factors influencing mussel habitat (**Figure 11**). Two major trends emerged from this regional analysis also present at the ten mussel locales (**Table 2**). First, Brazos River tributaries and the upper Colorado River have the highest streamflow variability in Central Texas (as indicated by Q34–Q77 slope, Q50/Q90, and Q20/Q90). Scouring flows and wetting-drying cycles in these streams may account for the current scarcity or absence of mussels at these locations. Second, tributary, headwater streams in the Colorado and Guadalupe-San Antonio River basins have the highest contribution of groundwater (as shown by mean BFI % and Q90/Q50), which is important for the maintenance of streamflow and associated mussel habitats during droughts. This analysis shows that the Guadalupe River above Canyon Lake has the highest groundwater contribution to streamflow, with the exception of the spring-fed headwaters of the Comal and San Marcos Rivers (which are essentially all groundwater; mean BFI = 95% for both streams).

3.1.4 Spring Distribution Relative to Mussel Sites

Mussel locations in relation to springs and aquifers were evaluated (**Figure 12**). Tributaries of the Brazos River (e.g., Sabana River, Leon River, and Yegua Creek) have relatively few springs near mussel locations. In the Colorado River basin, the San Saba River has numerous springs in the Edwards and Ellenburger-San Saba aquifers that maintain streamflow and aquatic habitat for mussels. In the Guadalupe-San Antonio River basin, dozens of springs feed the Guadalupe River upstream of Canyon Lake. Mussels are found near Goliad on the San Antonio River, which is fed by Comal and San Marcos springs and also by treated wastewater discharge from San Antonio.

3.1.5 Implications of Central Texas Stream Hydrologic Analysis for Maintenance of Mussel Habitat

This hydrologic assessment has important implications for the case of mussels being listed as endangered species. Maintaining groundwater-fed streams that flow during extended droughts is critical for future mussel habitat. Of the streams in the study area, those with a greater component of groundwater are Colorado River tributaries and streams in the Guadalupe-San Antonio River basin. Tributaries to the Brazos River in which mussels are found (i.e., Sabana River, Leon River, Yegua Creek) are relatively flashy, but the most upstream reaches show little low-flow variability (Q50/Q90 = 3–4). This suggests that groundwater inflows to these small streams are still important for the maintenance of aquatic habitat during droughts, particularly in isolated deeper-water pools. On the San Saba River, aquatic habitat for mussels near Menard is maintained during drought primarily by Edwards-Trinity aquifer discharge. In the Colorado River downstream of the confluence of the San Saba, mussel habitat is also supported by important Ellenburger-San Saba aquifer discharge, in addition to Edwards-Trinity aquifer inflows farther upstream. Guadalupe River mussel habitat is maintained by large Edwards aquifer springs (e.g., Comal and San Marcos springs), as well as groundwater inflows from the Edwards and Trinity aquifers to the Guadalupe River upstream of Canyon Lake. San Antonio River aquatic habitat near Goliad, while originally supported by groundwater inflows from the Edwards and Trinity aquifers, is now probably also maintained by San Antonio's treated wastewater discharge, which does not change substantially during droughts.

3.2 Determining Environmental Flows

In general, EFs are lower in upstream, tributary locations compared to downstream, main-stem sites (**Table 3**). EFs under the 95% probability of stream discharge exceedance scenario are much lower than the 75% probability of stream discharge exceedance (3–33% of the baseline condition compared to 13–67%, respectively). Because of its highly variable flow, the greatest EF as a percent of baseline occurs at the Sabana River near De Leon. The lowest impact under EFs is for Yegua Creek near Somerville.

The EFs determined by this study are in the range of those recommended by BBASC and BBEST (**Table 4**). For example, in the Brazos River basin, this study presents a range of EF at the Brazos River near Richmond of approximately 393,000–890,000 af/yr. BBASC suggested EFs of approximately 398,000–2,881,000 af/yr, which are slightly higher (Gooch et al., 2012). The Colorado River basin BBEST (Brzozowski et al., 2011) and Guadalupe-San Antonio River BBEST (GSA BBASC, 2011) also suggest EFs within the ballpark of this study (see **Table 4** for a complete EF comparison).

3.3 Changes in Water Availability Resulting from Environmental Flows

A hydrograph of regulated flows for baseline and EF scenarios for the Guadalupe River at Cuero (gauge 8175800) shows the greatest change of all gauges (**Figure 13**). At Cuero, EFs have the greatest impact on regulated flows under low-flow, drought conditions when a greater percentage of the river is required to satisfy EF requirements. For example, with a low EF, 1936, 1948, and 1966 are years with the greatest impacts to regulated flow (50,143 acre-feet, or 70% higher regulated flows under EF compared to baseline); under high EF, 1959, 1964, and 1988 show greatest impacts to regulated flow (101,286 acre-feet, or 63% higher regulated flows under EF compared to baseline). During median to high-flows, regulated flows do not change appreciably, because the river is flowing sufficiently to meet EFs without any water-management changes. Furthermore, this study does not consider pulse or overbank flows (for ease of modeling and to capture economically important low flows). Additional gauges exhibiting a lower degree of change in regulated flow are found in Supporting Information.

Biologists have identified Brazos River mussel locales mostly in small, less-altered streams with lower discharge compared to downstream reaches; these locales include the Sabana River, Yegua Creek, and Leon River (**Figure 2**). For example, the low EF is less than 4,000 af/yr in upstream areas (Leon River) (**Table 3**). The figure rises to approximately 15,000 af/yr for the high EF. In the Brazos River main stem, Richmond has an elevated EF (approximately 387,000 and 876,000 af/yr for low and high EFs, respectively). There are relatively few diversions between Richmond and the Gulf of Mexico, but upstream water rights may be impacted to maintain downstream EFs.

In the Colorado River basin, an EF at the Colorado River near San Saba could potentially affect water users in the relatively arid upper Colorado River basin, exacerbating already-existing water stresses (such as San Angelo in Tom Green County). EFs there could tie up 16% of stream discharge with a low EF rising to 49% of median river flow under high EF. EFs affect the San Saba River in a similar way, but economic losses in the primarily agricultural tributary region are minor. In downstream Wharton County, approximately 250,000 to 500,000 af/yr are reserved for EFs (low and high EF, respectively).

The effects of EF on water availability are the greatest in the Guadalupe-San Antonio River basin because of the limited water supply and highly productive uses of water in Bexar County, which includes San Antonio. EFs reserve approximately around ¼ of the water in the low EF scenario, rising to approximately 60% with a high EF.

3.3.1 Changes in Municipal, Commercial & Industrial, and Agricultural Water Availability

Water in a river is maintained by EFs, but changes in water availability are a function of how much a certain county depends upon surface water compared to other sources (e.g., groundwater and surface-water re-use). This surface water dependency is called residual demand. Residual demand is presented for Tom Green, Wharton, Bexar, and Medina counties, which have water supplies impacted by EFs. Evaluating residual demand also allows water allocation under baseline conditions to be distinguished from that under EF restrictions (**Table 5**, **Figure 8**). Uvalde County is also included, even though it has surplus water resources, because of the potential for trading to occur across Bexar, Medina, and Uvalde counties through the existing Edwards Transfer Agreement.

Residual demand in each sector indicates the level of water shortage that would arise if no water was available from the affected basins of operation and no transfers were possible across counties and across market sectors. Notice that residual demand is generally positive in each market sector (meaning EFs reduce water availability), although negative values (i.e., water surpluses) appear in some sectors, most notably for agricultural users. For example, Uvalde County has a 69,000 acre-foot surplus, primarily in the agricultural sector. Medina, Tom Green, and Wharton counties have agricultural shortages. Shortage in Wharton county is caused in part by low-reliability, run-of-the-river diversions (Alexander, 2012), while Bexar County has deficits primarily in the municipal sector.

Water shortages are shown by sector and county under baseline supply conditions, low EF restrictions, and high EF restrictions for normal and drought hydrologic conditions (**Table 6**). Water shortages appear in the baseline allocation in Bexar, Tom Green, and Wharton counties, and are exacerbated during drought. Water shortages are more severe in all cases under EF restrictions, as EFs exacerbate already-existing water supply issues.

How are economic inefficiencies caused by EF-induced shortages allocated and reconciled across users? In both the baseline and the EF allocations, users in some market sectors experience shortages during droughts, while at the same time users in other market sectors experience less shortages or even surpluses. For example, the agricultural sector of Bexar County has surplus water under all three water allocations (baseline, low EF, and high EF) at the same time that large shortages exist in the municipal sector (**Table 6**). Municipal water shortages can be reduced during droughts by reallocating surplus water to the residential sector; however, when water markets do not exist to execute transfers, it is unclear whether other institutions exist to match water supply to water needs. In practice, the water allocation that occurs is shaped by political and physical constraints that limit transfers across sectors and regions.

