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A Techno-economic and Policy Analysis of Integrated, Cross-sectoral Water Management and Conservation

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A Techno-economic and Policy Analysis of Integrated, Cross-sectoral Water Management and Conservation

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A Techno-economic and Policy Analysis of Integrated, Cross-sectoral Water Management and Conservation

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Increasing demands on water resources from growing populations and industries coupled with periodic, yet severe, drought have revealed vulnerabilities in water supplies around the world. However, in some locations, partnerships between water rights holders (such as the agricultural sector) and those with water needs and available capital (such as the energy sector) could improve water efficiency. A market with cross-sectoral participation that creates incentives for reduction of fresh water consumption could improve water availability for many stakeholders. This work lays out the methodology of evaluating these hypotheses with an original water and cost model that is developed and demonstrated using three case studies in the Lower Rio Grande Basin, the Brazos River Basin, and the Permian Basin in Texas with the intent that the findings would be generally applicable to other regions. This work uses an integrated, geographically resolved allocation model to evaluate water market participants and management strategies that could be implemented to encourage water demand reductions to supply new water users. Best practices are evaluated for increasing water availability through market mechanisms based on costs, benefits, and technological viability. The work closes with a discussion of regional variations to this integrated approach. Results of this analysis show that, in the Rio Grande

Basin, up to 900 million gallons per year could be made available through 15% water conservation in irrigation areas. The water would supply approximately 30% of the annual hydraulic fracturing demand for 2016 and 2017 in the area. Reductions would also improve reliability for irrigators. In the Brazos Basin, results show that low-cost conservation scenarios could lead to savings of up to 4.1 billion gallons of water per year with mixed effects on reliability and resilience in the basin. The price paid for water used in oil and gas operations would not offset conservation strategies in every scenario, but agriculture and some municipal strategies are available. In the Permian Basin in West Texas, results show that a market heavily reliant on centrally treated flowback and produced water would reduce water management costs and offset approximately 9 billion gallons of fresh water consumption annually. These transactions show that water could be provided without increasing total supplies through the combination of consumptive water conservation strategies and market mechanisms. Third party effects and transaction costs need to be fully evaluated, though. Moreover, spurring these saved water transactions might require incentives at the regional or state level.

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Chapter 1

Introduction

1.1 Motivation

Dwindling water supplies, change in climate, and increased demand on resources due to population and industry growth have increased water stress worldwide [36]. Water conservation is one option for mitigating water stress concerns. Incentives made clear through water markets could help finance investments in water conservation and link savings to new demands.

In some parts of the world, the agriculture sector makes a good candidate for investments in water efficiency, conservation, and management because it uses significant volumes of water for a relatively small overall portion of economic activity, and often has outdated, inefficient equipment. In other parts of the world, other water users might make good candidates for investments in efficiency, conservation, and management. For example, some municipal water systems experience large water losses and could benefit from capital investments to reduce loss for use in other purposes. Similarly, the oil and gas sector could reduce its own fresh water consumption through use of alternative water sources at an overall cost savings. Because oil and gas companies have significant capital to invest, because they require large quantities of water to fracture wells, and because they are willing to pay a higher price for water than water purchasers in other sectors, they can stimulate the market for water in each of these sectors, altering the current allocation and implementation of management practices used for efficiency, reuse, or recycling.

To assess the feasibility of investments in water savings, an analysis is conducted of the water market in Texas and the impact of the water demand for hydraulic fracturing in that market. This work explores four research questions:

1. can reductions in fresh water consumption accomplished through improved water management make significant volumes of water available for other purposes,
2. which water use sectors (agriculture, municipal, or thermoelectric power) are best suited to conserve water with the intent to sell to other users,
3. could a network of available treated flowback and produced water economically supply oil and gas sector water demands, and
4. if the energy sector or other high-value water use sector makes cross-sectoral or intra-sectoral investments in fresh-water-lean systems, can their water demands be fulfilled at a cost offset by the price paid for that water?

This work analyzes these research questions through four objectives:

1. develop an integrated framework including policy assessment, evaluation of participants, and allocation of water
2. apply the framework to an active surface water market,
3. apply the framework to a limited surface water market, and
4. apply the framework to a groundwater market.

Objective 1 involved generating a mixed-methods model that incorporates pricing, costs, water supply and allocations, and technological advances into an integrated, geographically-resolved hydrologic process to determine water conservation potential through a combination of technical and market solutions. Trends and price impacts are relevant to the prospects for innovations in water efficiency since understanding the underlying dynamics is useful for identifying the potential for engineering solutions to mitigate the various water-related challenges. The original water and cost model is developed and demonstrated in objectives 2–4 in the Lower Rio Grande Basin, the Brazos River Basin, and the Permian Basin in West Texas.

This dissertation augments the existing literature by combining these methods in an environment of previously unseen high marginal prices associated with energy extraction, cataloging the effects of this sustained, high-priced marginal user in the process. Because water supplies in many areas of the world are expected to increase in stress in the future, it is important to analyze the effect of new, high paying users and the ability of regions to react in ways that preserve supplies for future users within existing or, potentially, adjusted policy frameworks. Reducing consumptive water use could be a response to the increase in marginal price. Basins could make use of the high marginal price of water through investments in water saving infrastructure.

1.2 Organization of This Document

The organization of this dissertation includes background on the design of markets and examples of consumptive fresh water conservation (Chapter 2), methodology for the integrated, geographically-resolved hydrologic model used to assess fresh water consumption reduction within a market (Chapter 3), demonstration of the model's use in the Lower Rio Grande Basin (Chapter 4), the Brazos River Basin (Chapter 5), and the Permian Basin in West Texas (Chapter 6), a discussion of results (Chapter 7), and conclusions (Chapter 8). Supplementary information is included in the appendices.

Chapter 2

Background

Water extraction in many of the world's rivers is reaching unsustainable levels and continued supply of water of adequate quality for human and productive needs is threatened [39]. Continued scarcity of water has the potential to restrict agricultural, oil and gas, and electricity production. Water planners use a range of approaches to mitigate water scarcity concerns [171]. For example, the Texas State Water Plan (the recurring planning document that compiles regionally proposed water management strategies for a 50-year period) includes direct potable reuse, groundwater desalination, seawater desalination, aquifer storage and recovery, drought management, direct reuse, new groundwater wells, indirect reuse, municipal and irrigation conservation, new major reservoirs, and water transfers [21]. This dissertation does not go into detail about these strategies. This work examines how cross-sectoral and intra-sectoral water exchanges involving water conservation and efficiency could make water available for more users. However, it should be noted that this potential solution is one of many strategies available for mitigating water stress [171].

The importance of the work in this dissertation lies in determining potential areas for collaboration through water savings and trades while also highlighting po-

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tential unintended consequences and gaps in incentive alignment. The research in this dissertation builds on work in multiple fields. This chapter is intended to provide background on water exchanges in a market environment and on best practices for water conservation and efficiency in the irrigation, municipal (including home and public landscaping), thermoelectric power, and oil and gas sectors. The information in this chapter provides the basis for an analysis of the potential for and effects of trading saved water in a high marginal price environment outlined in Chapter 3.

2.1 Water Allocation Policies and Regional Water Management Strategies

2.1.1 Surface Water Allocation Policies

Managing shared water resources will be important to ensuring adequate supplies for water needs. Lack of access to water is exacerbated by resource scarcity and water allocation policies [171]. Surface water management today generally falls under three categories: riparian, public allocation, and prior appropriative rights [40]. In the United States, surface water allocation laws are generally split across the 100th meridian: the Eastern states have more water supplies and tend to use riparianism or regulated riparianism and the Western states generally use prior appropriation [41].

Under a riparian system, ownership comes with land that borders flowing streams, and water rights are not separable from that land [42]. Instead, water is held in common with other property owners [42]. Under Riparian water law, common in eastern states, shortages are shared equally among landowners adjacent to the water source [43].

Public allocation involves administered distribution of water [40]. Water is owned by the state and in trust for its citizens [42]. Its use is regulated based on public interest. Individuals hold the right to enjoy the use and advantages of water, as long as the use is deemed beneficial and reasonable [40]. Water use is subject to oversight by the state [40].

Under Prior Appropriation Doctrine, a permit to withdraw water is based not on land ownership but on the point in time at which the permit or "water right" was acquired [43]. Appropriative water rights are subject to state regulation of beneficial use and permitted priority withdrawal [42]. The system is often simplified as "first in time, first in right" because, upon application, a permitting authority gives a water right holder a priority date and an allocation amount that resides with the water right as long as it remains valid [171]. Thus, water shortages fall on those who last obtained a legal right to use the water. Water rights are not attached to land ownership [42]. Because appropriative rights exist separate from land ownership, they can be bought, sold, leased, or transferred [171].

Texas surface water is owned by the State of Texas and held in trust for its citizens but is allocated under the Doctrine of Prior Appropriation [171]. However, these water rights have limitations. Interbasin transfer is allowed but restricted [171]. Users must apply for and receive a water right or amendment to a permit [44]. The right is then junior in priority to rights granted before the time the application is accepted [44]. Moreover, the priority system is often termed "use it or lose it" because rights holders must use their entire volume or lose their right to it [171]. The system often encourages wasteful water use [42]. A market would allow potentially unused water to be leased to another water user under the original water right, creating an economic incentive to conserve where one might not have existed previously [171]. The seniority rule of prior appropriation often favors senior license holding irrigation users [45].

Water rights in the Lower Rio Grande, below the Falcon-Amistad reservoir, differ from those on other rivers in Texas in that they are allocated on an account basis in which the Water Master, the arbitrator of water rights in this basin, records withdrawals and subtracts use from allocated accounts [46]. Rights for municipal uses are set at one priority level in which allocations renew on a yearly basis while irrigation rights are set at another level in which balances carry forward into the next year [46]. Thus, irrigation accounts are more constrained than municipal accounts [46]. Surplus in the Falcon-Amistad reservoir for any given month is allocated to the irrigation users [46].

2.1.2 Groundwater Allocation Policies

Groundwater regulation also includes correlative rights, reasonable use, and the rule-of-capture [43]. Correlative groundwater rights, similar to riparian surface water rights, attach groundwater ownership and use to land ownership [43]. Water is allocated proportionally to land ownership. The State of California uses correlative rights to allocate groundwater. Reasonable use doctrine also attaches groundwater ownership to land ownership. Reasonable use does not allocate a certain amount of water but requires that water be used beneficially [43]. The rule-of-capture attributes the right to withdraw groundwater to the landowner residing above that water and providing that, absent malice or willful waste, landowners can withdraw as much water as they want without incurring liability, even if that withdrawal will inhibit access to water by neighboring landowners [47].

Because groundwater is a property right, it can be bought, sold, or traded [171]. However, lack of a specific allocation of water complicates any market environment. Groundwater is a classic common-pool resource, making management difficult due to the competing interests of the users [41]. If use is unconstrained, each user could freely pump as much water as they pleased [48]. Individual pump irrigators have no incentive to leave water in the ground for future use due to knowledge that neighbors might exploit or sell the shared water beneath their land [40, 49]. As a result, groundwater users have a tendency to extract water at a rate greater than recharge of the aquifer, also known as mining the aquifer [40,49]. Such extraction leads to externalities such as lowered water table leading to increased pumping costs, land subsidence, degradation of water quality, and exclusion of other potential irrigators from access to water due to lower supplies and higher costs [40]. The rate of extraction is also caused by the view that the present value of water is greater than its future value [51]. Producers often underestimate future value, though, leading to more extraction to maximize short-run profit [52]. Because of the underestimated value of groundwater in place in an exhaustible aquifer, producers and society benefit from limiting annual withdrawal of that groundwater [53].

2.2 Water Markets as a Means of Reallocating Water

Augmenting current water supplies has been the traditionally preferred method of water managers for dealing with water shortages [56]. However, some of the water could be used more productively than its current use through water markets and water trading [54]. Because water markets provide incentives for efficient allocation compared to other strategies [54]. Effectively transferring water to users who value the marginal water more increases total net benefits produced by the waters use [57].

Water markets exist around the world and in many western U.S. states. In Chile, property water rights have contributed to growth in the agricultural sector [54]. In Spain, market changes led to increases in regional income [55]. In Australia, water trades in the Murray-Darling Basin raised the value of water use and mitigated against drought [54]. Models in Alberta show measured gains in allocative efficiency from water transfers within and across the sub-basin [45].

Markets could provide benefits to water users, providing economic reallocation of scarce water among irrigators, industries, and households [58]. Compared to other forms of reallocation of water, markets empower water users, requiring consent to any reallocation of water and payment when water is transferred [40]. During drought, markets provide options to transfer water to meet demand, avoiding the increased cost of providing new sources [59]. Market transactions could provide system reliability by generating incentive to use transferred water rather than depleting storage [59]. Markets could also be used to transfer water to satisfy instream flow constraints [59]. In addition to reallocating water to other users, markets induce water users to consider the value of their water and the opportunity cost of its use, providing incentives to use water efficiently or invest in water-saving technology and reap the benefits themselves or sell the saved water [40]. However, markets have downsides, particularly in unregulated markets where third party effects are not addressed. Discussion of these downsides is included in the following sections.

Since agricultural water rights make up the majority of water entitlements in many water stressed basins, these rights play a central role in water reallocation [39]. Markets grant agricultural users flexibility to respond to changes in crop prices and water values by allowing transfers when prices are more favorable [40]. At lower prices, sellers of water are less willing but buyers, including other irrigators, are more interested. Water price increases as water scarcity increases, raising the marginal value of a unit of water [60]. Non-irrigation users tend to be able to pay high prices for water [45]. In parallel, irrigation users might find it more profitable to sell their water to non-irrigation users than to use it to grow crops [45, 61].

Multiple types of water contracts exist, including those for temporary water (short-term leases) and permanent water (sale of water right). Markets for temporary water are more common than those for permanent water [61].

To achieve efficient reallocation of water, ideal markets require well-defined tradable water rights and no transaction costs. The property rights should be specified, exclusive, transferable, and enforceable [62]. Well-defined water property rights "formalize and secure the existing water rights held by water users; economize on transaction costs; induce water users to consider the full opportunity cost of water; and provide incentives for water users to internalize and reduce many of the negative externalities inherent in irrigation [40]."

However, water rights are often poorly defined and might have high transaction costs [40, 59]. None of the allocations systems mentioned previously fulfills the conditions for well-defined property rights to water. For example, under appropriation systems, selling excess water might be used to show that water is no longer needed for beneficial use and negating that part of the water right [63]. The physical properties of water enable weak property rights that raise the cost of measuring, bounding, and enforcing individual claims [42].

In addition, an assumption of zero transaction costs does not hold true in real-world markets for water rights [40]. Transaction costs include information, legal fees, public agency review, technical studies, and conveyance–components that have nonzero costs [40, 59].

Regulatory authorities could aid in defining property rights and reducing transaction costs, providing support for private water rights exchange [42]. Authorities could provide accurate demarcation of water rights and facilitate and monitor trade activity. Groundwater could be unitized as is done with oil and gas to allow all parties to share in net returns of selling water and eliminate competitive withdrawal [42].

Unitization would require allocation of water supplies to the land and allow for pooling those resources for use by one well, also allowing for payment to users whose supply is withdrawn when that well is used. In addition, there might be public good considerations warranting regulatory oversight of water exchanges to protect public use [42]. Efficient reallocation of water requires better definition of water rights and a regulatory role for the state in addressing externalities [42].

It is also important to monitor and mitigate effects on third parties in an efficient market [40, 59]. Potential third party effects vary. For example, environmental flows might be affected, changing fish and wildlife habitat; causing land subsidence, overdraft, or well interference in aquifers; or degrading water quality [59]. In a rural environment, farm workers, farm service companies, and downstream farmers might be affected [59]. In an inefficient, unregulated market environment, third party effects might occur with little recourse for third parties. However, mechanisms exist to address third-party concerns including requiring monitoring, public review and regulatory approval; taxing transfers to compensate harmed third parties; requiring additional provision of water for environmental purposes; and restricting transfers to "surplus waters only [59]. These solutions increase the explicit cost of water transfers for the buyers and sellers to reduce the impact on third parties.

In addition to concerns over property rights and transaction costs, concerns exist over communication between users [171]. Negotiation of water trades might not result in optimum solutions if parties do not believe the optimal solution is fair. Highly dissatisfied parties might find certain solutions unfair and resist implementing them (both) [64]. Factors such as lack of trust, information, and communication can result in a tragedy of the commons [48]. Parties prefer to act based on individual rationality as opposed to group rationality [64]. Sub-optimal solutions exist that might be perceived as fair according to all parties and will emerge as more stable [64]. It is important to ensure a stable solution [171].

2.2.1 Markets as Strategies to Reduce Fresh Water Consumption

Water conservation involves comparing costs and benefits to beneficially reducing water use [67]. Conservation often involves behavior or management changes. Water efficiency refers to a ratio of inputs to outputs and often involves changes in technology to reduce water use [67]. This section will discuss conservation and efficiency together and focus on reductions in unproductive consumptive water use.

Withdrawals of water refer to water that is taken from the basin. Withdrawals that are discharged back to the basin at an acceptable quality are deemed non-consumptive. Consumptive water use refers to withdrawn water that does not return to the basin from which it was extracted. Consumptive water uses include transfer to another basin, injection, sequestration, contamination, evaporation, incorporation into plant biomass, seepage to a saline sink [68]. In areas where downstream and future generations depend on the unconsumed portion of diversions, including return flows and aquifer storage, investment in conservation could lead to water depletion [69]. Focus on conserving consumptive water use avoids these externalities.

Many allocation systems value water use as a public good and make judgments on its beneficial use, referring to the end use of the water but not whether that water is used productively. Productive water use contributes to societal goals, including production of goods and services [68]. Productive uses can include evaporative losses if they contribute to crop health [68]. Unproductive consumptive water uses include transpiration from weeds, evaporation from soils and irrigation canals, and evaporation from poorly designed irrigation systems [68]. Reducing unproductive consumptive losses through conservation and efficiency would make surplus water available to be used by the existing user or reallocated to other users [68]. For example, Gleick et al. (2011) reports that unproductive soil evaporation is 75-85% lower with drip irrigation systems compared to flood irrigation during early-stage cotton development [68]. That water could be allocated for more cotton production or to other users in the area.

Because markets induce water users to consider the value of their water and the opportunity cost of its use, they might also encourage users to save water with the intent of selling that saved water to other users [40, 65]. Water could be saved through expansion of water use by efficient new water users, adoption of water conserving technologies, and elimination of inefficient uses of water [60]. In addition, users could transfer reclaimed or surplus water [59]. Urban areas have taken advantage of this mechanism by financing improvements to irrigation districts, including lining of irrigation canals [59]. For example, a 35-yr contract between Imperial Irrigation District (IID) and Metropolitan Water District of Southern California (MWD) involves trading canal lining and other system improvements for saved water [59]. As water moves to new uses, conservation could potentially lead to an improvement in environmental flows, as well [66]

Trades for saved and surplus water must ensure that transferred resources are real water rather than paper water [59]. Paper water is that numerated in a water right. Real water is the supply that is actually received by the user [59] which might be less than what is allocated on paper. Water users do not know how much water they will receive because of seepage and environmental losses, withdrawals by upstream users, and changes in flow over time [59]. A junior water right holder in a prior appropriation system might not receive any of their allocation in a drought. Ensuring real water arrives is a challenge to incorporate into market transactions.

2.3 Water Consumption and Conservation in Irrigated Agriculture

Agriculture accounts for 80-90% of U.S. consumptive water use [70]. In 2007, irrigated farms accounted for 40% of the value of U.S. agricultural production, a total of $185 billion [70]. As of 2012, at least half of that irrigated farmland was still irrigated with less efficient, traditional systems [70]. This section focuses on options to reduce or conserve consumptive water through improved management and technology.

Saving consumed unproductive water might require changes in management practices, including at least one of the following goals:

- reducing the unnecessary evaporation or unwanted transpiration from soil or supply sources [70–72],
- improving rainfall use with precipitation capture and moisture retention techniques [70],
- restricting acreage or water use expansion in cropped areas [71, 72],
- switching to lower water-consuming crops [71, 72],
- irrigating current crops at a deficit [70–72],
- reducing deep percolation water that becomes severely degraded in quality or is uneconomic to recover [70], and
- reducing field runoff that is lost to the hydrologic system [70].

Potential irrigation efficiency opportunities lie in use of best management practices (BMPs) such as furrow dikes, which are small dams for each ridge between a planted row of crops; gated and flexible pipe to prevent seepage in irrigation channels and furrows; recovery of irrigation runoff water (tailwater recovery); and brush management. More efficient gravity irrigation such as furrow gravity irrigated acres or pipe or a lined open-ditch field water delivery rather than flood irrigation might save water, as well [70]. The Texas A&M Agrilife Extension has also suggested improving irrigation scheduling; developing improved irrigation water management practices; adopting drought tolerant crop varieties; continuing conservation practices adoption; and improving irrigation conveyance systems [73]. Other practices include monitoring soil moisture and reducing evaporation [74]. Enhanced biotechnology, including insect-, drought-, or herbicide-resistant crop varieties, could also save water. However, one study showed that use of biotechnology without water restriction did not save water but could actually increase water use [75]. Improving system dynamics without the users intent to reduce water use does not reduce water use. Furthermore, users should be careful in conserving when considering water at a basin scale. For example, drip irrigation is important for many reasons, including greater water productivity and food security [76, 77], but the water saved might have been important to other users downstream [78]. Similar to water markets, water conservation could have third party effects.