3.3.2 Changes in Steam-Electric Water Availability

The ability of electric power plants to draw water to cool their generators is also affected by EFs. The analysis shows that only Bexar County power plants (located on Calaveras and Braunig Lakes) are affected by the EF considered by this study. However, WAM modeling explores the boundaries in surface water availability and not necessarily actual power plant operational conditions. Under baseline (no EF) conditions, the minimum cooling reservoir operating level is maintained 99.1% of the time in Calaveras Lake and 99.6% of the time in Braunig Lake (**Table 7**). Under low EF restrictions, minimum operating level is reduced to 76% of the time at Calaveras Lake and 91% at Braunig Lake. Under high EF restrictions, minimum operating level is reduced to 67% of the time at Calaveras Lake and 47% at Braunig Lake.

Both Braunig Lake and Calaveras Lake were constructed in the 1960s and were designed to be filled primarily with treated sewage effluent diverted from the San Antonio River. Calaveras Lake is filled with unappropriated effluent water discharged by SAWS water treatment plants into the San Antonio River in an amount not to exceed 60,000 af/yr (CA#19-2162; Texas Water Rights Commission, 1977; Texas Water Commission, 1982). Diversions to Calaveras Lake are subject to senior and superior water rights (Texas Water Commission, 1982). Braunig Lake is filled with up to 12,000 af/yr of San Antonio River water subject to senior and superior water rights (CA#19-2161; HDR, 1999).

WAM modeling of surface water diversions to Calaveras and Braunig Lakes was done using TCEQ-provided input files (Run8) which reflect their interpretation of the power plant water rights outlined in CA#19-2161 and CA#19-2162. As such, the WAM input files view model effluent as state-owned water once it enters the San Antonio River and therefore subject to prior appropriation and possible calls by senior water rights holders elsewhere in the basin. As a result, this modeling shows that reservoir levels dip below minimum operating levels, even in baseline (non-EF) conditions, possibly because the modeling includes the drought of record of the 1950s which the 1960s-era reservoirs have not experienced.

3.4 Economic Losses from Environmental Flows

3.4.1 Municipal, Commercial & Industrial, and Agricultural Economic Losses

Water supply shortages translate into different economic losses, depending on where the shortages occur and what sectors are impacted. One-year economic losses were compared for segmented and integrated markets under baseline conditions as well as low and high EFs (**Table 8**). In the segmented markets case, diversion permits are constrained to remain within the county and market sector listed in the WAM output files for all counties. The exception is in Bexar, Medina, and Uvalde Counties (BMU), where the segmented markets case represents the current arrangement for EAA Transfers and Pumping (EAATP) (HDR, 2010d). In the BMU the EAATP currently allows up to 50% of groundwater pumping rights held by irrigation and livestock users to be re-allocated for municipal use in the region (HDR, 2010d).

In the integrated-markets case, diversion permits are constrained to remain within the county but can be traded freely across market sectors. In the BMU with integrated markets, water can move between sectors as well as counties. Under an integrated-market response, water units are bid to the highest-valued user through the action of a hypothetical water market. Under a segmented-market response, institutions do not exist for transferring water across market sectors and surplus conditions can exist in the agricultural sector at the same time that shortages impact the municipal sector. The actual water allocation that occurs across sectors depends on institutional responses as well as physical responses to a water shortage and is bounded by these extremes.

The calculation of economic losses in the integrated-markets scenario also takes into account transfers between municipal and C&I market sectors. Economic losses from water shortages in the C&I sector tend to be greater than losses in the municipal sector. Users in the municipal sector are better able to adjust to water shortages because municipal demand is more elastic than C&I (i.e., raising municipal water rates typically reduces consumption) and water shortages in the C&I sector also create additional losses through local employment effects. For this reason, most water agencies respond to water-supply disruptions with programs that specifically target the residential sector within municipal demand (e.g., limiting car washing and landscape irrigation).

A key finding of this study is that one-year economic losses of an EF-induced water shortage of a given magnitude for both normal and drought conditions are substantially lower in the integrated-markets case than under segmented markets. In this economic model, integrated markets reduce the overall economic cost of water shortages under baseline conditions as well as under EF restrictions by facilitating the transfer of water from agricultural users to municipal and C&I users in each county, as is generally seen in water transfers in the western United States (Griffin and Characklis, 2002; Hanak, 2005; Howe, 2000). However, this study does not account for compensating source regions for any economic impacts that may occur as a result of a water transfer (e.g., Colby, 1988; Easter et al., 1999; Howe, 2000; Hanak, 2005). In addition, functioning basin-wide water markets are not yet in place across Texas and may be a few years out. The comparison of losses in Bexar County and Medina County to losses in the BMU under segmented markets reveals the value of the current EAATP rules. Under baseline conditions, the ability to lease and transfer up to 50% of agricultural groundwater rights from the agricultural sector to the municipal sector under current Edwards Transfer rules (Griffin and Characklis, 2002; HDR, 2010d; RECON, 2011) has an annual value of $97M in the case of normal hydrologic conditions and $154M (i.e., $155.28M – $1.2M) during drought conditions (**Table 8**).

Indeed, the ability to transfer water across county lines by conveying groundwater pumping rights from the agricultural sector to the municipal sector in the BMU area provides considerably more value than an integrated market approach in Bexar County alone, as water shortages exist in Bexar County even when combining available water across sectors in the county. The EAATP allows the Bexar County municipal sector to meet what would otherwise be recurring water shortages by purchasing or leasing surplus groundwater pumping rights from the agricultural operators in Uvalde County.

Under fully integrated market conditions in the BMU, both the municipal and C&I sectors of the region have unlimited ability to purchase groundwater from irrigation and livestock users. Relaxing the constraint on water transfers to allow transfers greater than 50% of groundwater rights (70,172 acre-feet) from the agricultural sector completely eliminates losses during drought in both the baseline case and low EF restrictions. Under drought conditions and high EF restrictions, an overall water shortage exists that cannot be fully addressed by allowing market transfers of water across sectors in BMU and economic losses of $4.1M occur due to rationing in the agricultural sector (**Table 8**).

The implied Edwards transfers from irrigation users to municipal and C&I users are 70,482 acre-feet in the baseline case, 77,329 acre-feet under low EF restrictions, and 82,011 acre-feet under high EF restrictions. The magnitude of the leasing of agricultural groundwater in each case exceeds the current constraint on transfers of 50% of groundwater rights held by agricultural operators in the region.

One-year economic losses for each county and the total economic loss in the segmented-markets and integrated-markets scenarios are presented with the baseline removed to isolated economic losses caused by EF-related water shortages (**Table 9**). Economic losses are generally smaller with integrated markets than with segmented markets. Losses for Bexar and Medina counties are presented only for the case of segmented markets. Losses for the BMU are presented only for the fully integrated case that allows water trading to take place in excess of the existing constraint limiting EAATP groundwater leases. In several counties, the economic loss under EF restrictions is negative (i.e., the economic loss is smaller than under the baseline allocation) because more water would become available at that EF requirement location. For example, Wharton County would see gains in normal hydrologic conditions, but they disappear during drought conditions. This outcome is driven by WRAP modeling for the municipal and agricultural sectors of several counties under low EF restrictions compared to the baseline (**Table 9**).

Under normal hydrologic conditions, total annual economic losses for the case of a low EF restriction are -$5.21M (a gain) with segmented markets and -$1.11M with integrated markets (**Table 9**). For the case of a high EF restriction, the annual economic loss is $0.94M with segmented markets and $0.36M with integrated markets. Under drought conditions for the case of a low EF restriction, the annual economic loss is $37M with segmented markets and $1.7M with integrated markets; for the case of a high EF restriction, the annual economic loss is $79.7M with segmented markets and $11.2M with integrated markets.

One challenge with the integrated case presented here is that policymakers must assure that farmers receive fair market value for agricultural water that is transferred to other sectors and, perhaps, also receive compensation for economic impacts that result from long-term decreased agricultural activity in the source region (by way of a water transfer levy or fee). This will give farmers money to invest in improving farm irrigation efficiency (e.g., laser leveling, improved equipment) or to switch to a different crop. For example, interruptible water rights for irrigation provide water at low cost, but during supply shortages, the water is cut without farmers receiving payment; therefore, farmers endure economic losses without receiving the capital needed to improve operations.

3.4.2 Steam-Electric Economic Losses

This modeling exercise was completed using publically available data and water availability modeling that explored the boundaries of changes in surface water availability caused by EFs. The results of this study are not necessarily indicative of actual plant operation and are not a red flag that plants would reduce operational frequency under EFs. Revenue projections were market calculations done using publically available data that do not reflect actual revenue forecasts. Furthermore, steam-electric economic losses are based upon model assumptions—not necessarily indicative of actual operation—that water will not be reallocated to keep power plants online during any shortage. In reality, power generators were given priority during the drought of 2011.

Despite economic analysis limitations, EF restrictions result in impacts to the steam-electric sector. At all facilities, the EF restrictions will interrupt operations depending on hydrologic conditions that are impossible to predict with certainty, causing periodic losses in power generation as steam-electric plants turn to less-reliable sources of cooling water in order to safely operate.

Calculations of steam-electric losses are presented by plant (in real 2010 dollars; **Table 7**). The analysis indicates that the largest impacts are expected to occur at Calaveras Lake, where treated wastewater diversions from the San Antonio River are used to cool the coal-fired Spruce 1 and 2 and Deely 1 and 2 power plants. Across all impacted facilities, the one-year economic loss of low EF restrictions would be $36M and the economic loss of high EF restrictions would be $107M.

Because water trading is not allowed in the steam-electric analysis, economic losses represent a worst-case scenario. However, during the peak of the 2011 drought (the worst one-year drought in recorded Texas history), the State reallocated water to power plants as a matter of security and public health. This enabled power plants across Texas to continue generating. Furthermore, planned water transfers as well as interconnections with relatively secure municipal supply sources also would allow power plants to keep operating, despite climate- or regulation-induced water-supply reductions. Operators may also choose to lower pump intake depths or operate at lower efficiency (but not shut down as our model assumes) using warmer-than-ideal cooling water from a shallower-than-optimal reservoir. This was done by power plants in the United States Midwest during the 2012 drought. Ultimately, rather than shutting a plant down in a worst-case scenario of reduced water supplies caused by drought and EF, steam-electric operators may instead incur an incidental take (i.e., a short-term water diversion causing non-viable aquatic habitat that results in freshwater mussel deaths). Thus the $107M loss presented in this analysis shows results of a “what if” scenario that in reality would be mitigated through best-practice power plant operation guidelines. In addition, the steam-electric loss modeling is on an annual time step. If a power plant were to shut down only for a matter of days, actual losses would be less than the one-year shutdown assumed by this model.

3.4.3 Opportunities to Mitigate Economic Losses from Environmental Flows

In addition to incentivizing water markets to act as integrated markets, several other strategies can be employed to mitigate economic losses from EF. For example, aquifer storage and recovery (e.g., San Antonio Water Service Twin Oaks plant) can be used to store water underground when it is available (e.g., flood flows, or when a groundwater supply is plentiful). However, several barriers to ASR exist: it is capital-intensive to design, build, operate, and maintain an ASR facility. However, such costs may be less than those caused by impacted water supplies. Policy also makes ASR difficult in that injected water must be treated to drinking-water standards, which adds cost to the operation.

Conjunctive use of surface-water and groundwater is another solution that could increase water availability with existing supplies. When surface-water is available (i.e., during normal or wet hydrologic conditions), it is used. In times of drought, or when EF regulations limit available supplies, groundwater may be pumped in lieu of limited surface-water supplies. One example of this is a plan by the Lower Colorado River Authority to install a 10,000 acre-foot groundwater supply at the Lake Bastrop power plant cooling reservoir (Mashood, 2012b).

Interbasin water transfers add another layer to the integrated-market case, in that water can be transferred between basins, as is current practice in a number of parts of the state. Such transfers have diversified supplies for the cities of San Angelo and Midland-Odessa. However, invasive species, such the zebra mussel, present an impediment to implementation. Currently, zebra mussels are found in Lake Texoma and Lake Ray Roberts (TWDB, 2012c), but they could spread elsewhere. Finally, increasing water-use efficiency across the state in a suite of sectors can mitigate water shortages. For example, DuPont saved approximately ten percent in water use at a facility with reduced supplies from the Guadalupe River during the 2011 drought (Galbraith, 2012).

Several other strategies could also be considered. Off-channel reservoirs could store a portion of streamflow when it is available and release it during drought shortages exacerbated by EFs (LCRA, 2012). Surface-water spreading basins can also provide additional aquifer recharge for later groundwater well recovery by storing storm flows in shallow infiltration basins (Shaikh et al., 1995). Statewide water use across a variety of economic sectors may also be improved by raising wholesale water rates. Water re-use (i.e., delivering treated wastewater to customers) is another strategy used by several C&I customers in Texas, but water managers would need to be careful that reduced return flows to rivers would not result in streamflows below required EF regulations (Gregg et al., 2007). Economic impacts of EF regulations could also be reduced by increasing the efficiency of municipal water use. In addition to raising rates, some western water providers have used turf buy-back programs to reduce demands for keeping lawns green (Ryan, 2012).

CONCLUSIONS

Texas water resources, already taxed by drought, are becoming even more important as population grows. Environmental flows (EF) for aquatic habitat preservation could further reduce supplies if five Central Texas freshwater unionid mussel species are listed as endangered. This study estimates potential economic impacts caused by water shortages induced by EF for mussels in the Brazos, Colorado, and Guadalupe-San Antonio River basins by (1) characterizing the hydrology of Central Texas streams where mussels are found, (2) estimating possible EF requirements to maintain mussel habitats, (3) evaluating where potential water supply reductions caused by EFs may occur, (4) assessing potential economic impacts of EFs, and (5) presenting solutions that mitigate these impacts. This study did not evaluate economic impacts of adding critical habitat following a possible listing (as has been proposed by USFWS for Southeastern and Midwestern U.S. mussels), which may also have economic impacts above those caused by EFs.

What is the Hydrology of Central Texas Streams?

The regional hydrologic analysis of streams in Central Texas revealed that many streams in which mussels are found are reliant on groundwater inflows. If mussels are listed, these inflows would be especially important to the maintenance of aquatic habitat during droughts, when reduced rainfall decreases surface-water runoff to streams.

Groundwater inflows to streams are particularly important in the Colorado River basin, where the San Saba River is highly groundwater dependent. Similarly, the Guadalupe-San Antonio River basin also has streams that rely on significant inflows of groundwater. For example, dozens of springs flow into the Guadalupe River above Canyon Lake Dam, a segment of the river that is composed of 60–80% groundwater. Both the Comal and San Marcos Rivers are almost entirely spring-fed. In addition, the San Antonio River behaves as if it were spring-fed, with San Antonio’s treated wastewater effluent providing consistent low-flow contributions.

Thus, in order to maintain streamflows, especially during drought conditions, aquifers that drain into streams of the Colorado and Guadalupe-San Antonio Rivers must not be overpumped. This includes the Edwards-Trinity aquifer, which supports the Upper Guadalupe and San Saba Rivers, and the Ellenburger-San Saba aquifer, which supports the San Saba River. Pumping limits currently enforced by the EAA (as a result of *Sierra Club et al. v. Babbitt et al.,* 1993) should continue to preserve Comal and San Marcos spring discharge. This study also found that few streams in the Brazos River basin are highly groundwater-dependent.

The hydrologic analysis shows that some streams in the study area are ephemeral and go dry during droughts and even during some typical summers. This is especially true of the Leon River, Sabana River, and Yegua Creek in the Brazos River basin. Downstream at Richmond, the Brazos River is perennial. The Colorado River in our study area also has ephemeral streams (San Saba River and Colorado River at San Saba), but these streams go dry only infrequently. The

Guadalupe-San Antonio River basin has the most stable flows, and all of the sites evaluated are perennial streams. As in the case of the groundwater-dependent streams, groundwater extraction as well as reservoir operation should be managed to preserve aquatic habitat to assure that these streams do not become dry more often. In the Colorado River basin, the Upper Colorado River basin (i.e., San Angelo) should diversify supplies as to not increase the percentage of time that the Colorado River near San Saba runs dry.

What are Possible Environmental Flows for Mussels?

As expected, possible EFs to preserve aquatic habitat for mussels are lower in upstream tributaries than downstream main channels. In terms of discharge, EF in upstream reaches such as the Sabana River, Leon River, and Yegua Creek are in most cases only a few thousand af/yr. However, EFs at downstream locations, such as the Brazos River at Richmond, Colorado River at Wharton, or Guadalupe River at Victoria translate to 100,000s af/yr. In terms of EF as a percent of baseline (i.e., non-EF) conditions, low EFs (i.e., stream discharge with a 95% probability of exceedance) represent 3–33% of non-EF baseline flows. High EFs (i.e., stream discharge with a 75% probability of exceedance) comprise 13–67% of baseline streamflow.

Where Do Possible Water Supply Reductions from Environmental Flows Occur?

Water supply reductions as a result of EFs are less than assumed before the study was started. Only in areas with acute supply issues do EFs exacerbate water shortages. For example, in the Brazos River basin, no water shortages result from EFs because the EFs were located primarily in tributaries. In the Colorado River basin, worst-case (i.e., drought) shortages include Tom Green County (55,000 af/yr) and Wharton County (82,000 af/yr). Tom Green County includes the city of San Angelo, which already has low surface-water supplies. Wharton County water demand is composed primarily of junior, interruptible irrigation rights. In the Guadalupe-San Antonio River basin, EF shortages occur in Bexar County (74,000 af/yr) and Medina County (4,000 af/yr). Both counties have limited surface-water resources. However, shortages in both counties are reduced to 8,000 af/yr when groundwater is imported from Uvalde County (as is currently the case).

What Are the Potential Economic Impacts of Environmental Flows?