Farmers might want to conserve for many reasons, including to improve profitability through increased crop production [79], improved potential of meeting water demands, or sale of saved water. The average value of production from irrigated farmland was three times the average value for dryland in 2012 [70]. However, as water supplies decrease and farmers transition to dryland farming, individual and local revenues would suffer [80].

While BMPs might save water and improve profitability, irrigators still might be unwilling to implement them [171]. Many factors affect adoption of water efficiency mechanisms, particularly water price and farm finances, education, policy, and water availability [171]. Farmers are also likely to implement irrigation efficiency mechanisms on low quality land or if yield potential increased [81].

Water price has a direct impact on demand and secondary impact on choice of efficiency measure and capital investments [81, 82]. Similarly, purchasing water in water markets or other similar alternatives is cost effective compared to subsidies for investments in improved irrigation efficiency [83]. However, farms in southern Alberta have experienced challenges in implementing economic instruments to manage irrigation water because, as a concept, they have little support in the irrigation industry [74]. Moreover, where cost of water is small percent of total farm budget in Western Australia, investment is slow [74].

Most on-farm irrigation investment is financed privately [70]. However, capital for long-term investment in irrigation efficiency might not always be available [82]. Colorado irrigators, for example, implemented when practical or economical, and in Canada, surveys of two irrigation districts showed that farmers often did not implement water efficiency measures because of financial reasons [74]. Mechanisms that are easier to implement and provide demonstrable effects often have financial rather than sociological barriers while ones that require farmers to learn new skills also have sociological bnesarriers like education [74].

Improved control and farmer education is needed for increased participation in irrigation management [84]. A study in India found that training and education of farmers, in addition to "changes in government policies such as rules and regulations, pricing, institution building and infrastructure development" is needed to encourage adopting water efficient cultivation methods [85]. Other research has shown farmers who adopt water efficiency mechanisms earlier are often younger, more educated, more cosmopolitan, higher income, have larger farm operations, and receive primary sources of information about the technologies or management practices [74, 82, 86]. Farmers who have trialed a mechanism are also more likely to adopt [82]. Ultimately, farmers are risk-averse; mechanisms involving existing knowledge and skills are adopted before options that require costly, complex innovations [74]. A study in sub-Saharan Africa recommended investment in clear education for adopters of drip irrigation, focusing on repairs and maintenance [87].

2.4 Water Consumption and Conservation for Municipal Water Use

2.4.1 Water Consumption and Conservation for Turfgrass

As of 2006, in the United States, there were about 50 million acres of turf in residential lawns, athletic fields, golf courses, highway roadsides, cemeteries, and parks [50]. Many studies have been conducted to determine how to reduce water consumption for these turfgrasses.

Recommendations include applying deficit irrigation, or irrigation below a crop's maximum potential water demand but not low enough to result in a noticeable change in appearance and quality [88–91]. Turfgrasses are able to tolerate some deficit irrigation with little or no loss in turf quality because of their ability to form deeper roots [92]. For example, a 1981 study found that applying irrigation to 80% of field capacity reduced water use of Kentucky bluegrass by 20% and only reduced quality by 10% [93]. For St. Augustine grass in Florida, a 2000 study found that no substantial increase in quality is achieved beyond applying 75% of the maximum evapotranspiration (ET) capacity of turfgrass, and applying about 60% of the maximum ET capacity yields acceptable [94].

Soil management and water control systems have the potential to achieve this reduced water application rate while maintaining turf quality. A 2009 study found that soil management system based treatment produced good turfgrass while reducing water use by 11-53% [95]. ET controllers with comparable settings also achieved good turf quality, but ranged in water savings from -20% to 59% [95]. Finally, reducing the irrigation schedule by 40% and using rain sensors produced 36-53% water savings [95]. A 2011 study found that installation of weather-sensitive irrigation controller switches (WSICS) at athletic fields resulted in 121,000 gallons/acre/year of water savings in Massachusetts [96]. Audits, retrofits, and WSICS use in homes also resulted in water savings.

Management improvements could be made in addition to technological improvements. Higher mowing heights encourage deeper rooting, increasing turf survival during droughts and reducing water loss through evaporation [97]. Water managers and homeowners could also reduce area allowed for irrigation, limit watering days per week, or upgrade to natural plants that require minimal irrigation [98]. Other best management practices for turfgrass include hand watering, night watering, leak and loss control, metering, wetting agents, and improved education [99].

Water Consumption and Conservation in Turfgrass in Homes

Outdoor irrigation in homes varies based on climate. In desert cities, about 60-90% of water used by single-family residences is the landscape irrigation [100]. A study of Texas found that about 31% of single-family residential annual water consumption is dedicated to outdoor purposes [101]. Drier parts of the state generally use greater proportions of water for outdoor purposes than wetter areas [101].

Choice of irrigation system plays a role in how much water is used. In-ground and automatic systems generally use more water than irrigating manually. Homes with in-ground irrigation systems use 35% more water than homes without those systems [102]. Homes that use automatic timers for irrigation systems use 47% more water than those with in-ground systems operating them manually [102]. Operating systems appropriately is also important. Staff at Austin Water Utility observed water losses of 20-50% from inefficient irrigation system designor implementation [102].

Aside from implementing BMPs suggested in other parts of this chapter, homeowners could replace turf entirely or partially through cash-for-grass programs or using native plants with little to no water demand in a process known as xeriscaping. Xeriscaping could reduce water use by 20-53% in single family homes [100]

Water Consumption and Conservation in Turfgrass in Golf Courses

In the United States, golf courses maintain 1.5 million acres of turfgrass, about 80% of which are irrigated [103]. Golf courses use about 2 billion gallons of water per day, about 0.5% of total water use in the United States [103]. In Texas, about 115,000 acres are estimated to be devoted to golf courses, compared to 1,608,399 acres of landscapes and lawns [104].

The aesthetics of a golf course and, in turn, the management of water are important to its revenue [105]. In a survey conducted in 2009, about 12% of U.S. 18-hole golf courses reported using recycled water for irrigation. Of those, about 37% were in the Southwest, and 24% were in the Southeast [103]. In addition, about 82% of golf courses reported using soil moisture observations while 3% reported using soil moisture sensors. About 49% reported using weather forecasts, 18% reported using evapotranspiration estimates form a weather service, and 17% reported using ET estimates from an on-site weather station [103]. Golf courses could improve their irrigation with improved on-site estimates of ET and soil moisture. In addition, improved cultivars, adjusted mowing height, or other site-specific BMPs could be implemented. Improved cultivars resulted in water savings of 50% in Midwest golf courses [106].

2.4.2 Policy Methods Used to Reduce Water Consumption

The best management approach is favored by water managers due to its basis in science and incorporation of many possible solutions [107]. However, a 2002 survey of turfgrass managers in California found that implementation of BMPs is often limited by finances, education, and time [108].

Additional methods might be used at the municipal level to encourage reduction of water use. Two common methods are water pricing and the command-and-control approach (water ordinances).

Economic Strategies to Reduce Municipal Water Consumption

Adjusting municipal water prices is generally assumed to be the economically efficient method of reducing urban water use [109]. If the goal is to reduce water withdrawals, using prices to manage water demand is more cost-effective than implementing other non-price conservation programs due in part to the lower cost of monitoring and enforcement [110]. Generally, residential demand is relatively inelastic to price changes [111], and the time lag between use of water and impact of price negates the power of price as a conservation tool. But increasing block rate price policies do lead to consumer sensitivity and higher price elasticities than a standard low price for water [112].

Water price is also the more efficient tool in allocating welfare associated with water use, but not necessarily in reducing consumptive water use. Rationing outdoor water use in cities has welfare implications [113]. However, pricing structures tend to be more regressive than rationing because low-income households are more sensitive to price, and relatively high consumption households are less sensitive to price [110, 114]. Compared to other households, rich, big-lot households exhibit the least elastic outdoor demand [113]. If the goal is to reduce outdoor consumptive use of water rather than to maximize welfare, price might not be the best method.

Additional economic incentives include cash payments to replace turfgrass in lawns or inefficient fixtures, washing machines, or toilets and rebates on ET and smart water controllers [115]. In a 2008 study, installing low flow toilets reduced consumption by 10% per toilet, low flow showerheads by 8% per fixture, and adoption of water efficient irrigation technologies by 11% [116].

Noneconomic Strategies to Reduce Municipal Water Consumption

Command and control regulatory instruments reduce consumption [109]sometimes as much as 30% or more in water savings [116]. However, voluntary or mandated reduction in water use is achievable for short-term droughts under a mentality of sacrifice for the greater good, but is often intolerable in the long-term [117]. In addition, mandating water conserving technologies could result in a rebound effect of increased water use due to knowledge about the water savings. Moreover, ordinances could also result in public backlash if pushing against a cultural norm like outdoor water use or tree regulation, care, and maintenance [113].

Other non-economic strategies include education and awareness campaigns and behavior modification. Studies have looked at customized water billing or including emoticons or patterns of water use in water bills [118–120]. For example, messages providing social comparisons had a greater impact than social or technical information alone, especially among high-consuming households [121]. However, as with other voluntary conservation, this behavior change wanes over time [121]. Real-time information about water consumptive and water rate via smart meters could help customers reach water-use targets [116].

2.4.3 Water Consumption via Municipal Water Losses

Municipal distribution system water losses could be considered an unproductive consumption of water. Water is lost through leaks and overflows in the distribution system and is estimated to be about 16% of total water supplied in a water system [122]. About 75% of that water is generally estimated to be recoverable (meaning a system will likely not be able to recover about 4% of its water losses) [122]. According to the Environmental Protection Agency, the United States will need to spend up to $200 billion dollars to upgrade water transmission and distribution systems over the next 20 years [123]. About 29% of this amount is estimated to be needed for water loss control, specifically [122].

There are two types of water losses. Apparent water losses are those that occur because of data handling or meter errors–water that is consumed but not properly measured [124]. Real losses are the physical leaks and storage overflows. Real losses are not consumed by customers but inflate production costs [124]. Economically recoverable water losses are usually measured in water loss audits [125]. Audits might involve inspection of billing records, monitoring flow, or detecting leaks through acoustic, electromagnetic, thermal, or tracer methods [126]. Audits do not save water, but the actions taken as a result of an audit could result in cost and water savings [125]. Savings are usually seen in payment for identified apparent losses and avoided cost associated with pumping, treating, and distributing identified real losses [125]. Those identified real losses could become a future supply.

Detecting and managing water leaks could result in substantial economic and water savings. However, many states do not require water leak detection or collect voluntary reports [127]. Twenty-three states have no water loss reporting. Sixteen states have rudimentary water loss reporting. Four states, including Texas, require water loss reporting with American Water Works Association (AWWA) standard terminology. For example, in 2003, Texas House Bill 3338 required that retail public utilities file standardized water audits with the Texas Water Development Board (TWDB) every five years [128]. Later in 2013, Texas House Bill 857 required utilities with more than 3,300 connections to submit audits annually [128]. Six states and Puerto Rico require use of audit software, validation of water loss data, or system-specific, volume based performance benchmarking [124].

2.5 Water Consumption and Conservation for Unconventional Oil and Gas

The United States has seen significant increases in oil and gas production due to the use of hydraulic fracturing and horizontal drilling, technologies that made production of unconventional zones economically possible [129]. Production from these zones (shale and tight reservoirs) accounted for almost half of total U.S. production in 2016 [131].

Hydraulic fracturing (HF) involves injecting large volumes of fluid, mostly water, at high pressures to fracture shale and tight oil reservoirs to release the trapped natural gas and petroleum. Horizontal drilling involves drilling a vertical well and then, using a directional bit, turning that well until it runs the length of a desired production zone. Shale deposits are thin, sometimes relatively impermeable, layers of rock that contain significant quantities of natural gas or petroleum liquids and often cover a wide area underground [171]. Horizontal wells are more suited to shale exploration because of the increased exposure to the formation [132]. However, the longer length of the wells and the need for large volumes of high-pressured water make unconventional operations water-intensive. Moreover, drilling longer laterals (the horizontal portions of the well) has become more common and has increased the needed volume of water [133]. In the Permian Basin, volume required for unconventional wells increased by a factor of 10–16 per well and 7–10 if normalized by lateral well length over a period of 2008 to 2015 [134]. However, the volume of water required to extract unconventional oil and gas is dependent on many factors including geology, local climate, water availability and management, and operator practices [135] and varies even within single basins [136, 137].

In addition to affecting supplies available for HF, semiarid and arid climates are more prone to experience additional water stress from HF activities compared to other climates [136, 137]. An assessment of the impact of water use for energy development on groundwater availability showed declines in Texas aquifer levels due to population growth and HF operations in the Barnett Shale [138].

2.5.1 Water Acquisition for Unconventional Oil and Gas Activities

Many companies source brackish water or fresh water from deep aquifers [139, 140]. Some blend these sources with treated produced water, as well [140]. The Texas Oil and Gas Association reports that Anadarko Petroleum invested $550 million in water management, conservation, recycling and water infrastructure projects [140].

For many other water-intensive sectors, the price of new water might be prohibitive [171]. However, because of higher costs for other parts of the supply chain, and because water is used to produce an even higher-value product, water prices are unlikely to be a major hurdle for the oil and gas sector.

To illustrate, in 2012, Breitling Oil and Gas paid $68,000 (a mere 0.2% of the $3.5 million spent to hydraulically fracture the well) to truck 3.4 million gallons of water from Oklahoma to its operations [11]. In the Permian Basin, the cost to drill and complete a well might be up to $20 million with the cost of water purchase, transportation, and disposal only amounting to less than 10% of that cost [141]. While a non-trivial expense, the majority of costs are not water-related, which means the price of water is not the key financial determinant in the total cost of a well [171].

In 2014, the price of oil dropped precipitously due to changes in the global market, pushing down the value for water as well as that for other oilfield service industries. According to a report by Haynes & Boone, the drop in oil price caused 335 energy producers, oil field service companies, and pipeline operators in North America to file for bankruptcy from 2015–2018 [142]. Texas companies filed more than $74 billion in debt in that period, not including those that filed out of state [142].

With increases in the price of oil, it is expected that prices of services like provision of water rebound somewhat, as well [143]. Anadarko CEO Al Walker projected that service costs would rise 10–15% in 2018 along with the rise in oil price [143]. Anadarko operates in the Delaware portion of the Permian. Water customers from Select Energy in New Mexico, including Exxon Mobil, Conoco, and Chevron, paid $0.02 per gallon of water ($0.85-1.00 per barrel) in 2018 [144].

Longer-term contracts for large supplies of water are not as affected by changes in price of oil. Some companies have leveraged long-term contracts with wastewater treatment systems for the continuous provision of water. Pioneer Natural Resources has constructed a network of pipe to send a design flow of 6.3 million gallons of water per day from Odessa's Bob Derrington Water Reclamation Plant in Midland County, Texas to one of its water management facilities [145]. The cost of upgrades for the water plant is estimated to be $133.5 million [146]. The upgrades include additional treatment for the reclaimed water to ensure it is suitable for HF operations [146]. Another operator, COG Operating LLC acquired a contract with Gulf Coast Waste

Disposal Authority to receive wastewater at a rate of \$2.75 per 1000 gallons in year 1 (\$0.12 per barrel), \$4.52 per 1000 gallons in year 2 (\$0.19 per barrel), and \$5 per 1000 gallons in year 3 (\$0.21/barrel) and thereafter if the contract is renewed [147].

2.5.2 Wastewater Produced in Unconventional Oil and Gas Activities

There are multiple sources of wastewater in unconventional oil and gas operations. The well drilling process requires lubricants, called drilling muds. Unconventional wells often have long laterals and might have more drilling muds in turn. These drilling muds are a wastewater that needs to be managed. Compared to other wastewater sources, drilling muds are not high volume.

After drilling, wells are completed. In unconventional operations, completion usually involves HF with high volumes of frac fluids, including water, sand, and chemicals. Some percentage of frac fluid returns to the surface after fracturing during the short time after the well is completed [129]. The water that flows back to the surface is often called flowback water. Flowback water will be similar in quality to the frac fluid.

When the well enters the production phase, oil, gas, and other substances from the production zone, including water, will flow to the surface. The water that occurs naturally in the production zone is known as produced water and is extracted as a by-product with the oil and gas over the life of the well. Produced water volumes can average from 7–13 times the amount of produced crude oil in conventional wells [130, 134]. In conventional operations, produced water is often injected back into pressure-depleted oil-producing reservoirs for enhanced oil recovery [134]. Unconventional wells produce less water than conventional wells due to tighter reservoir formations [130]. Produced water quality varies across basins and, in unconventional operations, is often highly saline. This produced water cannot be reinjected into the shale reservoirs for enhanced oil recovery and is often disposed into nonproducing geologic intervals because it is the most affordable option [130, 134]. However, underground injection of produced water is raising concerns about induced seismicity [148–150].

It is possible to recycle flowback and produced water for reuse in oil and gas operations. However, supply and quality could be a hindrance. Volumes of flowback and produced water (FP) vary over different basins. For example, in the Eagle Ford Play, projected FP water volumes range from 20%-40% of that used for HF [131]. Alternatively, FP water in the Permian Basin in Texas exceeds the volume required for HF operations. Reuse of produced water with minimal treatment could reduce demand for fresh water for HF operations [134]. As of 2018, producers in the Permian Basin in southeast New Mexico operated 27 water treatment and recycling plants capable of treating 500 million gallons of water at a time [144].

2.6 Water Consumption and Conservation by Thermoelectric Power Plants

Thermoelectric power plants combust fossil fuels or split atoms in a nuclear reactor [151, 152]. Steam turbine power plants following the Rankine Cycle use that heat to boil water into steam to move a turbine and generate electricity [151, 152]. The steam is then condensed and continues its path back through its cycle. The most common cooling processes are open-loop or once-through cooling and closed-loop or recirculating cooling [152]. Once-through cooling involves withdrawing large quantities of water to condense steam and returning that water to the watershed at a higher temperature [152]. Once-through cooling involves little consumption of water, as almost all of the water withdrawn is returned to the source in the same form [152]. Recirculating cooling involves withdrawing smaller quantities of water to condense steam and then recirculating that water through a heat sink–a pond or a cooling tower with a mechanical or natural draft to induce evaporation and cool the water to a temperature that can then be reused [152]. Because the water is recirculated, less water needs to be withdrawn [152]. Some of the water is consumed via evaporation [152]. A larger amount of water is consumed for recirculating cooling than for once-through cooling, but a smaller amount of water is withdrawn for recirculating cooling than for once-through cooling [152].

Alternative cooling processes incorporate air cooling either in part or in total. Dry cooling processes use air for all cooling of steam within the cycle [152]. Hybrid cooling processes incorporate wet cooling and dry cooling and allow an operator to switch between sources as needed. For example, when water is unavailable, dry cooling could be employed [152]. Dry cooling is less efficient than traditional cooling with water and thus involves an efficiency penalty [153–156]. The penalty is estimated to be about 2% of energy that could be generated using wet cooling technology on average [153–156]. Efficiency losses vary with air temperature, meaning dry cooled power plants are less efficient during the summer at the same time that demands might increase due to higher loads from air conditioning, compounding the effect of the parasitic losses [157]. Thus, when water is available in a hybrid system, the operator might choose to cool with water.

A study of power plants in Texas found that switching cooling technologies from once-through to dry cooling could save up to 65–186 billion gallons of water withdrawn per year–enough water for 1.3-3.6 million people annually.

2.7 Markets for Saved Water in Areas of Energy Extraction

States could take advantage of the high price of water used in unconventional oil and gas activity by encouraging investment into water infrastructure. Many states already capitalize on oil and gas activity through severance tax revenues and taxes that are reinvested in addressing the negative externalities from the extraction process including clean-ups of air, land, and water pollution, as well as social problems [37]. As water shortages are expected to be a key environmental challenge of the next century [38], water use could be added to the list of externalities to be addressed using statewide tax and incentive programs. Doing so would be a means of economically addressing current concerns while also preparing for the future.

Price-motivated water conservation is not a new topic. Municipal water users, for example, might conserve to reduce their water bill. Irrigators have conserved with the aim of leasing saved water to nearby water customers. In one past example, in 2007, the City of Roma in Starr County was awarded \$2.8 million from the Economically Distressed Area Program to purchase water rights [158]. Rather than buying more water from the markets, the city engineers decided to make a trade for water rights with irrigation districts in Cameron County [158]. The city funded improvements to irrigation canal conveyance efficiency within Irrigation District No. 2 and received the excess water rights in return [158]. The City of Roma received the needed water supply, while the irrigation districts still received the water they needed and had about 26 million gallons (800 ac-ft or about 987,000 m^3) of additional savings per year. This example illustrates some of the potential for cross-sectoral water benefits from efficiency investments made by the marginal user [171].

This work evaluates the potential for trades like this on a larger scale in three water markets–existing surface water with two user types, emerging surface water with many user types, and emerging groundwater with two user types. To assess the feasibility of investments in water savings, this work conducts an analysis of the water market in Texas and the impact of the water demand for hydraulic fracturing in that market.