In a segmented market in which water cannot be transferred between economic sectors or between counties, economic impacts in affected counties are higher. Conversely, with an integrated market, water trading that occurs between economic sectors and between counties can reduce economic impacts. For example, under baseline conditions (no EFs) Bexar County annually avoids approximately $97 million (M) in economic losses during normal hydrologic conditions (i.e., defined as a year with water diversions with a 50% probability of exceedance) and $145M during drought (i.e., water diversions with a 90% probability of exceedance) by importing groundwater (conveyed through the Edwards aquifer using the natural west to east aquifer flow direction) from Medina and Uvalde Counties.

Using similar water transfers, one-year, worst-case (i.e., drought and high EFs) economic impacts to commercial and industrial, municipal, and agricultural sectors could be reduced from $80M to $11M. During drought with less stringent EFs, water transfers could reduce one-year economic impacts from $37M to $1.6M. Under normal hydrologic conditions, one-year economic losses are under $1M for both low and high EFs.

The steam-electric sector could potentially have one-year, worst-case economic impacts up to $36M with low EFs and up to $107M with high EFs in Bexar County from EF water supply reductions. However, water availability modeling explored the boundaries of changes in surface water availability and revenue projections are market calculations using publically available data and do not necessarily reflect actual revenue forecasts. Also, the J.T. Deely power plant is planned to be closed in 2018 and replaced with a plant in Seguin. Therefore, in the longer term, the aforementioned economic impacts may be overestimated. Also, power generators were granted priority during the 2011 drought and did not shut down. As a result, shortages are conservative and the economic impacts for steam electric are the highest that could reasonably be expected.

How Can Texas Plan for and Mitigate Economic Impacts of Environmental Flows?

Water transfers from agriculture to commercial and industrial sectors (as is typical of water transfers in the western United States) represent one strategy to mitigate economic impacts of EF regulations. However, barriers to implementation need to be addressed before basin-scale water markets can become an effective tool to manage water supply shortages in Texas. For example, polices should also be developed so that source communities receive a fair price for their water and are compensated for any long-term economic impacts resulting from transferring water out of traditionally agricultural areas (to mitigate so called “third-party” and “secondary” economic impacts resulting from reduced agricultural output).

In addition to the arrangement of water markets (likely some years off), the development of alternative water supplies could also mitigate economic impacts of EF regulations. For example, aquifer storage and recovery can provide additional water supplies during droughts by storing surplus groundwater or surface water when it is available. Conjunctive use of groundwater and surface water is another solution which uses surface water when it is available and switches to groundwater reserves during periods of surface-water shortages. However, as many of the Central Texas streams in which mussels are found rely upon groundwater inflows, water managers should ensure that groundwater pumping does not deplete streams during droughts. Interbasin transfers may also augment stressed supplies, but invasive species such as the zebra mussel may limit deliveries (in addition to the lack of existing infrastructure). Finally, increased system-wide efficiency and conservation are tools effectively used by industry during the 2011 drought; they could also mitigate effects of EF water supply reductions.

What Does a Future with Environmental Flows Look Like?

What all this means for the future in Texas is that even in the worst-case scenario, economic impacts of EFs specifically for the five Central Texas mussels considered are likely to be relatively moderate, as long as efficient and equitable water markets (that also adequately compensate source communities for economic losses) are established in the coming years to move water from water-rich to water-poor parts of the state during shortages. Many water management strategies, some of which are recommended in the Texas State Water Plan, can be used to increase water supplies and to mitigate economic impacts of EFs. Therefore, with increasing demands on Texas water supplies, there is an urgent need to develop approaches for EFs, and also to have a broad range of strategies to quantify economic and mitigate impacts of EF requirements.

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TABLES

Table 1. Comal and San Marcos springs minimum flow requirements for critical habitat protection

Species	Spring	ESA Status	Take (cfs)[1]	Exceedance Probability[2]
Fountain darter	Comal	Endangered	200	87%
Fountain darter	San Marcos	Endangered	60	>99%
Comal Riffle Beetle	Comal	Endangered	120	95%
San Marcos gambusia	San Marcos	Endangered	100	86%
Comal Springs Dryopid Beetle	Comal	Endangered	120	95%
Peck's Cave Amphipod	Comal	Endangered	120	95%
Texas blind salamander	San Marcos	Endangered	100	86%
Texas wild-rice	San Marcos	Endangered	100	86%
San Marcos salamander	San Marcos	Threatened	50	>99%
Edwards Aquifer Diving Beetle	Comal	Candidate	120	95%
Edwards Aquifer Diving Beetle	San Marcos	Candidate	50	>99%
Comal Springs Salamander	Comal	Candidate	120	95%
Texas Troglobitic Water Slater	San Marcos	Candidate	50	>99%

Notes: 1. Flow determinations below which a take would occur is from EARIP Habitat Conservation Plan (RECON, 2011). 2. Calculated by this study using long-term stream-gauge data (USGS, 2012). ESA = Endangered Species Act. cfs = cubic feet per second.

Table 2. Base flow and flow-duration curve indices.

Hydrologic analysis indicates Sabana River and Yegua Creek are ephemeral. San Saba and Guadalupe Rivers have important groundwater and spring inflows, while flows from San Antonio treated wastewater discharge resemble groundwater inflows.

ID #	Stream Name	EF Location	USGS Gauge	Mean BFI	Q20/Q90	Q50/Q90	Q90/Q50	Slope Q34–Q77	Q50	Q50	Std. Dev.	Coeff. Var.
				Base Flow Index (%)	Streamflow Variability	Low-Flow Variability	Proportion Surface Water from Groundwater	Low-Flow Slope	Median Flow (AF/yr)	Median Flow (cfs)	(cfs)	
	Brazos River Basin											
1	Sabana River	near De Leon	8099300	9	-	-	-	-6	1,014	1	282	8
2	Yegua Creek	near Somerville	8110000	*	-	-	-	-11	4,344	6	1,011	4
3	Leon River	near Belton	8102500	*	135	12	0.2	-7	46,334	64	1,409	2
4	Brazos River	at Richmond	8114000	*	15	4	0.3	-4	2,070,537	2,860	11,857	2
	Colorado River Basin											
5	San Saba	at San Saba	8146000	49	7	3	0.3	-2	61,537	85	1,367	6
6	Colorado	near San Saba	8147000	*	15	4	0.2	-3	149,861	208	4,288	4
7	Colorado	at Wharton	8162000	*	7	3	0.4	-2	912,195	1,260	5,008	2
	Guadalupe-San Antonio River Basin											
8	San Antonio	at Goliad	8188500	*	6	3	0.4	-2	255,559	353	2,085	3
9	Guadalupe	at Cuero	8175800	*	5	2	0.4	-2	752,923	1,040	4,943	2
10	Guadalupe	at Victoria	8176500	*	6	3	0.4	-2	723,964	1,000	4,427	2

NOTE: The symbol "-" indicates the value cannot be calculated because stream is ephemeral. The symbol "*" indicates BFI is not reliable because the gauge is influenced by upstream water management activities, such as reservoir operations or urban wastewater return flows. AF/yr = acre-feet/year. cfs = cubic feet per second.

Table 3. Environmental flows calculated at locations of known or likely freshwater mussel occurrences.

Baseline flow (median, 50% probability of exceedance discharge) and EFs are calculated using long-term stream-gauge data (USGS, 2012).

ID #	Stream Name	EF Location	Control Point	Refs.	Latitude	Longitude	USGS Gauge	Start Year	End Year	Baseline: No EFs Median Flow (AF/yr)	Low EF AF/yr	Low EF % of Median Flow	High EF AF/yr	High EF % of Median Flow
	Brazos River Basin													
1	Sabana River	near De Leon	SADL44	1	32.1140300	-98.6056070	08099300	1960	2012	2,172	724	33	1,448	67
2	Yegua Creek	near Somerville	YCSO62	1	30.3218770	-96.5074680	08110000	1924	2012	27,511	724	3	3,620	13
3	Leon River	near Belton	LEBE49	2, 3	31.0701790	-97.4413970	08102500	1923	2012	60,090	3,620	6	15,203	25
4	Brazos River	at Richmond	BRRI70	1, AOC	29.5824590	-95.7577280	08114000	1903	2012	2,063,336	387,321	19	875,996	42
	Colorado River Basin													
5	San Saba	at San Saba	F10000	4, 5	31.2132230	-98.7194870	08146000	1915	2012	63,710	13,031	20	35,474	56
6	Colorado	near San Saba	E10000	1	31.2179450	-98.5644840	08147000	1915	2012	153,483	24,615	16	74,568	49
7	Colorado	at Wharton	K20000	6, AOC	29.3091370	-96.1038480	08162000	1938	2012	912,212	254,835	28	524,874	58
	Guadalupe-San Antonio River Basin													
8	San Antonio	at Goliad	CP14	6, 7	28.6497150	-97.3847150	08188500	1924	2012	255,564	68,704	27	150,585	59
9	Guadalupe	at Cuero	CP37	6, 7, 8	29.0905310	-97.3297130	08175800	1964	2012	760,176	216,538	28	477,454	63
10	Guadalupe	at Victoria	CP15	6, 9	28.7930460	-97.0130430	08176500	1934	2012	723,978	156,376	22	443,790	61

References: 1. Randklev, 2012, 2. Howells, 2006, 3. Randklev, 2011, 4. Randklev et al., 2010a, 5. OSUM, 2011, 6. Burlakova and Karatayev, 2010, 7. Howells, 2003, 8. Howells, 1997, 9. Howells, 2009. AOC = Assumption of occurrence (per USFWS best practices). Note: at locations with very low discharge, a 95% probability of exceedance of 724 AF/yr (1 cubic foot per second) was used. AF/yr = acre-feet/year. Note: A low EF is defined as a stream discharge with a 95% probability of exceedance, while a high EF has a stream discharge with a 75% probability of exceedance.

Table 4. Comparison of environmental flows in this study, with stakeholder recommendations.

This study presents EFs that are within the range of EFs suggested by BBASCs.

	Guadalupe at Victoria[1]				**Guadalupe at Cuero[1]**				**San Antonio at Goliad[1]**			
BBASC Recs	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)
Base Flows	370	975	267,867	705,865	390	980	282,346	709,485	139	584	100,631	422,795
Subsistence Flows	110	160	79,636	115,834	86	130	62,261	94,115	60	60	43,438	43,438
This Study's EFs												
High	611		442,342		658		476,368		208		150,585	
Low	216		156,376		299		216,538		95		68,777	

	Colorado near San Saba[2]				**San Saba at San Saba[2]**				**Colorado at Wharton[2]**			
BBASC Recs	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)
Base Flows	72	360	52,125	260,627	32	110	23,167	79,636	314	1,512	227,325	1,094,634
Subsistence Flows	30	50	21,719	36,198	3	29	2,172	20,995	107	371	77,464	268,591
This Study's EFs												
High	99		71,672		48		34,750		725		524,874	
Low	31		22,443		16		11,583		352		254,835	

	Brazos near Richmond[3]			
BBASC Recs	Low (cfs)	High (cfs)	Low (AF/yr)	High (AF/yr)
Base Flows	930	3,980	673,287	2,881,377
Subsistence Flows	550	550	398,180	398,180
This Study's EFs				
High	1,230		890,476	
Low	543		393,112	

References: 1. GSA BBASC, 2011, 2. Brzozowski et al., 2011, and 3. Gooch et al., 2012. cfs = cubic feet per second. AF/yr = acre-feet/year. Note: A low EF is defined as a stream discharge with a 95% probability of exceedance, while a high EF has a stream discharge with a 75% probability of exceedance.

Table 5. Demand and residual demand by county and sector.

Residual demand (i.e., surface-water supply) calculated using TWDB regional water-planning reports. Values are acre-feet/year.

	Demand	Firm Supply	Residual Demand
Bexar County			
Municipal	262,106	177,567	84,539
C&I	29,533	28,193	1,340
Agricultural	16,592	24,728	-8,136
TOTAL Bexar	**308,231**	**230,488**	**77,743**
Medina County			
Municipal	7,576	6,993	583
C&I	197	1,456	-1,259
Agricultural	55,748	50,663	5,085
TOTAL Medina	**63,521**	**59,112**	**4,409**
Uvalde County			
Municipal	8,066	6,044	2,022
C&I	432	1,793	-1,361
Agricultural	1,597	71,755	-70,158
TOTAL Uvalde	**10,095**	**79,592**	**-69,497**
Tom Green County			
Municipal	23,494	14,128	9,366
C&I	2,299	150	2,149
Agricultural	106,599	55,053	51,546
TOTAL Tom Green	**132,392**	**69,331**	**63,061**
Wharton County			
Municipal	3,776	13,450	-9,674
C&I	1,044	4,164	-3,120
Agricultural	183,713	65,172	118,541
TOTAL Wharton	**188,533**	**82,786**	**105,747**

References: AECOM, 2010a, b; Freese and Nichols, 2011; HDR, 2010a, b, c; TWDB, 2011.

Table 6. Water shortages by county and sector.

Shortages presented for baseline conditions (using WRAP-modeled water availability) and under low and high EFs. Values are acre-feet/year.

		BASELINE		**LOW EF**		**HIGH EF**	
Sector	**Residual Demand**	**Normal**	**Drought**	**Normal**	**Drought**	**Normal**	**Drought**
Bexar County							
Municipal	84,539	56,425	70,065	55,227	76,667	56,643	81,187
C&I	1,340	-823	1,336	-1,239	1,172	-1,931	1,149
Agricultural	-8,136	-15,654	-12,115	-13,906	-9,227	-12,490	-8,588
TOTAL	**77,743**	**39,949**	**59,286**	**40,081**	**68,612**	**42,222**	**73,748**
Medina County							
Municipal	583	-337	-321	-337	89	-229	273
C&I	-1,259	-1,259	-1,259	-1,259	-1,259	-1,259	-1,259
Agricultural	5,085	-41,086	-14,569	-40,977	-5,906	-33,085	5,084
TOTAL	**4,409**	**-42,682**	**-16,149**	**-42,573**	**-7,076**	**-34,573**	**4,098**
Bexar, Medina, Uvalde Counties							
Municipal	87,144	58,110	71,766	56,912	78,777	58,436	83,482
C&I	-1,280	-3,443	-1,284	-3,859	-1,448	-4,551	-1,471
Agricultural	-73,209	-126,897	-96,842	-125,041	-85,291	-115,734	-73,662
TOTAL	**12,655**	**-72,230**	**-26,360**	**-71,989**	**-7,961**	**-61,848**	**8,348**
Tom Green County							
Municipal	9,366	-1,919	6,274	-1,916	6,251	-1,659	6,780
C&I	2,149	216	2,149	216	2,149	216	2,149
Agricultural	51,546	40,768	44,963	40,766	45,066	41,445	45,969
TOTAL	**63,061**	**39,066**	**53,386**	**39,066**	**53,466**	**40,002**	**54,898**
Wharton County							
Municipal	-9,674	-9,674	-9,674	-9,674	-9,674	-9,674	-9,674
C&I	-3,120	-3,120	-3,120	-3,120	-3,120	-3,120	-3,120
Agricultural	118,541	59,815	89,115	58,123	90,882	59,197	95,007
TOTAL	**105,747**	**47,021**	**76,321**	**45,329**	**78,088**	**46,403**	**82,213**

Notes: A low EF is defined as a stream discharge with a 95% probability of exceedance, while a high EF has a stream discharge with a 75% probability of exceedance. Normal water diversions occur under median hydrologic conditions (i.e., an annual diversion volume with a 50% probability of exceedance), while drought diversions have a 90% probability of exceedance.

Table 7. Steam-electric power generation losses from EF restrictions.

Low and high EFs result in one-year losses of $37M and $107M, respectively. Values are acre-feet/year.

			LOW EF			HIGH EF		
Plant Name	**Net Revenue (M $s)**	**Baseline Operating (%)**	**Operating (%)**	**Operating Loss (%)**	**Net Revenue Loss (M $s)**	**Operating (%)**	**Operating Loss (%)**	**Net Revenue Loss (M $s)**
Coal Power Plant								
J K Spruce_1	$40	99.1%	75.6%	23.5%	$9.3	67%	32%	$26.4
J K Spruce_2	$55	99.1%	75.6%	23.5%	$12.9	67%	32%	$36.6
J T Deely_1	$22	99.1%	75.6%	23.5%	$5.2	67%	32%	$14.7
J T Deely_2	$27	99.1%	75.6%	23.5%	$6.4	67%	32%	$18.1
Natural Gas Power Plant								
Arthur Von Rosenberg_CC	$13	99.6%	90.6%	8.9%	$1.1	47%	52%	$6.0
V H Braunig_1	$0.6	99.6%	90.6%	8.9%	$0.1	47%	52%	$0.3
V H Braunig_2	$0.6	99.6%	90.6%	8.9%	$0.1	47%	52%	$0.3
V H Braunig_3	$4	99.6%	90.6%	8.9%	$0.3	47%	52%	$1.8
O W Sommers_1	$3	99.1%	75.6%	23.5%	$0.6	67%	32%	$1.7
O W Sommers_2	$1	99.1%	75.6%	23.5%	$0.3	67%	32%	$0.7
Total					**$36**			**$107**

Note: M = million.

Table 8. Economic losses by water supply availability and market type.

Conveying groundwater from Uvalde and Medina counties to Bexar County nets approximately $97M in avoided costs under normal hydrologic conditions, and $154M during drought conditions (calculated by comparing losses of Bexar County with Bexar, Medina, Uvalde Counties segmented markets under baseline, no EF conditions). Values are acre-feet/year.