Chapter 3

Methodology

This work augments the existing literature through design of an integrated, geographically-resolved hydrologic process to determine water conservation potential through a combination of technical and market solutions. [171]. The research includes four parts:

1. Develop an integrated model framework including market assessment, evaluation of participants, and hydrologic characteristics,
2. Apply the model to an existing, active surface water market,
3. Apply the model to a possible emerging surface water market, and
4. Apply the model to an emerging groundwater market.

The methodology for each is explained in the following sections.

3.1 Designing the integrated, geographically-resolved hydrologic process to determine water conservation potential

The first step in this work is to develop the framework for the design of an integrated, geographically-resolved hydrologic process to determine water conservation

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potential. Previous analyses have built similar models to assess market transactions. Wang et al. 2008 built an initial water rights allocation for subsequent water and net benefits reallocation [159]. Vaux and Howitt 1984, Hurd et al. 2002, and Hurd et al. 2004 developed integrated basin-wide hydrologic models for policy analysis containing an economic objective [160–162].

The model is divided into four steps. First, assess the basic policy landscape. Second, identify past formal and informal water transactions, past participants, and potential future participants in the market are assessed and integrated. Third, evaluate the hydrologic conditions to estimate water allocations and the effect on supply for users, as well as third parties. Fourth, assess costs and benefits of saving unproductive consumptive water use for trade in a market.

3.2 Assessing the Policy Framework for a Water Market

3.2.1 Assessing the Water Market

For this integrated, geographically-resolved hydrologic process, the first step is to identify policy governing water rights to determine whether market efficiency is possible. An efficient market requires open information–like pricing and available water–as well as clearly identified property rights. Clearly outlined property rights are water rights that establish a volume and location and allow the user to sell or lease the right and are able to participate in a market.

Some water rights have stipulations that limit trading between sectors. For example, municipal water rights might need a firm allocation rather than an interruptible one. This rule limits trade from irrigation to municipal water use to only the firm part of the irrigator's allocation.

Some water rights do not establish an allocation volume, limiting total water withdrawals to available water supplies, a desired future condition for storage for the system, or reasonable use for each user. In these cases, property rights might exist–for example, a landowner owning access to water under their land–but the rights are not clearly outlined. Trade in a market without limits on withdrawal could lead to exploitation of resources. Conversely, water right regulations could protect private rights and promote economic activity between water rights holders.

Assessing the Water Market in Texas

The analysis in this work focus on regional transactions in Texas. Thus, it is helpful to outline the market framework at the state level. The subsequent analyses chapters will focus on the specific regional markets.

In Texas, formal water markets have been slow to develop. Water is rarely traded across Texas due to the large size of the state and the lack of natural or man-made conduits for large water transfers like those in California [163]. Where water is traded, local markets prevail, specifically in the Lower Rio Grande Valley (in the Southern tip of Texas), over the Edwards Aquifer (in central Texas), and in the Texas Panhandle. Other markets exist through local water trusts [171]. Despite the drawbacks to the current water trading system, water transfers have occurred in Texas for decades [171].

Usual transactions occur within the agriculture sector or from agriculture to non-agriculture users [163]. According to the Western Governors Association, Texas traded a total 925 billion gallons between 1988 and 2009 at an average 2.6 million gallons per transfer [164]. Trades increased between 2007 and 2009 resulting in 49 million gallons of transfers over those three years [164]. However, the ongoing drought in Texas triggered and increases in demand from various water use sectors, including oil and gas, has increased demand for water transfers across the state. During the drought in 2011, users sold or leased more than 555 billion gallons [164].

To assess the water market in Texas, various public and private datasets including hard data from governmental entities and soft data such as interviews with water marketers, local or state agencies, and landowners were curated and integrated. Existing market literature, as well as press releases for water sales across the state were also examined. Water transactions between 1987 and 2008 were compared to those between 2009 and 2014 [171]. The two time periods show the increase in value attributed to water with the increase in oil and gas production after 2009 due to the increase in unconventional oil and gas production. However, as the price of oil fluctuates, the value of water used to extract that oil (and natural gas) will fluctuate, as well. After the decrease in oil price in 2014, the value of water used for oil and gas production also decreased. This work does not capture that decrease in water value, but as the price of oil dropped by more than half of its market value, the price of water is assumed to have reduced by about 50%, as well. This analysis shows a range of mining sector prices, capturing the highs of 2014 with acknowledgement that those prices are most relevant in a high oil price environment and the lows captured within the market transactions are more relevant for a low oil price environment.

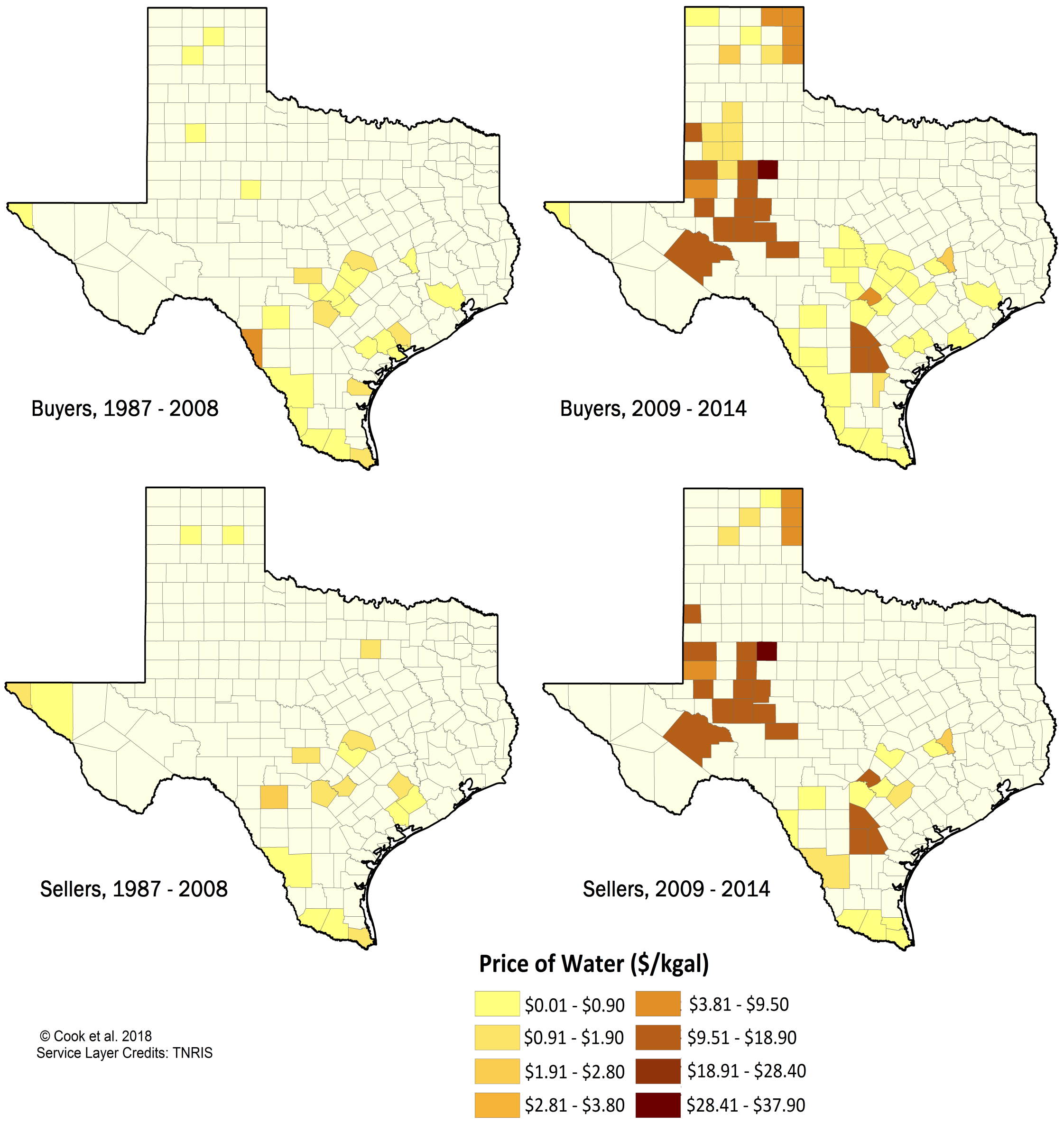
As the number of mining transactions has increased, so has the price of water per cubic meter. Between 1987 and 2008, prior to the increase in hydraulic fracturing in much of Texas, the median lease price for mining water was approximately \$0.11 per thousand gallons (kgal) and the average price was approximately \$0.38 per kgal [171]. Between 2009 and 2014, the median lease price was approximately \$14.80 per kgal and the average price was \$15.10 per kgal [171]. Figure 3.1 shows the average prices per county reported between 1987 and 2014. This period includes drought in the 1990s and early 2000s, as well as the most extreme one-year drought on record in

2011. The change in mining water price between the two periods analyzed reflects the effect of spot pricing and could also be due to the spike in water demand for oil and gas drilling as well as the decrease in water supplies caused by the intense, statewide drought that began in 2011, among other factors. However, the data show high water prices for oil and gas activity in 2013 and 2014 (after the end of the one-year drought), presumably due to the high value associated with the use of that water.

In examining Texas' water market, it is important to keep transaction costs in mind as they might create a significant barrier to market allocation of water resources and might cause implementation to lag [165]. Transaction costs are the resources used to define, establish, maintain, and transfer property rights [166]. These costs might include administrative costs or costs of exchanging ownership titles [166]. They are incurred by a subset of the actors [165]. Transaction costs vary across the state of Texas. Policies vary at the state level between groundwater and surface water management and availability and at the regional level between groundwater conservation districts, river basin authorities, and other districts. Previous research on transaction costs estimates ranges from 8–34% [166–170]. Transaction costs associated with administrative fees account for approximately 21% of total water costs in the Rio Grande Valley [171].

3.2.2 Determining Potential Market Participants

Potential market participants are chosen from water users in the basin–both long-established and new users. Current and future annual water supplies, demands, needs, and locations were evaluated. Water users with needs could provide stimulus to a market as demand points willing to pay for water. Water users with existing fulfilled demands could provide supply points to the market, saving water and leasing to others, depending on their conservation potential.


Buyers, 1987 - 2008

Buyers, 2009 - 2014

Sellers, 1987 - 2008

Sellers, 2009 - 2014

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Figure 3.1: Water transactions across the state of Texas often occur in local markets in the Lower Rio Grande Valley below Falcon Dam, in the Edwards Aquifer area, and in Northwest Texas. Between 2009 and 2014, transactions increased in South and West Texas and in the Panhandle due to the increase water demand for hydraulic fracturing. Data were compiled from various sources including private operators and [1–20].

Water users with existing demands must then be evaluated for their water use efficiency. For example, agriculture water users would be evaluated for their water application efficiency. Municipal water users would be evaluated for their water use per capita and water losses per system total. Thermoelectric water users would be evaluated by their water withdrawal and consumption per unit of electricity generated.

After evaluating water use efficiency, water management plans must be evaluated for users deemed to have low water use efficiency. In evaluating water management, "low hanging fruit" options for reducing water demand would be identified and users would be included in the market for conservation.

This work focuses on conserving unproductive consumption. A discussion of unproductive consumption is included in Chapter 2. In areas where downstream and future generations depend on the unconsumed portion of diversions, including return flows and aquifer storage, investment in conservation could lead to water depletion [69]. Focus on conserving consumptive water use avoids these unintended consequences. Unproductive consumptive water uses include transpiration from weeds, evaporation from soils and irrigation canals, and evaporation from poorly designed irrigation systems [68]. Reducing unproductive consumptive losses through conservation and efficiency would make surplus water available to be used by the existing user or reallocated to other users [68].

3.2.3 Hydrologic Models

It is important that negotiations for water trading include a baseline for water availability. Because a contract would be based on money paid for an amount of water provided, the negotiating point for both parties should be based on a drought year to set a conservative allocation. A farmer interested in selling water and still producing crops would want to ensure they will have enough water to do so after a trade as would the operator interested in fracturing wells with the saved water.

Existing water demands and hydrologic conditions must be evaluated to determine effects of water trading on water supplies, current water users, and new users. It is sometimes possible to use an existing model that is already calibrated to the hydrologic conditions of the basin as well as the demands and discharges of water users. Such a model might be employed within the basin for planning purposes, research, or both. The availability of a model of this caliber is the best case scenario but not always the case in practice.

Instead, it might be necessary to develop an allocation model if one is not available. Three allocation models are included in this section as they are used in the integrated process for each case study. Each model was developed and calibrated to its region. In developing an allocation model, it is important to choose a format that incorporates the necessary water supply, demand, and policy inputs over a time period sufficient for decision-making.

Because of differences in water allocation policies and hydrologic conditions across the state of Texas, three different computer-based models are used to simulate water resources and demand sites: Water Evaluation and Planning (WEAP), Groundwater Availability Models (GAMs), and Water Availability Models (WAMs) coupled with the Water Rights Analysis Package (WRAP). Each incorporates a set of climatic conditions, naturalized flows, and demand sites, and policies to determine current water availability. WEAP and WAMs also incorporate an allocative system to represent the priority systems that govern water rights in each basin. WEAP is also able to incorporate interstate compacts and international treaties in its allocation system.

3.2.3.1 Water Evaluation and Planning

Water Evaluation and Planning (WEAP) is a simulation environment that accounts for prioritized water demand sites linked to water supplies from rivers, reservoirs, and aquifers [172]. The model platform is able to simulate environmental and human parameters, including naturalized flows and demand sites such as municipal, industrial, and irrigation withdrawals. It can also incorporate policy settings such as water treaties and priorities. WEAP is able to be calibrated by adjusting parameters to achieve results closer to the historical conditions. All of these capabilities make WEAP an ideal choice to simulate water withdrawals and consumption in the Rio Grande/Bravo basin.

3.2.3.2 Water Availability Models

Water Availability Models simulate the amount of water that would be in a river or stream under certain conditions. The WAMs consist of a modeling program, the Water Rights Analysis Package, and the WAM text input files of basin-specific information [173]. The Texas Commission on Environmental Quality (TCEQ) uses WAMs to evaluate existing water rights and allocate new withdrawals or amend existing ones [173]. WAM and WRAP together simulate current water rights holders in a river basin using demand sites, naturalized streamflow, historical precipitation and evaporation, and corresponding reservoir operations over a period between 1934 and 1998, capturing the 1950-1957 Texas drought of record (but not the most 1-year intense drought of 2011). If water is available, the models estimate how often the water would be available [174].

One WAM is of interest to our analysis, the full execution model. The full execution model simulates perpetual water rights holders withdrawing their entire permitted volume with no return flow to the river basin [173]. The full execution is a worst-case scenario for water use as usually most water users return some of their allocation to the river. It is used by TCEQ to evaluate availability for new perpetual water rights and amendments [173]. TCEQ issues a permit when 75% of the proposed water diversion is available 75% of the time except in cases of municipal water use in which permits are issued when 100% of the proposed water diversion is available 100% of the time [175]. Allocation rules are relaxed when backup water rights are secured, though.

The Water Rights Analysis Package (WRAP) simulates the text file of WAM data of permitted water rights for full execution and current conditions with naturalized streamflow and observed meteorological condition over a historical time period in a computer-based model [174]. WRAP is a set of Fortran-based programs used to model diversions based on priority and location over daily and monthly timesteps [174]. Together, the text WAM and the WRAP simulation reveal the actual amount of water diversions available to current water rights holders based on observed historical climate conditions. With this model, it is possible to evaluate changes in water use by current users, effects of additional users on the basin, and potential effects of historical drought on current water users.

3.2.3.3 Location-Allocation of Groundwater

Groundwater Conservation Districts

Groundwater Conservation Districts (GCDs) are regional authorities tasked with managing groundwater supplies for their district [176]. As of 2017, 99 GCDs operate in Texas, 61 of which are single-county districts. Parts of the state are not governed by a GCD, though; only 174 of the 254 counties in Texas are included either fully or partially in a GCD. GCDs can set well spacing and water production requirements and are required by statute, passed in House Bill 1763 in 2005, to permit only to their managed available groundwater [176, 177].

Groundwater Availability Models

A groundwater availability model (GAM) is a tool that can be used to assess managed available groundwater based on hydrologic and human inputs like hydraulic head, recharge, and well pumpage [178]. The GAM is a numerical groundwater flow model and mathematical representation of the physical characteristics of an aquifer [178]. The model calculates hydraulic head at discrete locations within a grid and is calibrated to measured hydraulic heads [178]. The GAM uses MODFLOW-2000 due to its public domain and wide-spread use in groundwater models [178]. The GAM is limited by data availability and should only be used on a regional scale due to the grid size [178].

Desired Future Conditions

Groundwater Management Areas are larger areas that cover all of the major and minor aquifers of the state. Each encompasses multiple GCDs as well as areas without a GCD. GCDs determine their Desired Future Conditions, the physical conditions of the aquifer that the GCD intends to meet in the future. DFCs have to be physically possible and compatible with other DFCs in the Groundwater Management Area [177]. GCDs in the same groundwater management area meet to determine the Modeled Available Groundwater of the aquifer based on DFCs and the results of GAMs [177]. The State does not directly decide how much groundwater is available; GCDs decide in the DFC and GMA processes [177]. In developing their groundwater management plans, GCDs must use GAMs if they are available.

Modeled Available Groundwater

While the GAMs show a physical representation of water available, the DFCs represent the political water available and sometimes allow for over-exploitation of the aquifer in the short term. This work uses the modeled available groundwater (MAG) determined from the GAM and DFC process to assess impact on groundwater resources.

Location-Allocation

Groundwater is not allocated by any policy in Texas. Fresh groundwater, along with other alternative water sources, is often reallocated from its source based on price, though. To simulate price-induced reallocation of varied water sources in West Texas, a model of water supplies and demands is constructed within ArcGIS using the location-allocation network analysis.

Location-allocation is a solver used for facility location that chooses facilities to satisfy demand and minimize weighted distances [179]. Because of the large number of potential solutions, ArcGIS location-allocation uses heuristic solution methods (partial search algorithms) reported in Densham and Rushton 1992 [180] to reduce the amount of solutions evaluated to find the optimal solution. The solver generates an origin-destination matrix of shortest path costs and then constructs an edited version of this matrix through Hillsman editing [179, 181]. The solver uses this edited matrix to generate a set of semi-randomized solutions and refines those solutions by applying a Teitz and Bart vertex substitution heuristic [179, 182]. Teitz and Bart (1968) vertex substitution heuristic is useful because it frequently converges to the optimum solution, irrespective of problem size, and it usually converges on a solution after a small number of iterations [180]. Hillsman editing reduces the original problem size and thus reduces the number of iterations required [180]. The location-allocation method then uses a higher-level heuristic (metaheuristic) to create better solutions [179]. The location-analysis returns the final solution when no improvement

Table 3.1: The hydrologic models have specific assets and existing uses.

Model	**Policy Inputs**	**Physical Inputs**
Water Evaluation and Planning (WEAP)	• Treaties, • Priorities, and • Allocations	• Naturalized flows, • Groundwater/surface water interaction, and • Water uses
Water Availability Model (WAM) and Water Rights Analysis Package (WRAP)	• Prior appropriation	• Naturalized flows (including groundwater return flow to stream) and • Water uses
Location-Allocation	• Price-based allocation	• Supplies and demands and • Physical network of choice

is possible [179]. This set of tools does not necessarily develop an optimal result but develops near-optimal results. A summary of the hydrologic models mentioned in this section is included in Table 3.1.

Results presented in this analysis do not include uncertainty. However, it is important to acknowledge that there is error inherent in estimating water allocations through each of the models applied within the integrated process in this dissertation. Each model carries its own technical errors associated with approximating flows, water allocations, and discharges. The near optimization of the location-allocation, for example, generates an unrealistic approximation of actual activities. The inherent imperfection of model results underscores the need to ensure high quality data, appropriate model choice, and a long period of study in an effort to reduce the error incorporated in the results. In addition to technical errors, each of the water models is attempting to approximate human activity. A good water model could highlight areas of human error and opportunities for improvement in system allocation activities.

3.2.4 Cost Comparison Metrics for Water Demand Reduction Methods

Assessing Volume and Cost of Water Demand Reductions

Irrigators are one candidate for water savings and leases. In this study, the ranges in potential water savings available are measured per area covered, $\sigma_w[gallons/acre-yr]$, for irrigation water-saving best management practices (BMPs) [171].

The water savings, V_{ws}, in $gallons/yr$ possible from implementation of a water-efficient practice is calculated using Equation 3.1 where A_{irr} represents the amount of irrigated land in $acre$ [171].

$$V_{ws} = \sigma_w \times A_{irr} \tag{3.1}$$

The estimated total cost, C, in one year of the implementation of one of these irrigation efficiency practices over a stretch of irrigated land is calculated using Equation 3.2, where A_{irr} represents the amount of irrigated land in each county in $acre$ and C_{area} represents the cost per area [171].

$$C = C_{area} \times A_{irr} = C_{area} \times \frac{Vws}{\sigma_w} \tag{3.2}$$

The estimated cost per volume $[gallons/yr]$ of water savings, C_{vol}, is then determined using Equation 3.3 [171].

$$C_{vol} = \frac{C_{area}}{\sigma_w} \tag{3.3}$$

The equations are used to estimate the total water savings that could be made available, the total cost, and the cost per volume of water saved through use of irrigation BMPs. The cost is then compared to the market price for water used for hydraulic fracturing.