	NORMAL		DROUGHT	
Sector	**Segmented**	**Integrated**	**Segmented**	**Integrated**
Bexar County				
Baseline	$97,204,078	$42,671,852	$155,280,667	$81,590,619
Low EF	$93,252,897	$42,876,281	$190,817,118	$108,971,015
High EF	$97,936,595	$46,278,728	$219,714,809	$127,342,765
Medina County				
Baseline	$0	$0	$0	$0
Low EF	$0	$0	$82,203	$0
High EF	$0	$0	$2,726,880	$1,951,940
Bexar, Medina, Uvalde Counties				
Baseline	$0	$0	$1,200,015	$0
Low EF	$0	$0	$7,105,117	$0
High EF	$0	$0	$11,700,565	$4,086,409
Tom Green County				
Baseline	$24,053,300	$23,486,562	$54,670,910	$36,929,775
Low EF	$24,052,287	$23,486,966	$54,551,721	$37,016,981
High EF	$24,720,230	$24,250,812	$60,704,508	$38,614,000
Wharton County				
Baseline	$34,636,791	$25,653,403	$60,543,760	$48,132,708
Low EF	$33,382,630	$24,545,053	$62,424,175	$49,731,893
High EF	$34,176,218	$25,246,583	$66,997,108	$53,601,615

Notes: A low EF is defined as a stream discharge with a 95% probability of exceedance, while a high EF has a stream discharge with a 75% probability of exceedance. Normal water diversions occur under median hydrologic conditions (i.e., an annual diversion volume with a 50% probability of exceedance), while drought diversions have a 90% probability of exceedance. A segmented market does not allow water transfers between economic sectors and counties, while an integrated market permits water transfers.

Table 9. Economic losses of EF restrictions.

Economic losses presented here have baseline losses removed to isolate losses caused by EFs. With low EFs, water transfers among sectors reduce total commercial and industrial, municipal, and agricultural losses in the study area from $37M to $1.6M in a drought. With high EFs and a drought (i.e., a worst-case scenario), water transfers reduce losses from $80M to $11M. Under normal hydrologic conditions, no economic losses would occur with low EFs, and economic losses are nominal (i.e., less than $1M) with high EFs. Values are acre-feet/year.

	NORMAL		**DROUGHT**	
Sector	**Segmented**	**Integrated**	**Segmented**	**Integrated**
Bexar County				
Low EF	-$3,951,181		$35,536,451	
High EF	$732,517		$64,434,143	
Medina County				
Low EF	$0		$82,203	
High EF	$0		$2,726,880	
Bexar, Medina, Uvalde Counties				
Low EF		$0		$0
High EF		$0		$4,086,409
Tom Green County				
Low EF	-$1,013	$405	-$119,189	$87,206
High EF	$666,930	$764,250	$6,033,598	$1,684,224
Wharton County				
Low EF	-$1,254,161	-$1,108,350	$1,880,416	$1,599,184
High EF	-$460,573	-$406,820	$6,453,348	$5,468,906
TOTAL LOSS				
Low EF	-$5,206,355	-$1,107,946	$37,379,881	$1,686,390
High EF	$938,874	$357,430	$79,647,969	$11,239,540

Notes: A low EF is defined as a stream discharge with a 95% probability of exceedance, while a high EF has a stream discharge with a 75% probability of exceedance. Normal water diversions occur under median hydrologic conditions (i.e., an annual diversion volume with a 50% probability of exceedance), while drought diversions have a 90% probability of exceedance. A segmented market does not allow water transfers between economic sectors and counties, while an integrated market permits water transfers.

FIGURES

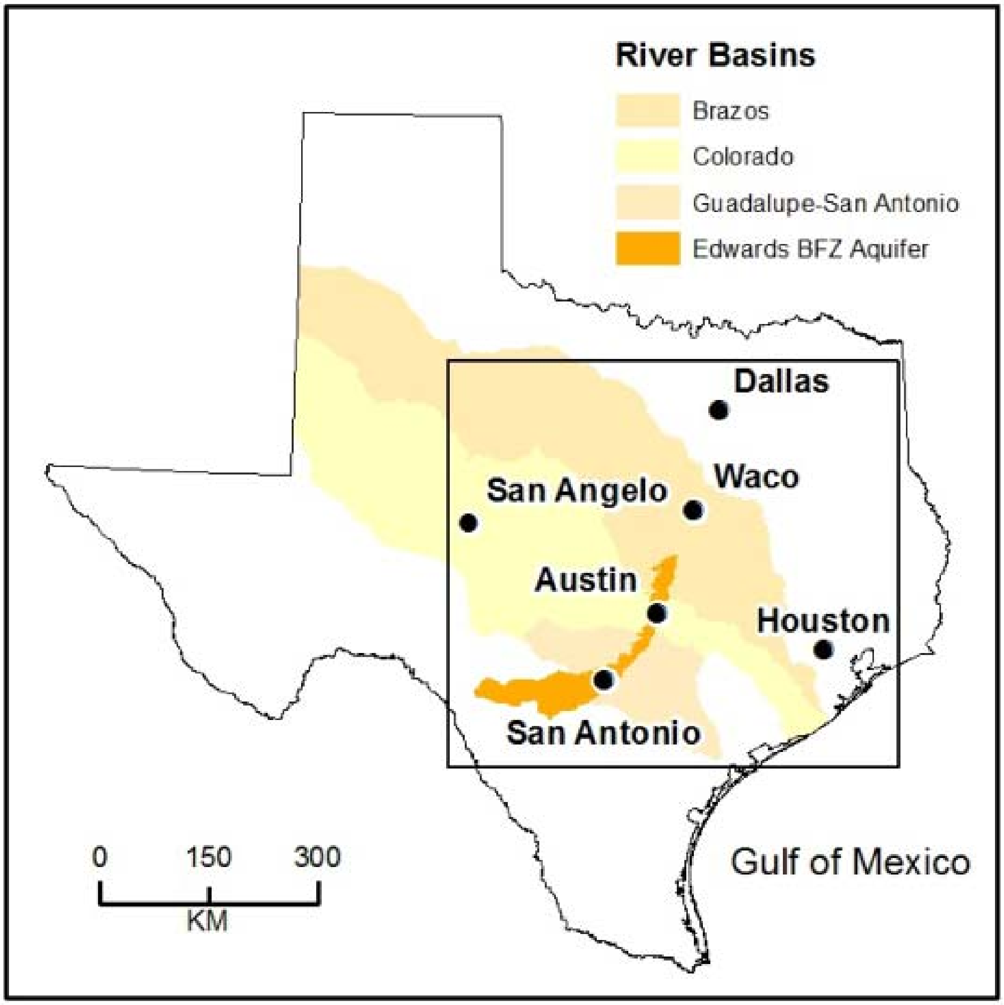

Figure 1. Study area: major river basins and Edwards Aquifer.

The study area includes Brazos, Colorado, and Guadalupe-San Marcos River basins (36% of Texas, approximately 95,000 square miles).

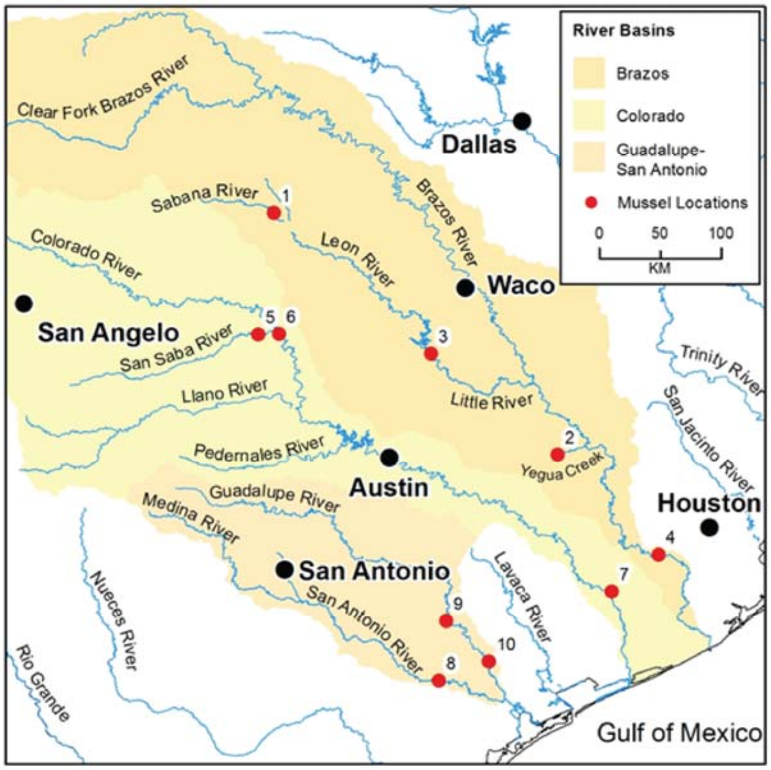

Figure 2. Known or likely freshwater mussel locales.

At these locations, EFs used for water availability modeling (gauge ID numbers are also shown). The gauges are (1) Sabana River near De Leon, USGS gauge 08099300, (2) Yegua Creek near Somerville USGS gauge 08110000, (3) Leon River near Belton, USGS gauge 08102500, (4) Brazos River at Richmond, USGS gauge 08114000, (5) San Saba River at San Saba, USGS gauge 08146000, (6) Colorado River near San Saba, USGS gauge 081470000, (7) Colorado River at Wharton, USGS gauge 08162000, (8) San Antonio River at Goliad, USGS gauge 08188500, (9) Guadalupe River at Cuero, USGS gauge 08175800, and (10) Guadalupe River at Victoria, USGS gauge 08176500.

Figure 3. Freshwater mussel survey on San Marcos River near Luling (October 2011).

Photo courtesy of Clint Robertson (Texas Parks and Wildlife Department).

Figure 4. Texas freshwater mussel in river substrate.

Photo courtesy of Clint Robertson (Texas Parks and Wildlife Department).

Figure 5. Texas freshwater mussel filtering water.

Photo courtesy of Clint Robertson (Texas Parks and Wildlife Department).

Figure 6. Texas freshwater mussels.

Photo courtesy of Clint Robertson (Texas Parks and Wildlife Department).

Figure 7. Texas freshwater mussel.

Photo courtesy of Clint Robertson (Texas Parks and Wildlife Department).

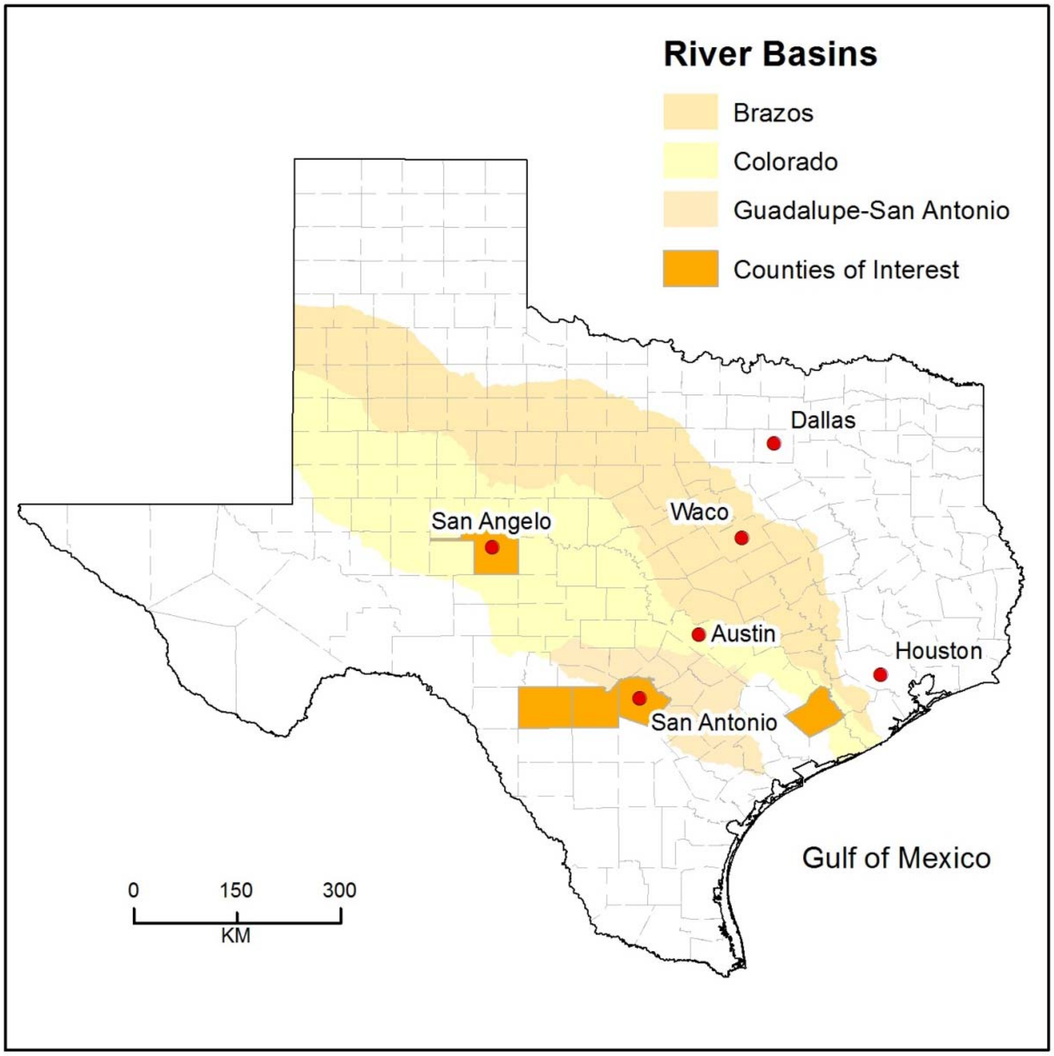

Figure 8. Counties of interest in economic analysis.

Results of water availability modeling analysis show that four counties (dark orange polygons) have unmet needs caused by EFs: Tom Green (San Angelo), Wharton (100 miles southeast of Austin), and Bexar (San Antonio). Medina county (west of Bexar county) only has shortages with a high EF and drought. Also included was Uvalde county (west of Medina county), which has surplus water that may be used to mitigate EF impacts near San Antonio. Brazos River basin is not substantially affected by EFs.

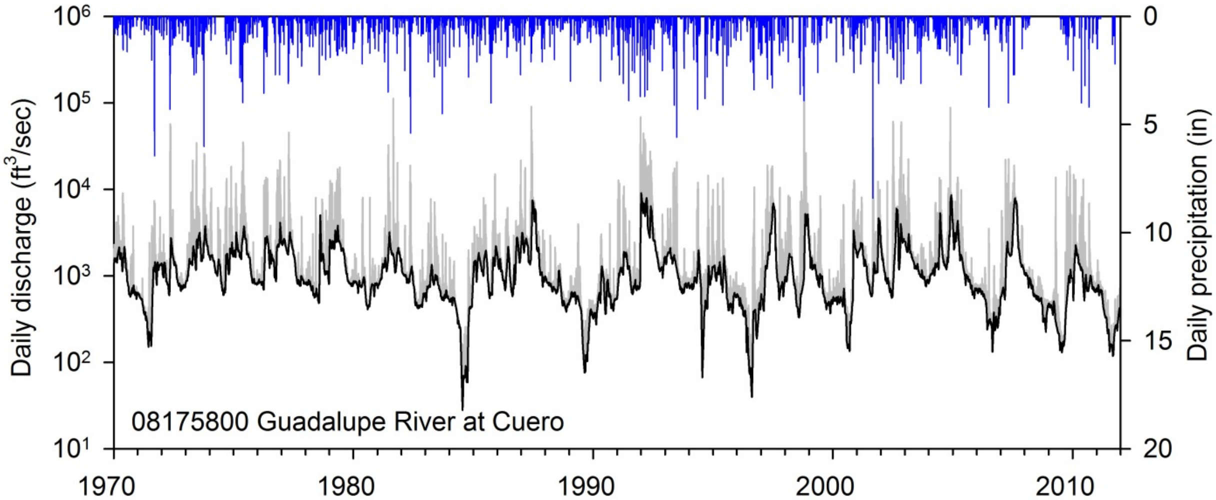

Figure 9. Hydrograph for the Guadalupe River at Cuero (USGS 8175800).

Hydrograph (gauge ID# 9) shows mean daily streamflow (gray), calculated base flow (black), and precipitation (blue). Additional hydrographs provided in the Supporting Information.

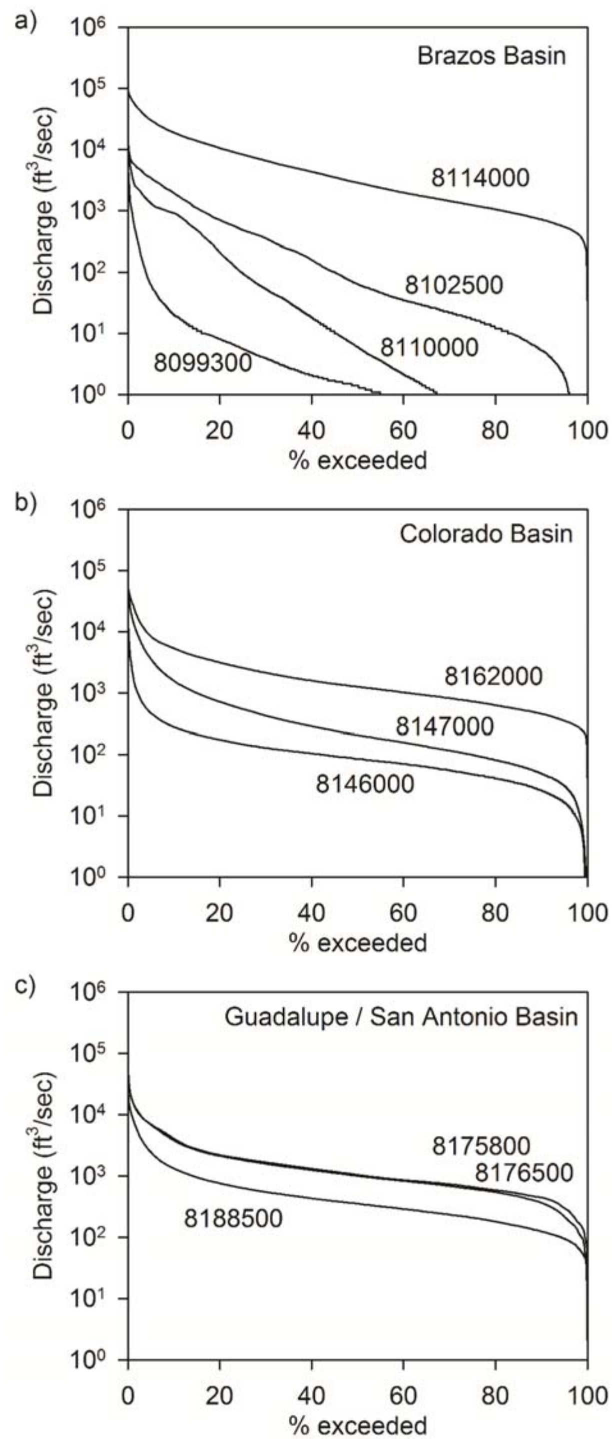

Figure 10. Flow-duration curves for gauges at mussel sites in each basin.