Because systems have different lengths of effect, before comparing costs between systems, we assess the net present value, NPV, and recurring yearly payment, R_t, of each system so comparisons can be made on equivalent values. If the cost of the system is given as a recurring yearly payment, the net present value is estimated from the recurring payment, R_t, over a period, t, using a discount rate, i. The discount rate is the rate that could be earned on an investment and is assumed to be the market interest rate for agricultural loans as reported by TWDB, 3.15% [22]. However, many conservation projects are financed privately under different interest rates. Examples of the cost of irrigation and municipal conservation varied by common payment periods and interest rates reported by TWDB are shown in Figure 3.2 and in Appendix A.

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{3.4}$$

Conversely, the recurring yearly payment, R_t can be calculated from the net present value as

$$R_t = \frac{NPV \times (i \times (1+i)^n)}{(1+i)^n - 1} \tag{3.5}$$

where n is the number of recurring yearly payments.

Irrigation water demand reductions are an integral part of a water conservation and efficiency market. However, it is also relevant to explore water reductions in municipal, industrial, and thermoelectric power water use as those sectors also represent significant water demands. For each type of water demand reduction, total cost, volume estimated to be saved, and the cost per volume are determined. To determine best practices for conservation in these sectors, relevant literature and publicly available data from TWDB, TCEQ, the Energy Information Administration (EIA), municipalities, and the literature is evaluated. It is important to choose methods that negligibly reduce productivity or for which costs incurred due to loss in produc-

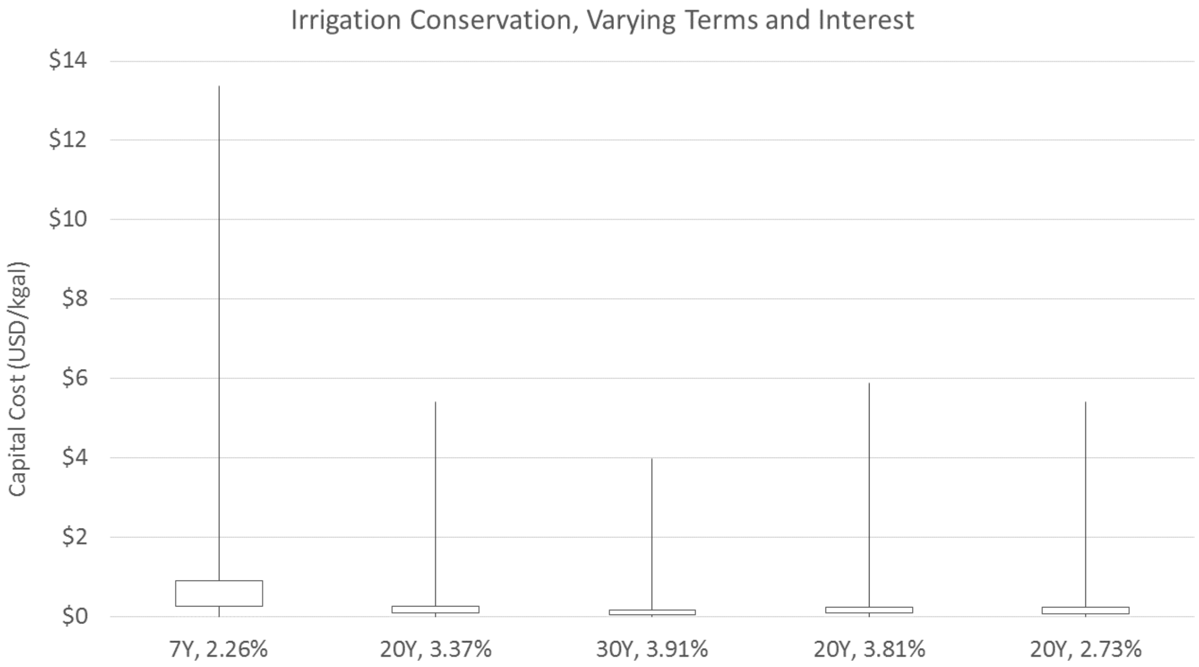

Figure 3.2: The capital cost of irrigation conservation reported by TWDB [21] is shown using interest rates and loan lengths (years, signified with a Y) offered by TWDB or the market and reported by TWDB [22].

tivity can be offset by water trade. Low cost, high yield options are identified when available as these “low hanging fruit” will be most feasible to implement. High cost, high yield or low cost, low yield options might be possible, as well if market prices for water allow. High cost, low yield options are likely poor choices for implementation.

For each conservation scenario, the cost to conserve water is determined as outlined above and compared to the cost of water as determined in Section 3.2.4. The baseline value to the water user is the total profit of selling surplus water each year. Profit of increased conservation, efficiency, or management is then estimated.

The net profit of water lease, π, is calculated as the benefit of leasing water (price of water, p, multiplied by the volume of water sold, V) less the cost of water savings (cost per volume of water saved C_{vol} multiplied by the volume of water conserved, V_{ws}). It is not assumed that the total amount of water saved would reach the oil and gas operator in every period.

$$\pi = \text{benefits} - \text{costs} \tag{3.6}$$

In a water lease scenario, the net profit of water lease is for the lease of water less the cost to save that water:

$$\pi = (p \times V) - (C_{vol} \times V_{ws}) \tag{3.7}$$

In the baseline scenario where no water savings occurs, $V_{ws} = 0$, but there is a cost associated with not irrigating farmland or otherwise beneficially using water C_{val}. The net profit of water lease is for the lease of water less the value of water used for another purpose and Equation 3.7 reduces to:

$$\pi = (p \times V) - (C_{val} \times V_{ws}) \tag{3.8}$$

Implementation costs are minor compared to the current purchasing price for water in the mining sector in Texas, indicating the potential for partnerships in which the energy sector pays for the water demand reduction measures in other sectors and receives the water made available in return.

3.2.5 Reliability, Resilience, and Vulnerability

As water demand changes for certain users in the hydrologic models, it is relevant to assess what the changes in demand mean for water supplied to that user and to other relevant users in the basin. To do that, we use performance criteria: the deficit, reliability, resiliency, and vulnerability of water supplied to target users in each study area.

Deficit

Water demand is not always fulfilled with water supplied. The value of unmet demand at time, t, for the ith water user is termed the deficit, D_t^i, as shown in Equation 3.9.

$$\begin{cases} D_t^i = (X^i_{Target,t} X^i_{Supplied,t}, & \text{if } X^i_{Target,t} > X^i_{Supplied,t} \\ 0, & \text{if } X^i_{Target,t} = X^i_{Supplied,t} \end{cases} \tag{3.9}$$

If the water supplied to the ith water user, $X^i_{Supplied,t}$, is less than that demanded by the user, $X^i_{Target,t}$, the deficit is $X^i_{Target,t} X^i_{Supplied,t}$. If the water supplied to the ith water user is equal to or exceeds the demand of that water user, the deficit is 0.

Reliability

Water demand reliability is the probability that the water supplied to each user meets its water demand during the period of study [183].

$$Rel^i = \frac{\text{No. of times } D_t^i = 0}{n} \tag{3.10}$$

Time-based reliability, shown in Equation 3.10 as Rel^i, is the portion of time that each user is supplied the water it demands or the number of times there is a nonzero deficit, $D^i \neq 0$, over the total number of time intervals considered (n months or years) [184].

Resilience

The system's resilience is its ability to recover from a period of failure or an unsatisfactory condition and must be considered to assess the effect of varied hydrologic conditions on water supplied under altered demand conditions.

$$Res^i = \frac{\text{No. of times } D_t^i = 0 \text{ follows } D_t^i > 0}{\text{No. of times } D_t^i > 0 \text{ occurred}} \tag{3.11}$$

Mathematically, resilience, shown in Equation 3.11 as Rel^i, is the probability that a satisfactory value will follow an unsatisfactory value [185] or the number of times $D_t^i \neq 0$, follows $D_t^i > 0$ for all times $D_t^i > 0$ occurred [184].

Vulnerability

Vulnerability is the probable value of the water deficits [183] and can be considered as the severity of failures [184]. Here, vulnerability is considered to be the average failure or expected value of the water deficits as used by Loucks et al. 2005 [186] and shown mathematically in Equation 3.12.

$$Vul^i = \frac{\frac{\sum_{t=0}^{t=n} D_t^i}{\text{No. of times } D_t^i > 0 occurred}}{\text{Water demand}^i} \tag{3.12}$$

In the annual average failure is the sum of the deficits, $\sum_{t=0}^{t=n} D_t^i$, divided by the amount of times a deficit occurred for the ith water user. Dimensionless vulnerability is calculated by dividing the annual average failure by the annual average water demand for the ith water user.

3.2.6 Flowchart of Model Methodology

The research methodology outlined in this section is represented graphically in Figure 3.3. Dotted lines represent exit points–property rights are not clearly defined, water use efficiency is already adequate and thus savings for lease are not feasible, or low hanging fruit are not available and cost might be prohibitive. In the first case, the policy framework does not encourage market activity. A policy change would need to occur to make market conditions available. In the latter two dotted line cases, it might be possible to re-iterate and find other water users to participate in the market. The framework ends with determinations of profit and water supply metrics of reliability, resilience, and vulnerability. If each improves compared to baseline, the market would yield benefits for all water users involved.

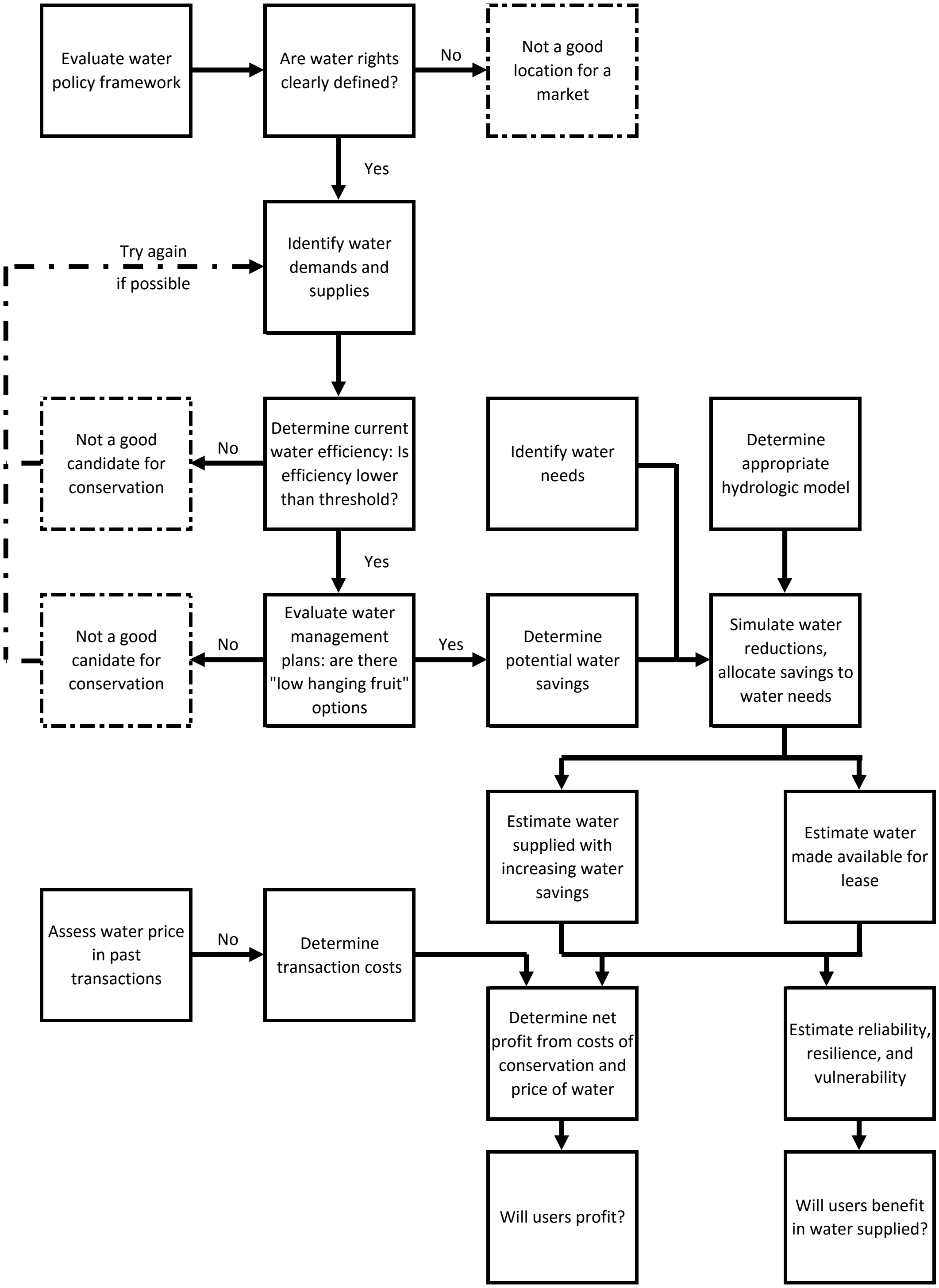

Figure 3.3: The research methodology outlined in Section 3.1 is represented graphically in this figure.

Chapter 4

Objective 2: Existing Active Surface Water Market

4.1 Apply the Model to an Active Surface Water Market

To assess the potential of saving water through trade, the integrated, geographically-resolved allocation model is applied to an existent surface water market in the Rio Grande Basin in South Texas. The entire basin is shown in Figure 4.1. This analysis focuses on the portion of the basin at the border of Texas and Mexico, nearing the Gulf of Mexico.

Trade is evaluated between two types of water users only: oil and gas operators and irrigators. In this basin, municipalities are growing rapidly and often buy or lease water rights from irrigators. Since they compete with oil and gas operations for surplus water resources, they are not considered as a source for surplus from conservation at this time. In the future, however, municipalities could be a source for conserved water for their own use or for other buyers within the basin.

Water reductions associated with market activity are compared to baseline water supplies. With the surge in oil and gas drilling in the nearby Eagle Ford Shale, energy companies have been buying or leasing water rights on the Rio Grande in

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Figure 4.1: The Lower Rio Grande in South Texas is the focus of this analysis. The entire watershed stretches across four states in the United States of America and five states in the United Mexican States.

South Texas [164]. One of the major irrigation districts in the Lower Rio Grande, Hidalgo County Irrigation District No. 2, has added diversion points in the Middle Rio Grande where water can be easily delivered to energy entities [164]. Landowners in other parts of the shale basin have sold water from their wells to oil and gas producers. Landowners might sell their water through water marketing firms [164]. One firm reportedly sold more than 58 million gallons to oil and gas companies [14].

With active trading in the area for both irrigation water rights and supply for oil and gas, the Rio Grande Basin makes a good testbed for analysis of the potential for conservation water trading through application of the integrated, geographically-resolved allocation model.

4.2 Market Framework and Participants

4.2.1 Rights in the Rio Grande

The first step in application of the integrated, geographically-resolved allocation model is outlining the relevant policy framework. Water rights in the Lower Rio Grande, below the Falcon-Amistad reservoir, differ from those on other rivers in that they are allocated on an account basis in which the watermaster, the arbitrator of water rights in this basin, records withdrawals and subtracts use from allocated accounts [46]. Rights for municipal uses are set at one priority level in which allocations renew on a yearly basis while irrigation rights are set at another level in which balances carry forward into the next year [46]. Thus, irrigation accounts are more constrained than municipal accounts [46]. Surplus in the Falcon-Amistad reservoir for any given month is allocated to the irrigation users [46]. As water rights of certain types are on the same priority and allocations are recorded and essentially banked by the watermaster, the policy framework is favorable to market transactions.

4.2.2 Market Participants

Irrigators

The second step in application of the integrated, geographically-resolved allocation model is identifying market participants. As a major agricultural producer for Texas and the United States as a whole, irrigators in the Lower Rio Grande Valley region consume a large amount of water –about 79% of total regional water use [23]. The counties with the highest irrigation water withdrawals in the valley, Cameron and Hidalgo Counties, consume about 114–195 billion gallons (432–740 million m^3 or 350,000–600,000 ac-ft) of water per year, respectively. The Lower Rio Grande Valley could be a prime candidate for large-scale irrigation efficiency improvements. Some Best Management Practices (BMPs) have already been implemented in irrigation districts in the valley [73]. However, many BMPs, including brush management, crop residue management and conservation tillage, and tailwater recovery and reuse systems are not in wide-spread use [73].

Furrow dikes (small dams for each ridge between a planted row of crops); gated and flexible pipe to prevent seepage in irrigation channels and furrows; recovery of irrigation runoff water (tailwater recovery); and brush management are potential methods of demand reduction for irrigators in the Lower Rio Grande Basin. Past studies have shown the furrow dike system, for example, is a cost-effective management practice for producers in the Southeastern U.S. that positively impacts natural resource conservation, producer profit margins, and environmental quality [100]. Costs of water savings via BMPs are calculated as mentioned in Section 3.2.4.

Oil and Gas Operators

The Eagle Ford Shale resides beneath Webb and Dimmit Counties in the Rio Grande Basin. Counties in the Lower Rio Grande Valley could benefit from future

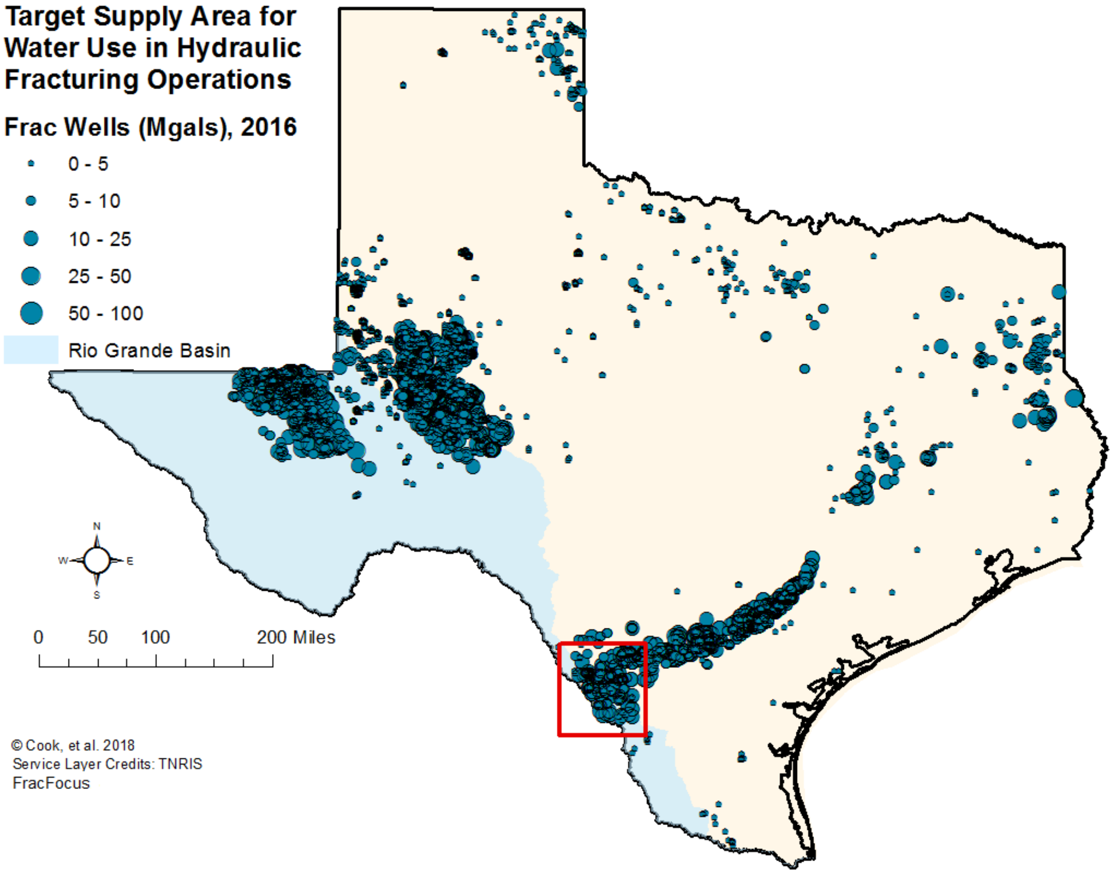

Figure 4.2: This model of market transactions seeks to supply users paying high prices for water: oil and gas operations in the Lower Rio Grande.

economic growth of the oil and gas industry; either due to increased oil and gas production or water sales. The target area of water reallocation to hydraulically fractured wells is shown in Figure 4.2.

Use of recycled municipal effluent or flowback and produced water (FP) is possible, but the supplies are relatively low compared to the demands of hydraulic fracturing. In a lifecycle analysis, Ikonnikova et al. 2017 [131] found that FP water supplies are about 40–60% of hydraulic fracturing demands. It is possible to treat and reuse this water, but demands will also require the use of fresh or brackish water resources. Thus, this analysis focuses on reducing consumed fresh water as a source for supply.

4.3 Hydrologic Model: WEAP

The next step in application of the integrated, geographically-resolved allocation model is to simulate the allocations of the market participants within the policy environment. Water supplies and uses were simulated using Water and Evaluation and Planning (WEAP), a tool that is able to simulate water supplies and demands over time, incorporating policy dynamics. All of these capabilities make WEAP a useful hydrologic model for the Rio Grande/ Bravo basin.