Flow-duration curves (FDC) show probability of streamflow exceedance based on long-term stream-gauge data. Individual FDCs provided in the Supporting Information. Brazos River basin has several ephemeral streams. Most other streams in study area are perennial.

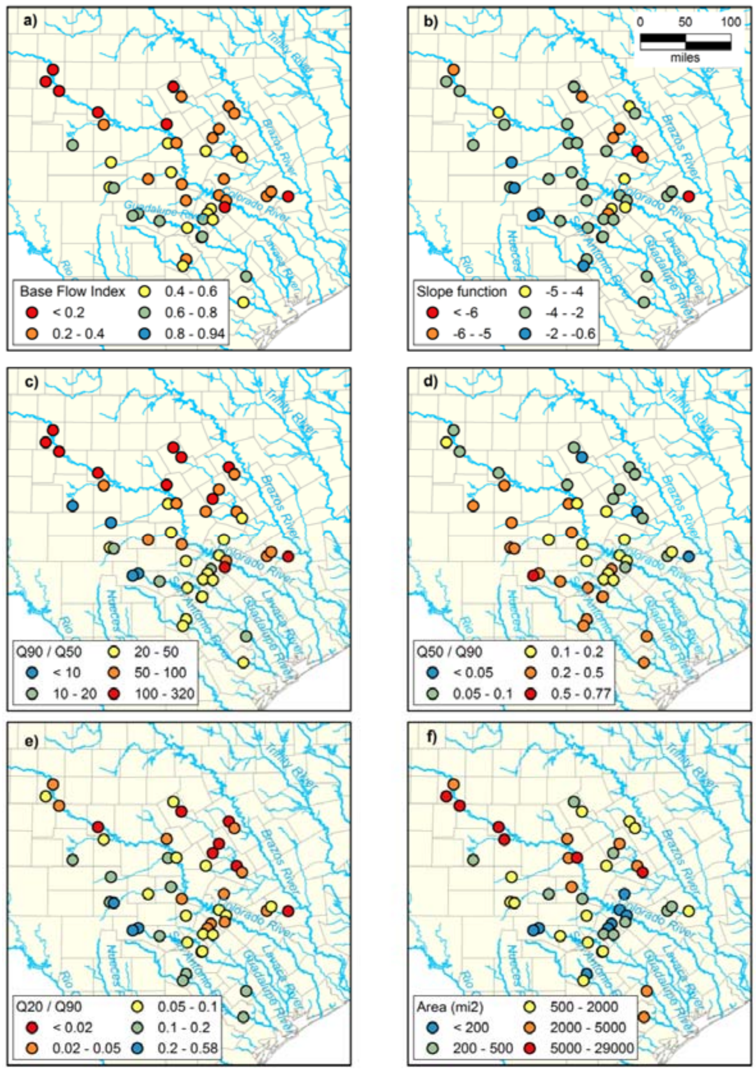

Figure 11. Streamflow indices of the Brazos, Colorado, and Guadalupe-San Antonio Rivers and tributaries.

(a) Base flow index (BFI) indicates percentage of streamflow that originates from groundwater discharge to stream. (b) Slope function indicates groundwater inflows are important for maintenance of streamflow when slope is low. (c) Q90/Q50 shows relative proportion of surface water from groundwater. (d) Q50/Q90 shows low-flow variability. (e) Q20/Q90 is an index of streamflow variability. (f) Watershed areas are also shown.

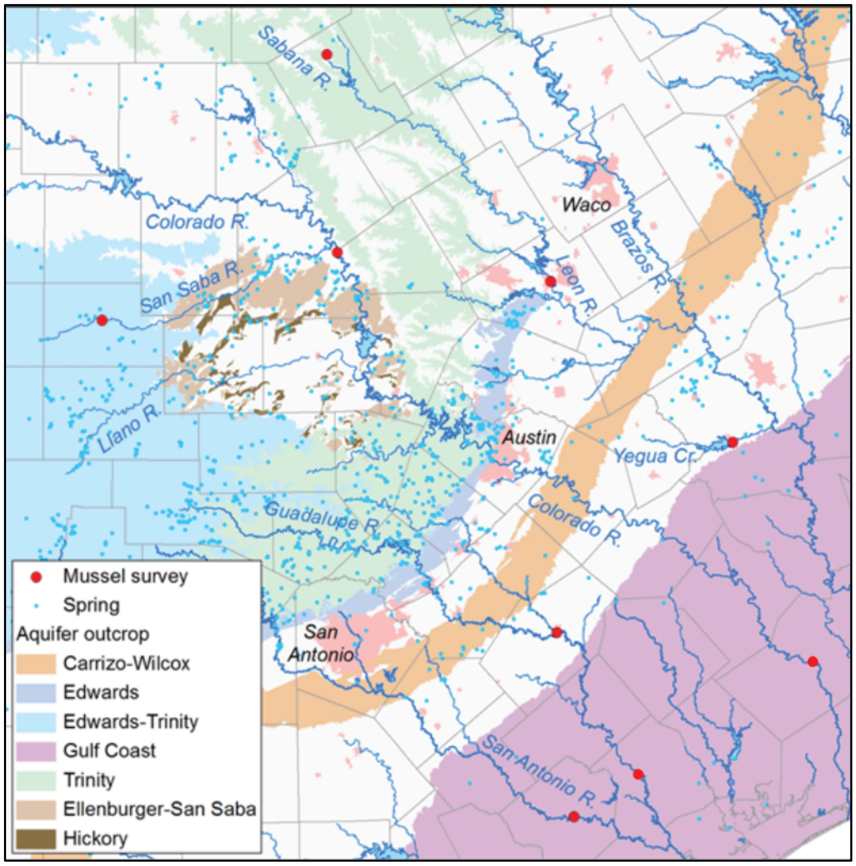

Figure 12. Mussel locations in relation to springs and aquifers.

Brazos River basin has few springs near mussel sites. Colorado River basin has many springs along San Saba River. The Guadalupe-San Antonio has dozens of springs upstream of Canyon Lake. Comal and San Marcos springs provide important groundwater flows to Guadalupe River, and San Antonio wastewater acts as a relatively constant discharge, similar to groundwater inflow.

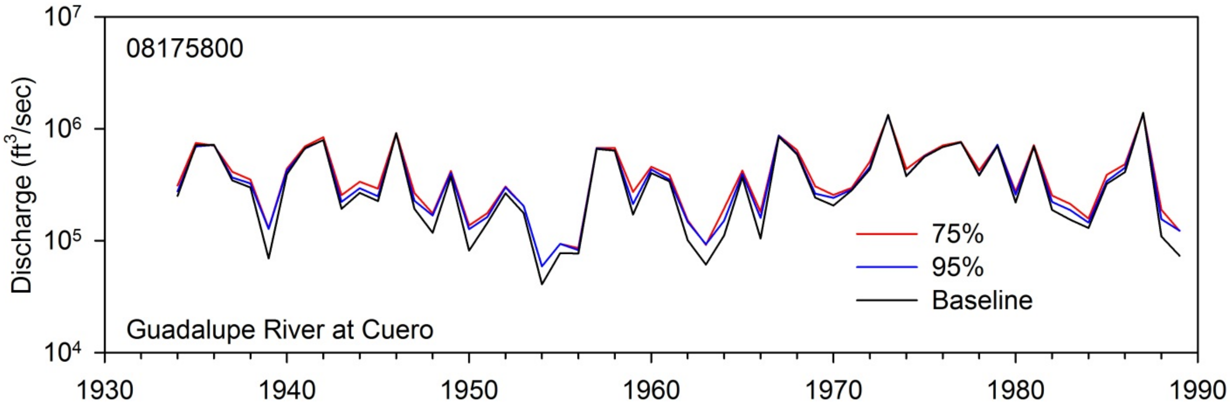

Figure 13. Modeled regulated flows for the Guadalupe River at Cuero (USGS 8175800).

Regulated flows (gauge ID# 9) are modeled stream discharge after diversions have occurred to satisfy water rights, fill reservoirs, and maintain EFs. Regulated flows are higher than EFs during droughts at Guadalupe River at Cuero because more water stays in river to meet EF requirements. During periods of high flow, EFs are met without any additional water being reserved to stay in the river.