The water supplies for the Rio Grande/Bravo river basin were simulated using hydrologic data obtained by Teasley 2009 [172] and Sandoval et al. 2011 [187] through a joint effort between the Center for Research in Water Resources, the Texas Commission on Environmental Quality (TCEQ), Conagua, and the Mexican Institute of Water Technology [172]. The model simulates a 60-year period (October 1940–September 2000) of data that includes the drought of record for the State of Texas, as well as other times of high and low flow. The model includes naturalized flows for the Rio Grande/Bravo and its major tributaries, as well as losses due to evaporation, evapotranspiration, and seepage.

WEAP is also able to incorporate municipal, irrigation, and other demand sites. The WEAP model for the Rio Grande/Bravo simulates water deliveries based on the account of water in the two major reservoirs in the basin, Amistad and Falcon, and the priority of the water rights attached to demand sites. Municipal and agriculture water demands are allocated by a watermaster at different priorities– municipal, then agriculture rights at the A priority, followed by agriculture rights at the B priority.

Due to the large number of demand sites in the Rio Grande/Bravo basin, demands are aggregated by use type, priority, and region. Users in Texas are divided by section in the watermaster jurisdiction (watermaster section).

WEAP allows integration of policy settings such as water treaties. The Rio Grande/Bravo basin is subject to the 1906 Convention, the United States-Mexico Treaty of 1944, Interstate Compacts for the Rio Grande between New Mexico, Colorado, and Texas, and Texas Watermaster rules. The WEAP model of the Rio Grande/Bravo basin was calibrated to historical conditions in previous work by Teasley 2009 [172] and Sandoval et al. 2011 [187]. The model is then validated by entering historical demands for a 15-year period to determine if the simulation matched historical operations.

Water demand reductions are modeled as percent reductions in demand at certain irrigation watermaster sections of 1%, 5%, 10%, and 15%. Water leases to oil and gas are modeled as additional nodes that demand water at an amount equal to the reduction at the irrigation watermaster site. The full execution of the WEAP model of the Rio Grande/Bravo is for 1940-2000 using climatic conditions of that period, reduction in demand due to best management practices of 1%, 5%, 10%, and 15%, and subsequent lease to an oil and gas operator. The total amount of water supplied to oil and gas over that period is then summed to estimate the amount of water that could be leased to oil and gas over the 60-year period with an investment in irrigation management.

Reducing Impacts on Third Parties

Reductions in irrigation water use associated with water conservation could result in reduced return flows to the Rio Grande/Bravo or reduced infiltration to aquifers beneath agricultural activity. To limit impacts on aquifer recharge, watermaster sections residing above aquifer recharge zones were not considered for this analysis. While they could still participate in a market, the impact to future groundwater resources–including both the impact of reduced irrigation and the impact of increased groundwater use for hydraulic fracturing as the alternative to surface water–should be considered before reducing irrigation for other purposes.

The watermaster sections assessed for the reductions are sections 5, 5A, 5B, 6A, and 6B which reside between Falcon and Amistad Reservoirs and sections 6AL, 6BL, 7A, 7B, 13A, and 13B, below Falcon Reservoir, as shown in Figure 4.3. Watermaster sections 8–12 reside above the recharge zones of local aquifers. Conservation in the latter sections was not simulated to avoid effects on aquifer recharge in the near-term. Watermaster sections 1–4 are upstream of oil and gas activity. Transporting water from these watermaster sections would incur increased transmission losses and potential third-party effects as water from upstream users passes by downstream users to get to the new oil and gas water users. They were also not included in the analysis. All watermaster sections could participate in a market. However, the recharge and third-party effects should be acknowledged in future water allocations.

4.4 Assessing Potential Costs and Benefits

4.4.1 Water Deliveries

Water demands and deliveries are simulated for all users in the Rio Grande/Bravo Basin and water reductions for water leases to oil and gas only at watermaster sections collocated or downstream of the Eagle Ford Shale for each watermaster section of interest. The water that could be made available to oil and gas operators from each watermaster section after 1%, 5%, 10%, or 15% water conservation is shown in Figure 4.4. If operators were interested in reducing effort by seeking out one area to conserve water (rather than all districts analyzed), the results suggest working with

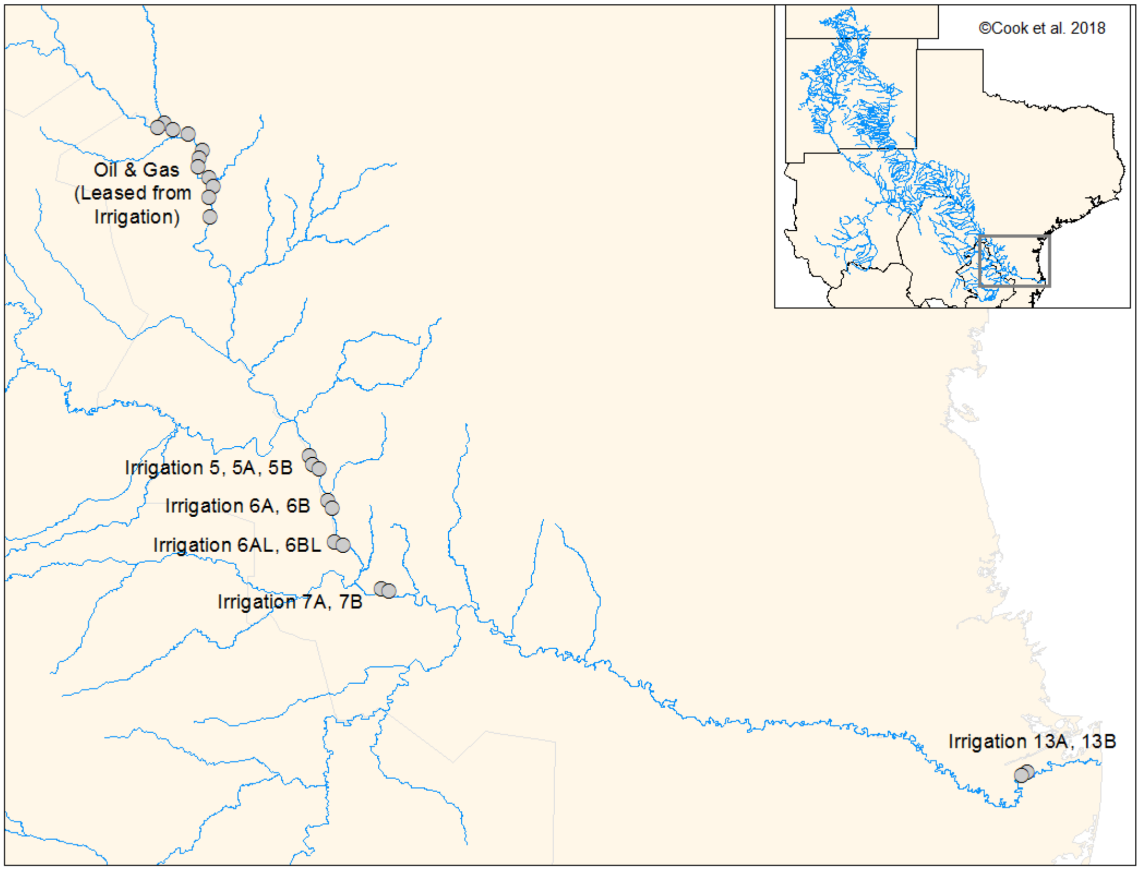

Figure 4.3: The watermaster sections assessed for the reductions are sections 5, 5A, 5B, 6A, and 6B which reside between Falcon and Amistad Reservoirs and sections 6AL, 6BL, 7A, 7B, 13A, and 13B, below Falcon Reservoir.

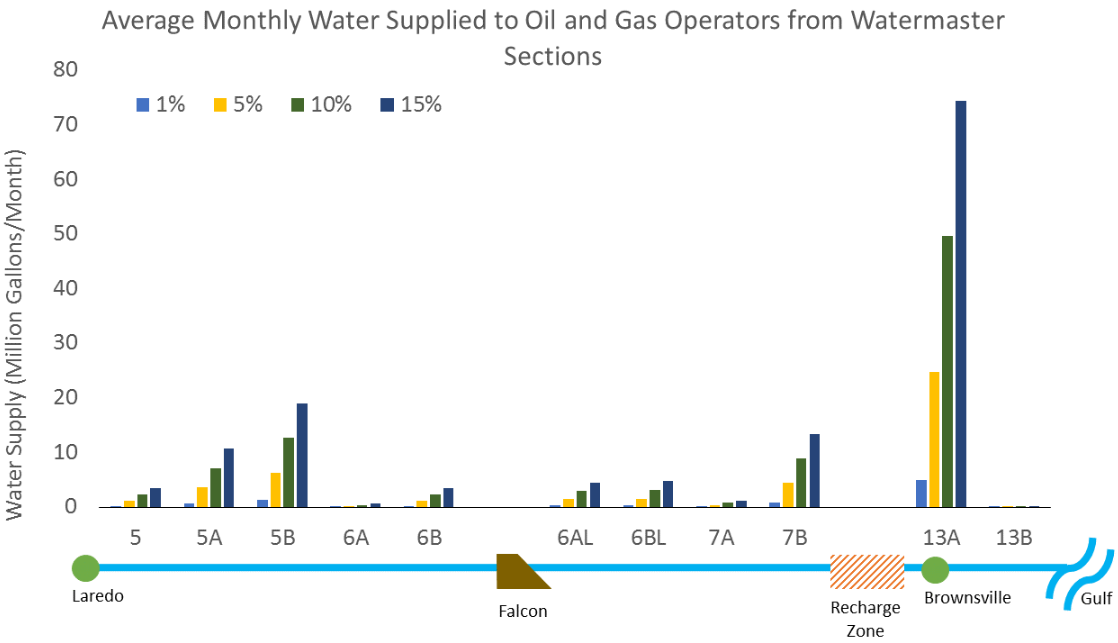

Figure 4.4: Water that could be saved by irrigation districts and made available to oil and gas operators is shown by watermaster section. Watermaster sections are shown from upstream to downstream in a left-to-right order.

the 13A district of irrigators would yield the most water.

The potential water savings opens up the opportunity for a water market in the Lower Rio Grande Valley. Wells fractured in Webb and Dimmit Counties consumed about 3 billion gallons of water in 2016 and 2017 [24]. The 900 million gallons of water saved by all watermaster sections conserving 15% of their water use could provide about 30% of the water needed in those counties, offsetting an increase in water consumption of the same amount.

4.4.2 Reliability, Resilience, and Vulnerability

For each scenario, including baseline and water reductions of 1%, 5%, 10%, and 15%, the water demands and deliveries are calculated in the WEAP model. From

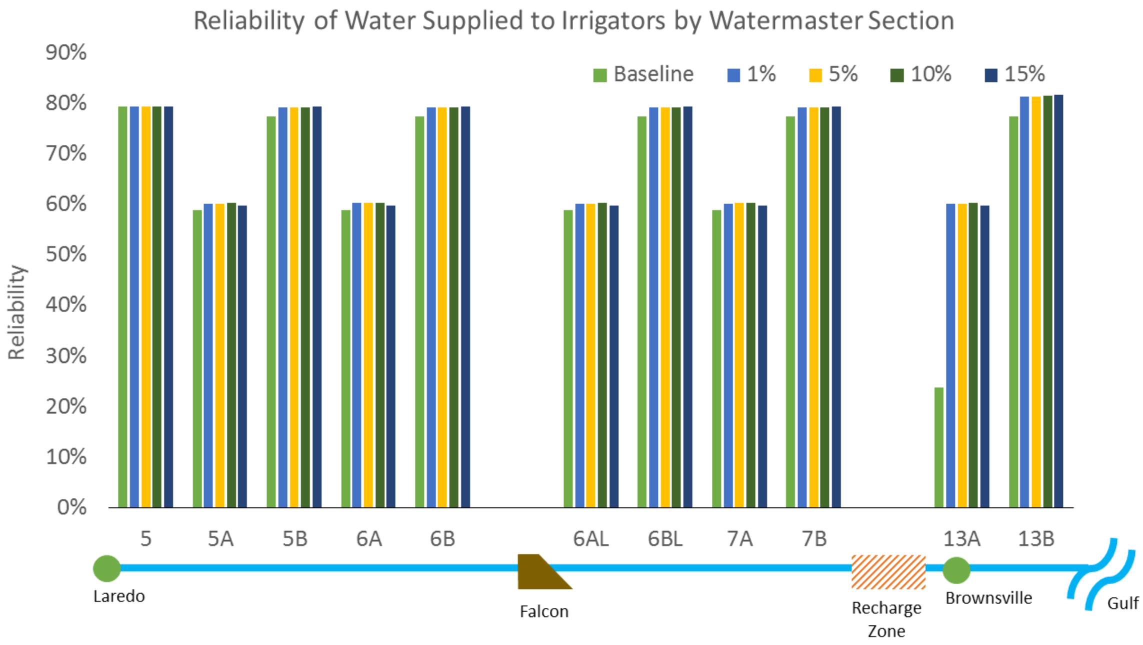

Figure 4.5: Reliability for irrigators following trades of varying amounts of saved water, shown by watermaster group saving water. Reliability for all irrigation sections is shown to increase from baseline in all scenarios of conservation and trade.

the demand and delivery calculations, deficit, reliability, resilience, and vulnerability of water supply is estimated for the water users of interest. Baseline and conservation scenarios are compared to determine whether users benefit from water reductions and leases in terms of improving their supply. As shown in Figure 4.5, reliability of water supplied to irrigators involved in water trades increases from the baseline in all scenarios. Since reliability is the frequency of meeting demand over the analysis period, the irrigators benefit from an increase in reliability. It is important to analyze the effect of allocations on performance parameters such as reliability, in addition to the desired parameter, volume of water supplied, to ensure changes do not have unintentional negative impacts on expected supply.

4.4.3 Costs and Benefits of Water Sales

Cost to Conserve Water

Figure 4.6 shows the estimated cost of BMP implementation per cubic meter of potential water savings upon installation. These implementation costs are minor compared to the current purchasing price for water in the mining sector in Texas, indicating the potential for an energy-agriculture partnership in which the energy sector pays for the improved irrigation efficiency measures and receives the water made available in return. Given that buying water in water markets is more cost effective than other policies intended to encourage improved irrigation efficiency through subsidies, there is potential for irrigation efficiency improvements through market mechanisms [83].

By incorporating irrigation BMPs, irrigation districts would likely be able to save water, maintain their crops, and profit from the sale. Simultaneously, shale oil and gas companies would have access to freshwater for hydraulic fracturing while reducing their risk of exposure to municipal restrictions and water shortages. The increase in water availability could also make more water available for ecosystems. Thus, this makeshift water market could solve water needs for multiple sectors.

While oil and gas operators can pay for water now, that purchase often offsets other water uses, for example, reducing the amount of irrigated agriculture activity or increasing stress on water supplies. A water market promoting irrigation efficiency measures might encourage better resource allocation and increase the amount of water available for economic activity (e.g. hydraulic fracturing as analyzed in this paper) and/or ecosystems as Texas considers instream flow requirements into its bays and estuaries.

The market already exists. However, there is a potential for the market to

Figure 4.6: The price of water varies per BMP, but all water conservation measures cost less than the wholesale price of water for hydraulic fracturing in Texas. The box plot of water price shows the 1st and 3rd quartiles within the boxes. The lines extending beyond the box, or whiskers, show the data outside of those quartiles. The price paid for mining water does not include transaction costs which vary regionally. (Figure created by the authors based on analysis and data from private operators and [1–20, 23]).

move toward integrated partnerships that benefit irrigators and oil and gas operators rather than existing adaptive strategies to combat water stress. This energy-agriculture partnership could work in areas where water allocations are nearing their maximum capacity. When water is inexpensive, it is not cost-effective to save it or make investments to reduce consumption. However, when water is expensive, or if there is a buyer who will pay a lot for it, there is an economic incentive to reduce usage either to reduce costs or to gain revenues in the sale of water.

A trade instigated by the irrigator or the oil and gas company would be possible in a market. A proposal by either party during negotiations for water exchange brought on by oil and gas operators in need of water could instigate a trade. Similarly, irrigators seeking capital for efficiency investment could post volumes available for lease. The latter would be less likely as few existing portals exist through which to advertise such a sale. However, by investing in efficiency measures, an irrigator or irrigation district could sell more water without reaching a limit (if there is one) or otherwise overdrawing their resources (if there is not a limit). The cross-sectoral investment could be proposed by the irrigators, possibly in an effort to reap extended benefits from the surge in capital or for other reasons or by the oil and gas company, possibly for increased public approval or other social benefit. For example, Southwestern Energy mitigates the impacts of its hydraulic fracturing operations on the environment by rehabilitating lost wetlands or creating a new habitat in Arkansas [188].

4.4.4 Profits for Water Trades

To determine economic benefit of conserving water, the cost to conserve water is determined and compared to the price of water as determined in Section 3.2.4.

The net profit of water lease, π, is calculated as the benefit of leasing water (price of water, p, multiplied by the volume of water sold, V) less the cost of water savings (cost per volume of water saved C_{vol} multiplied by the volume of water conserved, V_{ws}). Profit calculated for each BMP in this chapter is shown in Table 4.1. The lost cost of water associated with selling without conserving in the baseline scenario is estimated from the average value of irrigation, reported as \$4.7 billion in 2007 for 5.9 trillion gallons of water use [189]. The average value of that water is \$0.98 per kgal in 2018 dollars. This value for agriculture is similar to values reported by Cooley et al. for crops in California [190]. Foregoing the profit of growing agriculture with water and selling it yields a net profit of \$13.82 under a high oil price scenario and \$6.42 under a low oil price scenario (50% of the price reported by Cook and Webber 2016 [171]). All options for agriculture conservation analyzed yield a profit in a water trade. Three options yield an increased profit over the baseline. The cases analyzed with WEAP are technology agnostic, so any of the three options in Table 4.1 could be used to save and sell water at a profit.

4.4.5 Third Party Effects and Transaction Costs

Third party effects, such as conflicts between consumptive and in situ water uses, are important but not usually considered in water market analysis (Edwards et al Murray Darling working paper). These effects might create issues for water trades involving hydraulic fracturing as water would be consumed in hydraulic fracturing operations rather than discharged to the watershed as in agriculture operations. However, water withdrawn from the Rio Grande is discharged to the Arroyo Colorado.

Regional water markets, as opposed to state- or basin-wide markets, often create pockets of favorable market conditions– water rights are defined clearly with low transaction costs [165]. Because of the existing vibrant water market in the Lower Rio Grande, the water market and its transaction costs are examined at this level rather than as part of the state-wide system. The watermaster keeps current water balances

Table 4.1: Average profit associated with conserving and selling water to oil and gas operations are shown for low and high oil price scenarios. Profits are reported as U.S. dollars per kgal of water, in terms of seller's benefits. Six options for agriculture water conservation yield a profit in a water trade.

Best Management Practice	**Cost to Conserve [$/kgal water]**	**Profit, Low Oil Price [$/kgal water]**	**Profit, High Oil Price [$/kgal water]**
Furrow Dikes	$0.23	$7.17	$14.57
Brush Management	$0.01	$7.39	$14.79
Gated and flexible pipe for field water distribution systems	$0.07	$7.33	$14.73
Tailwater recovery	$2.23	$5.17	$12.57
Sell		$6.42	$13.82

for each water right holder [191]. The watermaster acts as a broker of water, and individuals interested in purchasing or leasing water can get information on available water from the watermaster relatively inexpensively over the phone [191]. Water price is determined by negotiation between buyers and sellers, allowing price to fluctuate based on supply and demand [191]. Water rights are protected via monitoring by TCEQ.

Transaction costs incurred in the water market in the Lower Rio Grande Valley in Texas are captured by the watermaster department at the TCEQ. Water rights holders in the Lower Rio Grande Basin, the Concho River Basin, and river basins in South Texas pay TCEQ for permits, licenses, and fees [46]. These funds are then allocated toward administrative costs of the watermaster offices [192]. While water rights in the Rio Grande watermaster area account for the majority of water market activity in watermaster service areas, they account for 40% of diversions by volume. Assuming water rights fees are proportional to the amount of diversion, water rights holders on the Rio Grande pay their watermaster \$627,000, or \$0.04 per gallon (\$0.01 per m^3) of water in 2013–2014 [46]. Water transactions in the basin draw \$2,350,000 in sales and leases over the same period, meaning transaction costs account for 21% of total water costs [192]. A transaction cost of \$0.04 per gallon is approximately 30% the cost of the average purchase price of agriculture water between 2009 and 2014. However, it is approximately 0.23% of the average purchase price of mining water over the same period. Additional transaction costs are associated with increased irrigation analysis and water monitoring. This cost fits within ranges found in previous work in which water market transaction costs range from 8–34% [166–170].

4.5 Discussion

Of the four research questions laid out in Chapter 1, questions 1, 2, and 4 were explored in this chapter in the context of the Lower Rio Grande Basin. To summarize, (1) options are available to reduce fresh water use in the Rio Grande Basin, (2) low cost conservation options are available within the agriculture sector, and (4) if the energy sector paid for water, the low-cost fresh water reduction methods available could be implemented economically and offset about 30% of the water demand for oil and gas activity in this basin.

In this analysis, scenarios are evaluated to assess potential for trading irrigation savings from implementation of best management practices for use in oil and gas operations. Results show that if watermaster area irrigation districts conserve 15% of their water allocation, up to 900 million gallons per year could be made available for use in oil and gas operations at a cost offset by the price of water. While 900 million gallons might not be much water for a municipality, it is enough to provide about 30% of the 3 billion gallons of water demanded per year in 2016 and 2017 for hydraulically fractured wells.

This work highlights best management practices (BMPs) that result in a benefit to the agriculture or municipal water user. On average, the use of furrow dikes (small dams for each ridge between a planted row of crops), gated and flexible pipe (to prevent seepage in irrigation channels and furrows), and brush management to reduce fresh water consumption could be accomplished at a net economic benefit to the irrigator. Tailwater recovery is a more expensive method; the cost is sometimes offset by the price of water but not at a benefit to the irrigator over simply selling their water.

Reliability, resilience, and vulnerability of supply are evaluated to determine the effect on the irrigators of selling their water. Irrigation districts would experience an increase in reliability of their supply, meaning their full demand is estimated to be satisfied more frequently (another benefit in addition to the increased profit associated with selling conserved water). Vulnerability and resilience are generally unchanged. Evaluating water allocations in terms of these performance parameters allows planners to assess the likelihood of failure to water meet demand (deficit), recovery from previous deficit, and average magnitude of deficit. Consideration of these metrics helps in addressing negative consequences of reallocation of water resources.

Finally, it should be noted that this analysis does not fully address transaction costs. Trades occur frequently with low transaction costs in this basin due to the transparency associated with record-keeping and arbitration by the watermaster. However, additional negotiation, capital, and operations expenses that should be evaluated before engaging in water conservation surplus trading are not included in this work.

Chapter 5

Objective 3: Inactive Surface Water Market

5.1 Apply the Model to an Inactive Surface Water Market

In this section, the integrated, geographically-resolved hydrologic model is applied to a potential surface water market on the Brazos River, shown in Figure 5.1. The river supplies many users based on a priority allocation system. In a case in which a user did not receive its allocated water, under Texas state law, that user can call the Texas Commission on Environmental Quality (TCEQ) to request that users with a lesser priority be cut-off from accessing water with a result that the more senior users would receive their allocation. The action has been used on the Brazos, resulting in water deficits for lower priority farmers, cities, and power plants and causing health and safety concerns. Because of the desire to manage water more effectively and attempt to ensure even lower priority users receive water, a watermaster like that of the Rio Grande Basin has been established for the river.

Water trades in a market could pay for the cost of conservation and making those trades could lead to more reliable water supplies for those involved. This hypothesis is evaluated using the integrated, geographically-resolved hydrologic model with the WAM and WRAP programs.

5.2 Market Framework and Participants

Surface Water: Prior Appropriation

Water on the Brazos River is allocated via Prior Appropriation, where a permit

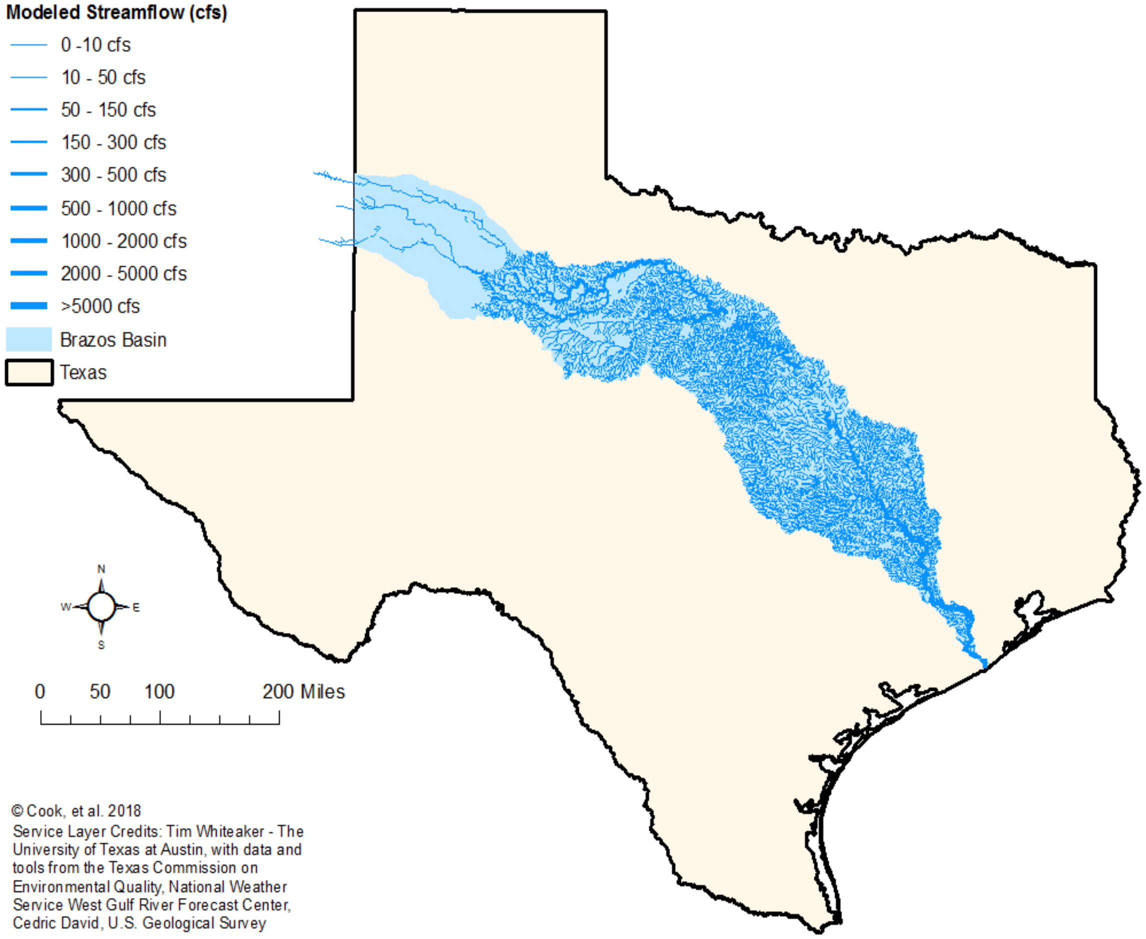

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Figure 5.1: The Brazos River in Texas is the focus of this analysis.

to withdraw water is based not on land ownership but on the point in time at which the permit or "water right" was acquired [43]. A discussion of this system of water rights is included in Chapter 2 of this work. Because appropriative rights exist separate from land ownership, they can be bought, sold, leased, or transferred, forming the basis for a surface water market. However, because water use is evaluated based on beneficial use, users might not be interested in altering authorities to the existence of surplus water. The priority system is often termed "use it or lose it" because rights holders must use their entire volume or lose their right to it. The system often encourages wasteful water use. A market on this river system could allow potentially unused water to be leased to another water user under the original water right, creating an economic incentive to conserve where one might not have existed previously.

A watermaster, similar to that for the Rio Grande in Texas, has been established for the Brazos River. It is assumed in this work that the watermaster will eventually be able to function as more than an authority on water withdrawals, but as an information center for possible water needs and surpluses as well as a monitoring and enforcement agent able to handle third party effect claims. Under the previous system without a watermaster, water withdrawals were permitted but not directly monitored, meaning water allocations were not exact and junior water rights, in particular, were affected by low flows.

5.2.1 Market Participants

The Brazos river has multiple types of users at various priority, irrelevant to the type of use– although irrigators and power plants, in particular, have older priority rights compared to cities as irrigation pre-dates municipal growth in much of the state. The Brazos River Authority also operates many water rights on the river. In 2020, the Texas Water Development Board estimates water needs from the irrigation, municipal, mining sectors (including hydraulic fracturing) throughout the basin, the power sector in certain counties, and the manufacturing sector at the mouth of the river will be unmet. Some water needs will be supplied by water supply projects at the local and regional level. However, some needs might still go unmet, possibly leading to over-extraction of aquifers or water shortages. Users with water needs could participate as demands in a water market. Here I assume only oil and gas operators would participate as buyers in the market and set prices, but other users could participate, as well. For reference, oil and gas operations in the Brazos River Basin are shown in Figure 5.2.

Irrigation Water Consumption

Water demand reduction points in the Brazos River basin are identified as outlined in Section 3.2.4. Irrigation efficiency varies throughout the basin. Thirty-one counties in the basin have irrigation application efficiencies between 0–40%, another four have application efficiencies between 41–50%, another fourteen have application efficiencies between 51–60% percent, and another seven have application efficiencies between 61–70%. Counties with large irrigated acreage and low application efficiencies are targets for analysis. In the Brazos River basin, twenty-nine counties have over 500 acres of irrigated farmland and estimated application efficiencies of less than 70%. For future market transactions, site-specific analyses are needed to determine actual application potential for BMPs. For this analysis, it is assumed that water consumption could be reduced to similar application efficiencies found in other parts of Texas.

An application efficiency of 10 acre-feet per acre (approximately 3.3 million gallons per acre) is common in the regions of Texas that grow rice, a very water-intense crop. Yet, other regions of Texas, including those in the Brazos River Basin,

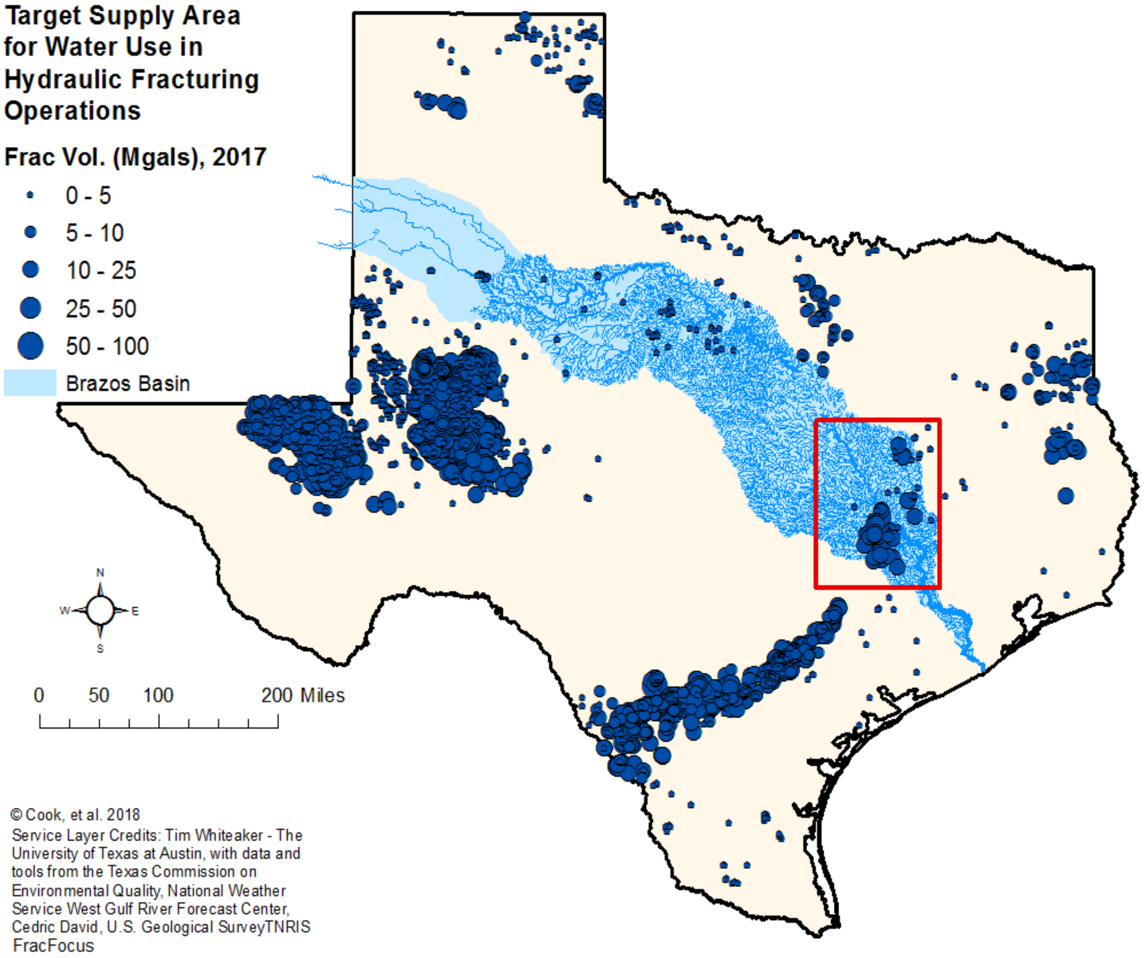

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Figure 5.2: This model of market transactions seeks to supply users paying high prices for water: oil and gas operations in the middle Brazos.

Table 5.1: Cases of agricultural irrigation conservation assessed in the WAM/WRAP analysis of the Brazos River.

Agriculture Cases	**Diversion [Mgal]**	**Control Points**	**Savings [Mgal]**
Case 1: Irrigation less than 0.7 million gallons per acre	18,205	79	14,096
Case 2: Irrigation less than 3.3 million gallons per acre	1,125	20	769

irrigate at levels exceeding 3.3 million gallons per acre per year, as shown in Figure 5.3. If all irrigated acres in the Brazos used less than 3.3 million gallons per acre per year, 1.6 billion gallons per year could be saved. However, not all irrigators possess their own water rights; therefore, the incentive to conserve and sell excess water is not as obvious. Instead, if all irrigation users with their own surface water rights were to implement consumption reducing management practices to achieve this level of conservation, 1.1 billion gallons could be saved per year, as shown in Table 5.1.

An application efficiency of 2 acre-feet per acre (approximately 0.7 million gallons per acre) is common in the water scarce regions of west Texas. Regions in the Brazos River Basin irrigate at levels exceeding 0.7 million gallons per acre per year. If all irrigated acres in the Brazos used less than 0.7 million gallons per acre per year, 92 billion gallons per year could be saved. If all irrigation users with their own surface water rights were to implement consumption reducing management practices to achieve this level of conservation, 18.2 billion gallons could be saved per year, as shown in Table 5.1. Counties in the Brazos River Basin irrigating at an intensity over 3.3 million gallons per acre and over 0.7 million gallons per acre are shown in 5.3.

Municipal Water Consumption

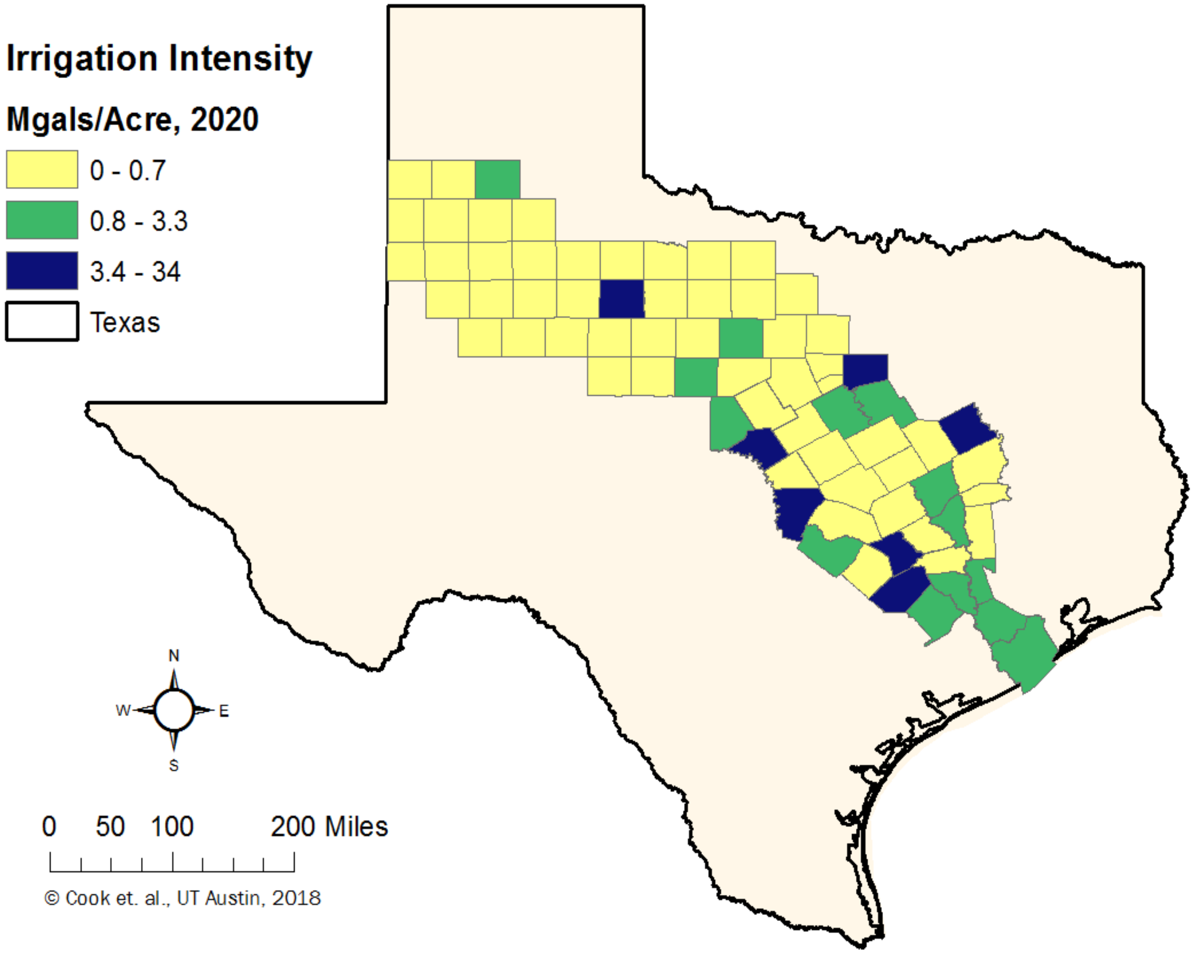

Figure 5.3: Water consumption per irrigated acre is shown for counties in the Brazos River Basin. Those irrigating at an intensity over 3.3 million gallons per acre are shown in dark blue. Those irrigating between 0.7 and 3.3 million gallons per acre are shown in green.

Water demand reduction potential of the municipal sector is also evaluated. The average system water loss is 16%, but potential losses could be decreased to approximately 4%. System water loss is identified through self reporting to the TWDB. More on this topic is included in Chapter 2 of this work.

Most systems exceed the target ideal water loss. Seven municipal water suppliers are identified with over 30% system water loss and another thirty-one municipal water suppliers with 15–30% system water loss in the Brazos watershed [193]. Of these systems, ten municipal water providers withdraw surface water from the Brazos River via water right and exceed 15% system water losses. Reducing water withdrawals to 15%, just below the national average, could save 12.5 billion gallons of water per year, as shown in Table 5.2. Reducing water losses to 5% of total, slightly above the ideal savings, could conserve 31.1 billion gallons of water per year, as shown in Table 5.2. These systems have an incentive to participate in a market that could help them reduce system loss, reduce money spent in treating unsold water, and profit from the water lease.

Additional water savings could be incurred at the municipal level through application of best management practices including private or public landscape programs involving improved monitoring or plant replacement. More on this topic is included in Chapter 2 of this work. Assuming an average amount of conserved water savings at municipalities with rights to water on the Brazos River, approximately 29.2 billion gallons of water could be saved per year, as shown in Table 5.2.

Water Consumption by Thermoelectric Power Plants

Power plants can reduce their water demand through use of more water-efficient cooling technologies, more efficient prime movers, and more water-lean fuels. Nine power plants in this basin use once-through (open-loop) cooling with or without

Table 5.2: Cases of municipal conservation assessed in the WAM/WRAP analysis of the Brazos River.

Municipal Cases	**Diversion [Mgal]**	**Control Points**	**Savings [Mgal]**
Municipal Case 1: Reduce Water Loss to 15%	12,533	10	438
Municipal Case 2: Reduce Water Loss to 5%	31,115	21	1,894
Municipal Case 3: Municipal Water Conservation	29,165	19	2,203

a cooling pond or recirculating (closed-loop) cooling with a cooling pond rather than more water-efficient systems–cooling towers, hybrid cooling, or dry cooling. Switching from once-through cooling to hybrid or dry cooling will not conserve consumed water. However, augmenting a cooling tower with a dry cooling system or switching to dry cooling could conserve water that would normally be evaporated out of the watershed. For this analysis, seven power plants are analyzed. Three power plants have open-cooling systems, meaning water saved could have been discharged and used by others downstream. In these cases, conserving released water could cause third party effects to downstream users. Four power plants have water-lean cooling towers but could conserve that consumed water in a water market environment. Four of the power plants are analyzed individually as the volume saved could supply the full demand of oil and gas activity in the northern Eagle Ford Shale. Three power plants are modeled together as a single analysis to provide a larger combined total water savings. Water savings for hybrid cooling replacements are assumed to be half of the original water diversion as is seen in the literature [152].

Water savings for dry cooling replacements are assumed to be approximately

10% of what a cooling tower would use. For power plants using a cooling tower, the diversion was reduced by 90%. For power plants using a once-through system, the consumption for dry cooling is calculated as that required for a cooling tower. An air-cooled power plant would likely use approximately 10% of that consumed by a cooling tower for its toilets and other on-site water demands [157]. The calculation for cooling tower water consumption is shown in Equation 5.1.

$$Q = \varepsilon f G \tag{5.1}$$

The calculation for dry cooling water consumption is shown in Equation 5.2.

$$Q = 0.1 \times \varepsilon f G \tag{5.2}$$

Using methods employed by [157], Q represents the annual diversion [gallons]. The constant ε is a dimensionless ratio of diversion over consumption for cooling towers, reported as 1.25 by Stillwell et al. 2011 [152]. The variable f represents water consumption for power generation [gallons/MWh], and G represents net generation at the power plant of interest [MWh]. Water consumption for power generation was determined as a function of fuel, cooling technology, and river basin using data for previous consumption reported to the Energy Information Administration [194,195]. Hybrid and dry cooling scenarios modeled in this analysis are shown in Table 5.3; estimated savings of switching cooling technology varies between 1.4 and 10.5 billion gallons of saved consumptive fresh water per power plant per year.

5.3 Water Allocation Model: WAM and WRAP

After identifying users, hydrologic water allocation model is used to assess the amount of available water that might be made available for other uses. Surface water use is the main focus as it is the main source of water for most users in the lower basin

Table 5.3: Cases of conservation of water consumption for thermoelectric power generation assessed in the WAM/WRAP analysis of the Brazos River.

Power Cases	**Diversion [Mgal]**	**Control Points**	**Savings [Mgal]**
Power Plants 1-3, Hybrid Cooling	3,626	3	1,813
Power Plant 4, Hybrid Cooling	11,275	1	8,766
Power Plant 5, Hybrid Cooling	7,553	1	3,777
Power Plant 6, Hybrid Cooling	4,301	1	2,151
Power Plant 7, Hybrid Cooling	2,737	1	1,369
Power Plants 1-3, Dry Cooling	3,626	3	3,358
Power Plant 4, Dry Cooling	11,275	1	10,486
Power Plant 5, Dry Cooling	7,553	1	6,798
Power Plant 6, Dry Cooling	4,301	1	3,871
Power Plant 7, Dry Cooling	2,737	1	2,725

and because it is consistent with the policy framework– Texas water law considers surface water and groundwater separately.

To conduct this analysis, an existing river basin-based model of Texas surface water rights holders is adapted: the Water Availability Model used in the Water Rights Analysis Package. A discussion of the WAM/WRAP model is included in Section 3.2.3. The model was developed by Wurbs [174] and is regularly used to assess water availability for application for water rights to rivers in Texas. In addition, the WAM/WRAP model was previously used to evaluate the technological and economic feasibility of alternative cooling technologies at thermoelectric power plants and an evaluation of changes in reliability of supply based on increased surface water storage [175]. Current conditions are modeled and then edited within the WAMS to reflect addition of temporary water rights users intended to reflect oil and gas water use and reductions in water demand at sites identified for water conservation and lease.

The WAM includes control points for water rights with diversion amount, location, and priority. A full execution of water rights is employed in this analysis. These conditions are modeled using the existing surface water diversions. The WAM is then amended to allow decreases in diversions at control points conserving water and increases in diversions at control points receiving saved water. After amending the WAM and executing the model using the Water Rights Analysis Package [174], results are organized using post-processing algorithms. A summary of each set of scenarios is included in Tables 5.1, 5.2, and 5.3.

5.4 Assessing Potential Costs and Benefits

5.4.1 Water Deliveries

As shown in Table 5.4, all scenarios could provide millions of gallons of saved water, ranging from 356 million to 10.5 billion gallons of water depending on the user and conservation method. However, costs of conservation vary as shown in Figures 5.9, 5.10, 5.11. Similarly, the benefit of implementing conservation strategies for the original water right holder varies, as well, as shown in Tables 5.5, 5.6, and 5.7.

5.4.2 Reliability, Resilience, and Vulnerability

Results of the WAM executions for each scenario are evaluated based on statistical parameters: reliability, resilience, and vulnerability. A discussion of the mathematics and importance of these parameters is included in Section 3.2.5.

In most cases, basin-wide reliability, resilience, and vulnerability is unchanged when comparing current conditions to cases of conservation, lease, and use in downstream oil and gas operations because changes for individual users are averaged across all users. However, for the agriculture cases, under increased irrigation conservation (Agriculture Case 1), basin-wide reliability decreases by 2% and resilience decreases by 1% for the entire period 1940–1997. Under drought conditions, reliability decreases. For the drought of record period, 1950–1957, reliability decreases by 3% compared to current conditions. Agriculture Case 2 also sees a decrease of 1% in basin-wide reliability during drought conditions.

Third party effects are not apparent when viewing reliability, resilience, and vulnerability only at the basin scale. Instead, these results are able to be displayed graphically using ESRI ArcGIS geographic information systems. Instream flows could benefit from upstream releases to downstream buyers or could be impacted by these

Table 5.4: Average Volume Supplied by Conservation Cases.

Conservation Cases	**Average Volume Supplied [Mgal]**
Power Plants 1-3, Hybrid Cooling	1,813
Power Plant 4, Hybrid Cooling	8,766
Power Plant 5, Hybrid Cooling	3,777
Power Plant 6, Hybrid Cooling	1,963
Power Plant 7, Hybrid Cooling	1,368
Power Plants 1-3, Dry Cooling	3,358
Power Plant 4, Dry Cooling	10,486
Power Plant 5, Dry Cooling	6,798
Power Plant 6, Dry Cooling	3,871
Power Plant 7, Dry Cooling	2,725
Municipal Case 1	420
Municipal Case 2	1,893
Municipal Case 3	2,219
Agriculture Case 1	4,109
Agriculture Case 2	356

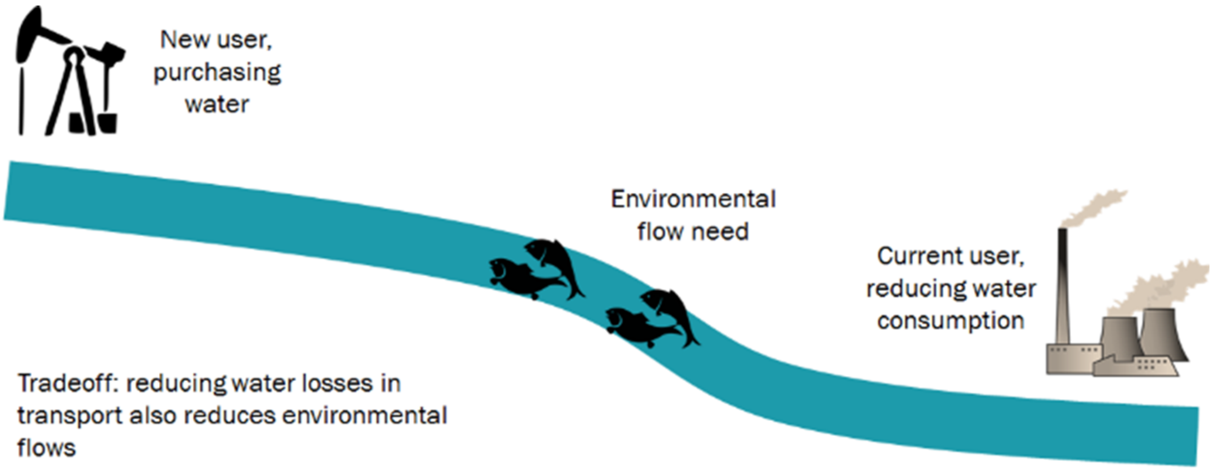

Figure 5.4: Trading could cause negative impact on instream flows due to moving water withdrawal control points upstream to supply water trades.

flows due to moving water withdrawal control points upstream to supply water trades. Figures 5.4 and 5.5 show the theoretical effect of such trades. The negative impact on instream flows is a cost that trades in an unregulated market do not take into account.

Examples of the application of the performance parameters reliability, resilience, and vulnerability are shown in Figures 5.6, 5.7, and 5.8. Figure 5.6 shows a general increase in reliability, or frequency to receive demand in full, for many individuals in the basin. Figure 5.7 shows a general decrease in resilience, or ability to recover after a deficit, for many individuals in the basin. One consideration in the calculation of resilience is when reliability increases, resilience might decrease simply as a result of less deficit periods occurring. Figure 5.8 shows some users experiencing small increases or decreases in vulnerability compared to the baseline, meaning deficits increase or decrease on average, respectively, for the individual users in question.

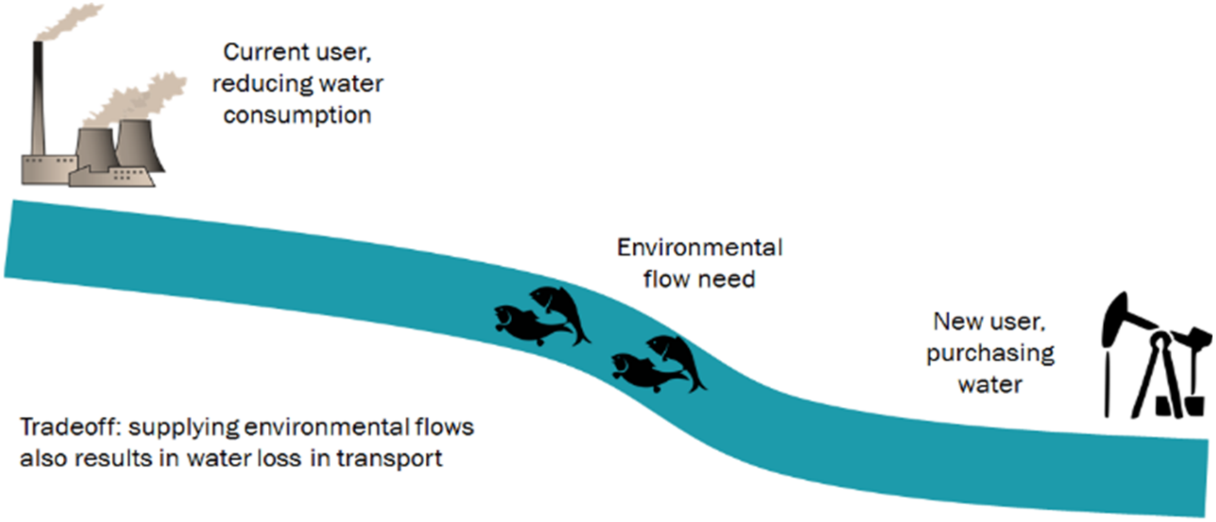

Figure 5.5: Trading could create a benefit for instream flows due to upstream releases to downstream buyers.

5.4.3 Costs and Benefits of Water Sales

The cost of conserving water in agriculture fluctuates by technology and management method. Figure 5.9 includes costs for irrigation best management practices possible for Brazos valley irrigators, as well as the general cost of agriculture conservation ascribed by the Texas Water Development Boards State Water Plan for 2017. These costs are compared to the range of prices for water seen in the oil and gas sector.

The cost of water loss reduction varies, as well. The San Francisco Public Utilities Commission, Nashville Public Works, and Las Vegas Valley Water District performed detailed water audits, detected, and repaired leaks for a total of \$1,347, \$976, and \$1,424 per million gallons, respectively [196]. Detecting and repairing leaks at the Los Angeles Department of Water and Power cost \$1,065 per million gallons saved [196]. Water loss and control programs at the California Department of Water Recourses, Orange County Utilities, and another large utility in the western United

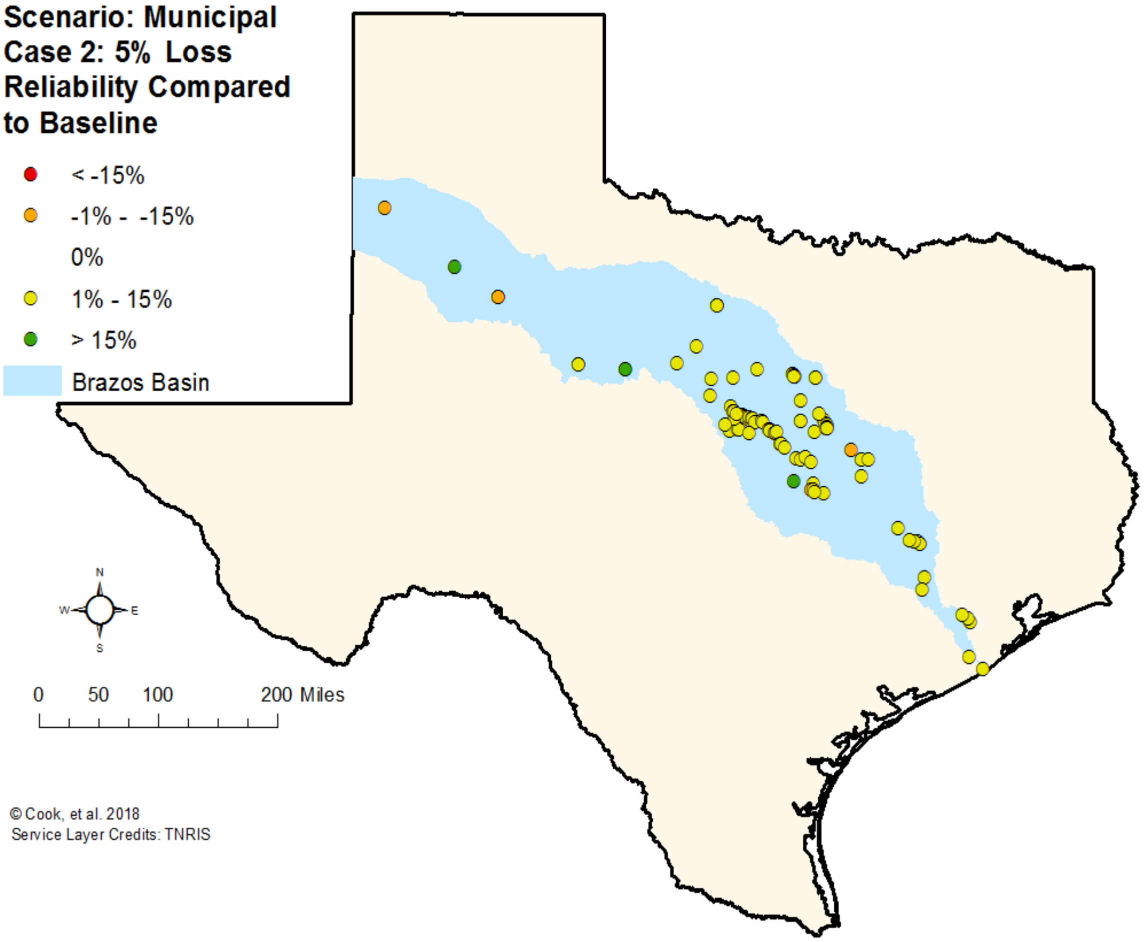

Figure 5.6: After trading for saved water under Municipal Case 2, many users benefit from improved reliability and some users experiences reduced reliability. All decreases in reliability are under 15% compared to the baseline.

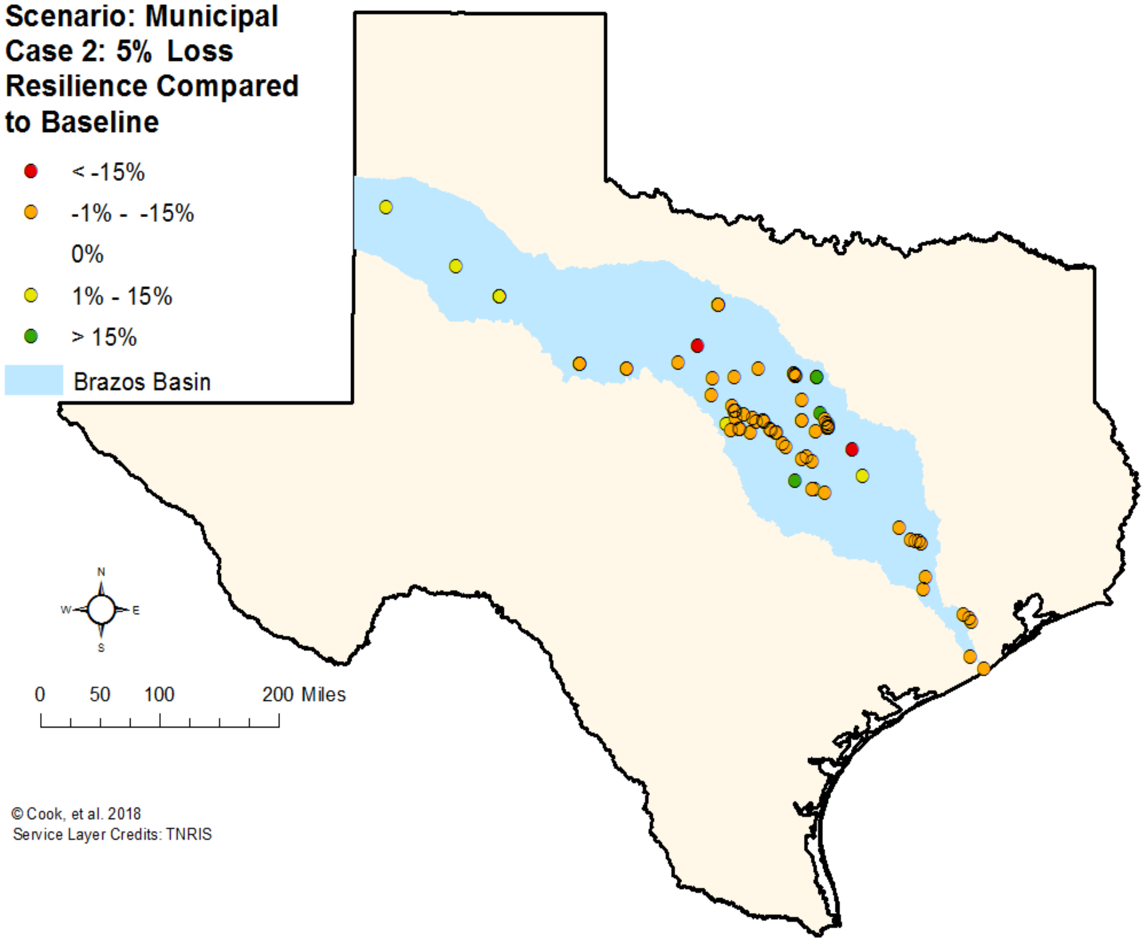

Figure 5.7: After trading for saved water under Municipal Case 2, many users benefit from improved resilience and some users experience reduced resilience. Two users experience large reductions in resilience (more than 15% compared to the baseline).

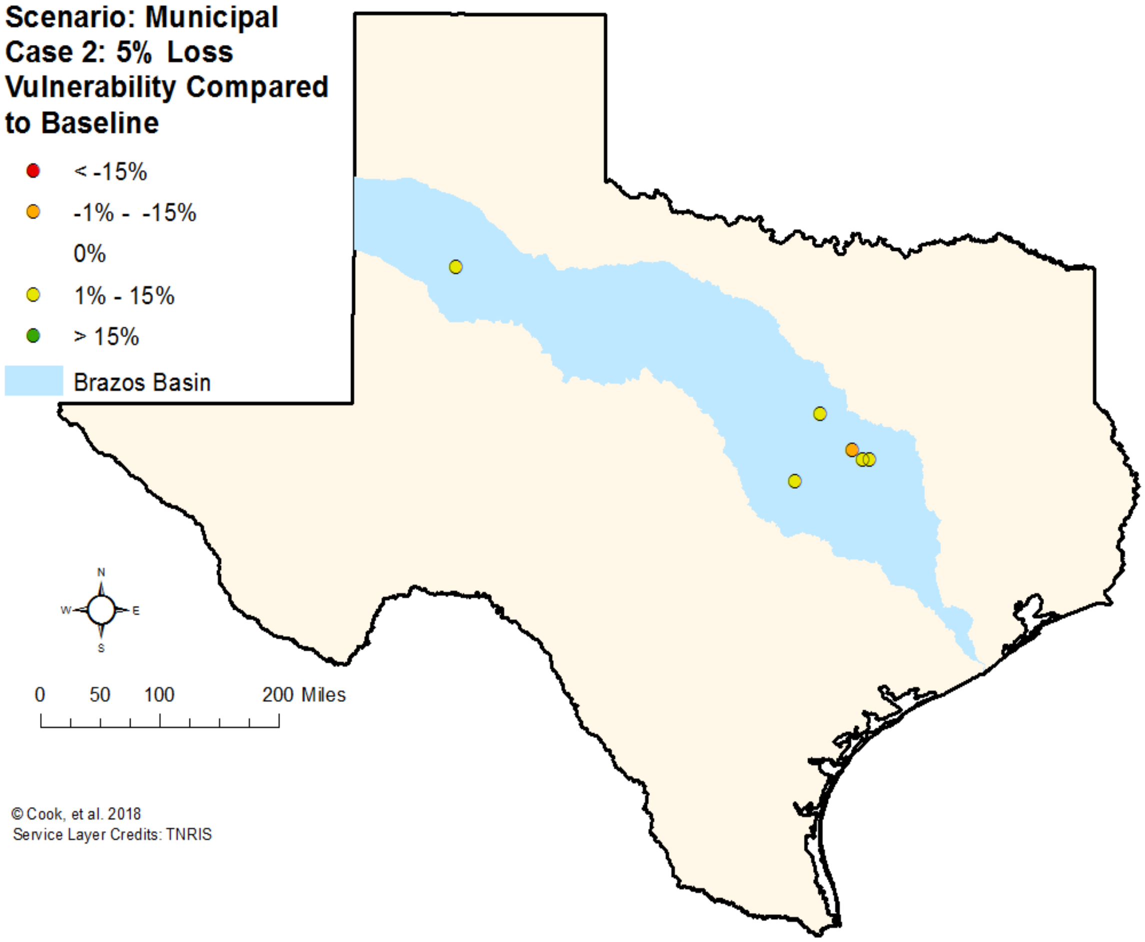

Figure 5.8: After trading for saved water under Municipal Case 2, some users experience a small increase in vulnerability (less than 15% compared to baseline). One experiences a small decrease in vulnerability.

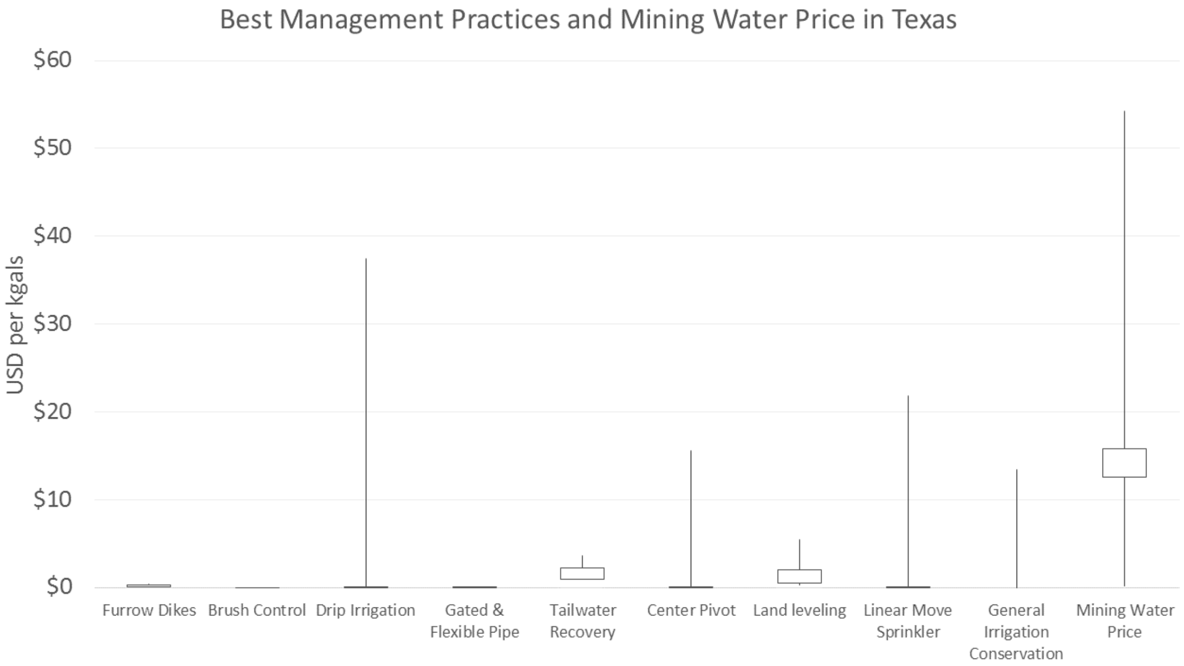

Figure 5.9: Cost of irrigation best management practices varies but is, generally, much lower than the price paid for water used by oil and gas operators.

States cost \$2,019, \$1,421, and \$976 per million gallons saved [196]. Low end for Texas which estimates water loss control and reduction at an average \$4,588 per million gallons of water saved per year (assuming a 60 year planning period) [21]. Texas estimates are used in this chapter.

The cost of saving water through specific landscape programs that incentivize replacement of turfgrass for native plants (cash-for-grass) was evaluated in select programs across the United States by Hilaire et al. in 2008 [115]. Costs range from \$0.55 (Albuquerque, NM) to \$1.33 (El Paso, TX) per square foot of grass [115]. Annual calculated water savings ranged from 18–62 gallons per square foot of turf [115]. Cost per thousand gallons of water saved is \$21 in North Marin Water District, CA and Southern Nevada, \$29 in Albuquerque, NM, and \$74 in El Paso, TX [115]. The Southern Nevada Water Authority helped replace 125 million square feet of turf, saving nearly 7 billion gallons annually [102]. More recently, San Antonio, TX offered \$100 per 200 square feet (\$0.50 per square foot) for up to 1,600 total square feet of lawn replacement with a required irrigation audit before and after lawn replacement [197]. Assuming a similar range of water savings seen in 2008, this water replacement program would result in a cost of \$8–28 per thousand gallons saved. These costs are updated to the 2018 value of the dollar and reported in Figure 5.10.

Technology changes at power plants are expensive decisions. Moreover, water-lean thermoelectric power cooling technologies have an efficiency penalty on the heat rate of the plant, and therefore require more fuel per unit of energy generated [157]. The cost of replacing cooling technologies, including the expense of an efficiency penalty, is calculated using values reported in Stillwell and Webber, 2013 [198] and is included in Figure 5.11. It is assumed that the power plants using hybrid cooling would implement a dry cooling system in addition to the current wet cooling tech-

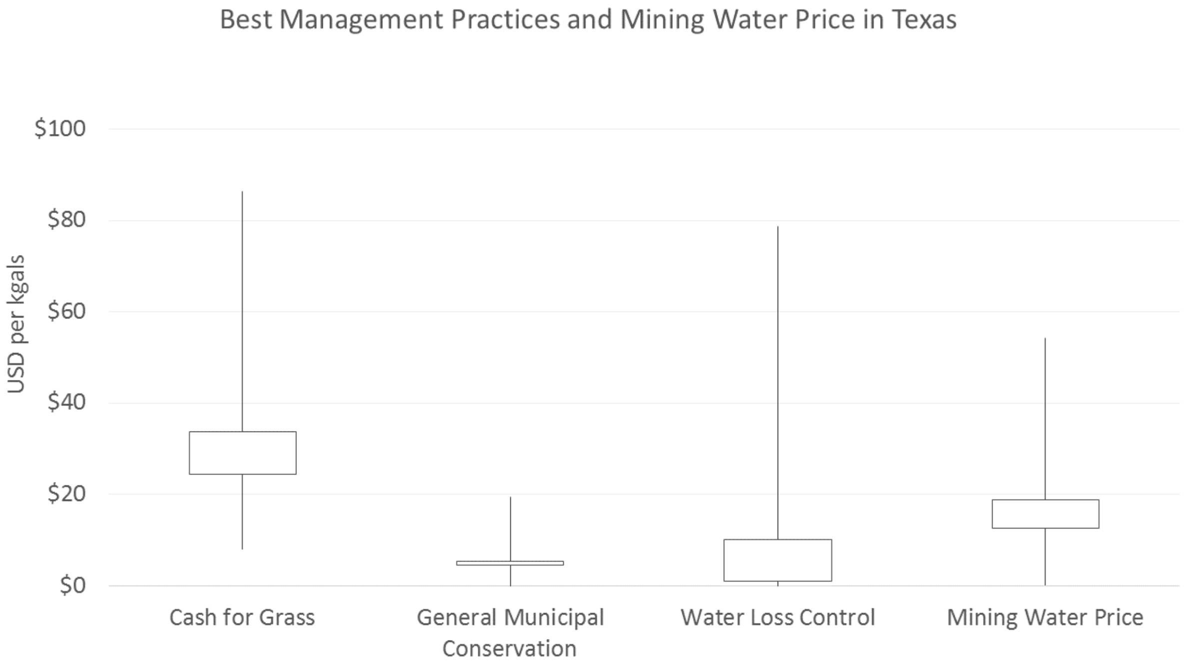

Figure 5.10: Cost of municipal best management practices and water loss reduction and control could potentially be offset by the price paid for water used by oil and gas operators. However, in some cases the cost for conservation is greater than price of water.

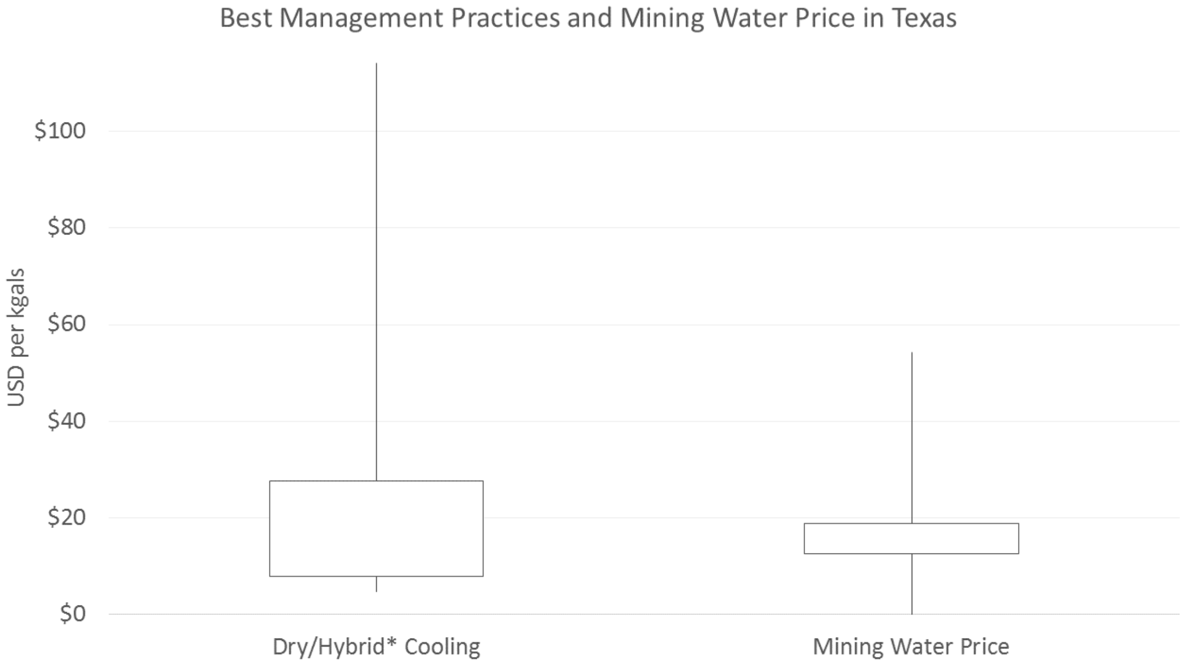

Figure 5.11: Cost of retrofitting a power plant with dry cooling or hybrid cooling technology is, generally, greater than the price paid for water used in oil and gas operations.

nology. Therefore, the cost of hybrid cooling in this study is assumed to be the same as the cost for dry cooling. However, in situations where a wet cooling system is also required, the cost for hybrid cooling will be greater than that for wet cooling [198].

Generally, even at a low price paid for water by oil and gas operators, agriculture technology costs could be covered in whole at a payback period of ten years and an interest rate offered by the TWDB, as discussed in Section 3.2.4. Municipal water conservation and in some cases, municipal loss repair, could also be paid for by the price paid by oil and gas operators. However, in very few cases would a replacement of cooling technology be offset by the price paid for water. In a market environment in which least cost options are selected first, oil and gas operators would likely select conservation of agriculture, then municipal uses and losses, and finally water consumed by power plants.

5.4.4 Profits for Water Trades

To determine economic benefit of conserving water, the cost to conserve water is determined and compared to the price of water as determined in Section 3.2.4.

The net profit of water lease, π, is calculated as the benefit of leasing water (price of water, p, multiplied by the volume of water sold, V) less the cost of water savings (cost per volume of water saved C_{vol} multiplied by the volume of water conserved, V_{ws}). Profit calculated for each irrigation BMP in this chapter is shown in Table 5.5. As outlined in Chapter 4, foregoing the profit of growing agriculture with water and selling it yields a net profit of \$13.82 under a high oil price scenario and \$6.42 under a low oil price scenario (50% of the price reported by Cook and Webber 2016 [171]). All options for agriculture conservation analyzed yield a profit in a water trade. Six options yield an increased profit over the baseline. The cases analyzed in the WAM/WRAP allocation analysis are technology agnostic, so any of the six options in Table 5.5 could be used to save and sell water at a profit.

Profit calculated for each municipal BMP in this chapter is shown in Table 5.6. The lost cost of water associated with selling without conserving in the baseline scenario is estimated from the average water rate for 2017, \$37.31 per 5,000 gallons. Under a hypothetical scenario in which water is sold to oil and gas operations rather than selling to a municipal use, there is foregone profit associated with the sale that yields a net profit of \$7.37 under a high oil price scenario and a loss of \$0.03 under a low oil price scenario (50% of the price reported by [171]). Two of the three municipal conservation options yield a profit in a water trade and an increased profit over the baseline. Municipal cases 1 and 2 analyzed in the WAM/WRAP represent reductions in water loss, and municipal case 3 represents general conservation. All three cases

Table 5.5: Profit associated with conserving and selling water to oil and gas operations are shown for low and high oil price scenarios. Profits are reported as U.S. dollars per kgal, in terms of seller's benefits. Six options for agriculture water conservation yield a profit in a water trade.

BMP	**Cost to Conserve [$/kgal]**	**Low Oil Price [$/kgal]**	**High Oil Price [$/kgal]**
Furrow Dikes	$0.23	$7.17	$14.57
Brush Management	$0.01	$7.39	$14.79
Drip/micro-irrigation	$0.11	$7.29	$14.69
Gated and flexible pipe for field water distribution systems	$0.07	$7.33	$14.73
Tailwater recovery	$2.23	$5.17	$12.57
Center pivot sprinkler	$0.04	$7.36	$14.76
Land leveling	$1.98	$5.42	$12.82
Surge flow	$0.07	$7.33	$14.73
Sell		$6.42	$13.82

Table 5.6: Profit associated with conserving and selling water to oil and gas operations are shown for low and high oil price scenarios. Profits are reported as U.S. dollars per kgal, in terms of seller's benefits. Two options for municipal water conservation yield a profit in a water trade.

BMP	**Cost to Conserve [$/kgal]**	**Low Oil Price [$/kgal]**	**High Oil Price [$/kgal]**
Cash for Grass	$37.43	($30.03)	($22.63)
General Municipal	$4.89	$2.51	$9.91
Water Loss	$4.12	$3.28	$10.68
Sell		($0.03)	$7.37

result in increased profit over the baseline.

Profit calculated for selling water saved from dry or hybrid cooling is shown in Table 5.7. The lost cost of water associated with selling without conserving in the baseline scenario is estimated from the water consumption per mdalegawatt-hour (MWh) generated and the value of energy generated in the Electric Reliability Council of Texas in 2017 (27.47 $/MWh). Under a hypothetical scenario in which water is sold to oil and gas operations rather than used to cool a power plant generating electricity, the sale yields a net loss of $13.51 under a high oil price scenario and a loss of $20.91 under a low oil price scenario (50% of the price reported by [171]). Even under the lowest value of water, shown in Table 5.7, conserving and selling water from thermoelectric power plants does not generate a profit for the power plant in a water trade.

Table 5.7: Profit associated with conserving and selling water from thermoelectric power plants to oil and gas operations are shown for low and high oil price scenarios. Profits are reported as U.S. dollars per kgal, in terms of seller's benefits. Conserving water used for thermoelectric power does not generate a profit in a water trade.

BMP	**Cost to Conserve [$/kgal]**	**Low Oil Price [$/kgal]**	**High Oil Price [$/kgal]**
Dry/Hybrid Cooling	$25.50	($18.10)	($10.70)
Sell		($20.91)	($13.51)

5.4.5 Transaction Costs

There will be transaction costs associated with water traded in a market on the Brazos River. Specifically, some oil and gas wells are closer to the river than others. While some wells could experience lower conveyance costs associated with retrieving water from the Brazos River. Conveyance costs could be quite high for wells up that are up to 30 miles from the main river. Depending on the type of water transfer used and whether multiple wells operate separately or together to transfer water, the cost of transferring traded water might make total water costs prohibitive, negating any benefits of trading water in a market.

Transition costs in a relatively unregulated, unmonitored market such as the Brazos will likely be higher than those in the active market of the Rio Grande Valley. Under all conditions, a site-specific water audit or technical analysis should be conducted to determine actual costs and savings. This site analysis is part of the transaction costs associated with a water transfer. In addition, in some cases, there will also be non-beneficial third party effects. The newly instated water master could play a role in monitoring and mitigating these costs and externalities as well as in outlining property rights and assessing and disseminating water supply and trade information to reduce the costs of these externalities and streamline a market environment.

Managing water through a watermaster incurs administrative costs. TCEQ allocated 1.3 million U.S. dollars between 2014 and 2015 towards creation of a new watermaster on the Brazos River in Texas [192]. Water right holders see an additional transaction cost via an annual fee of $50 plus a use fee based on authorized amount of water and type of use [199]. In other basins, costs imposed by current institutional choices on future efforts to reverse or alter water use patterns and infrastructure, otherwise known as institutional lock-in costs, prevent changes to the system [168].

However, keeping the Texas legal system in its current status as an unregulated market, potentially resulting in depleted aquifers and impacts on estuaries, is a cost of its own [166,200]. Prior appropriation yields third party effects on junior water rights holders, especially if trade moves water downstream of junior water right holders [200]. In a correlative right system like the Lower Rio Grande Valley, all users share in losses or gains in supply due to drought or precipitation and water shortages are not unequally applied to those newer users [200]. Water markets are more economically efficient and provide private and social benefits compared to policies encouraging irrigation efficiency through subsidies [83]. A step change in policy similar to that used in Australia might be necessary to change Texas' water policy direction toward a system more favorable to market transactions [168]. Iterative reforms, including informal trading, diversion limits, water rights reform, and adaptation, took hold over three decades in the Murray-Darling Basin in Australia [168]. If this gradual policy development is used as an example in Texas, policies should be directed at water trade while minimizing concerns over where the water goes or how it is used [200]. Effective institutional investment in transition costs yields stable transaction costs [165].

5.5 Discussion

Of the four research questions laid out in Chapter 1, questions 1, 2, and 4 were explored in this chapter in the context of the Brazos Basin. To summarize, (1) options are available to reduce fresh water use in the Brazos Basin, (2) low cost conservation options are available within the agriculture and municipal sectors but not within the thermoelectric power sector, and (4) if the energy sector paid for water, the low-cost fresh water reduction methods available could be implemented economically and offset billions of gallons of demand for oil and gas operations.

In this analysis, scenarios are evaluated to assess potential for trading water savings from the agriculture, municipal, and thermoelectric power sectors for use in oil and gas operations. Results show that, generally, irrigation conservation methods are the least cost choice, followed by municipal conservation, and then water conservation in thermoelectric power. Low-cost scenarios could provide between 356 million and 4.1 billion gallons of water, depending on the user and conservation method. Thus, under water trading scenarios, agricultural and municipal users could increase profits by conserving consumptive uses and selling to oil and gas operations.

This work highlights best management practices (BMPs) that result in a benefit to the agriculture or municipal water user. On average, the use of irrigation BMPs to reduce fresh water consumption could be accomplished at a net economic benefit to the irrigator. However, tailwater recovery and land leveling are more expensive methods; the cost of each is sometimes offset by the price of water but not at a benefit to the irrigator over only selling their water. Reducing municipal water losses, reducing turfgrass water use for public landscapes, or implementing rebate programs for home appliances could result in profitable water savings at the municipal level. However, cash-for-grass programs and conservation in the thermoelectric power sector are not profitable at current water prices (though they might be valuable options for municipalities to consider under increased price or water stress scenarios as they provide significant amounts of water).

Reliability, resilience, and vulnerability of supply are evaluated to determine the effect on water users within the Brazos Basin. System level reliability and resilience is unchanged in most scenarios. However, in the agriculture cases, reliability decreases during drought years. In agriculture case 1, reliability and resilience both decrease at the system level for all years. In addition, individual users experience mixed effects. Vulnerability is generally unchanged at the system level. As is mentioned in Chapter 4, evaluating water allocations in terms of these performance parameters allows planners to assess the likelihood of failure to water meet demand (deficit), recovery from previous deficit, and average magnitude of deficit; consideration of these metrics helps in addressing negative consequences of reallocation of water resources.

Finally, this analysis does not address administrative transaction costs or the additional negotiation, capital, and operations expenses. Transaction costs should be evaluated before engaging in water conservation surplus trading. Moreover, because costs and third party effects of existing reallocations are unmeasured, existing externalities are currently unmitigated. Future work should consider these costs and externalities and determine methods to address them. Similarly, this analysis does not address the political favorability that might be required to engage in public water conservation with the intent to trade savings to another sector, a component that should be included in future analysis of water savings potential, as well.

Chapter 6

Objective 4: Groundwater Market

6.1 Apply the Model to a Groundwater and Alternative Source Market

The Permian Basin resides in drought-prone West Texas where many of the area's reservoirs were less than 3% full in 2014 [201]. The Permian Basin sits under the Ogallala Aquifer in the northern part of the basin and under the Edwards-Trinity Aquifer in the southern part of the basin. Landowners selling fresh water to oil and gas operations supply water from these two aquifers.

The Permian Basin has historically experienced ups and downs of oil production. With the increase of hydraulic fracturing, horizontal drilling, and discoveries of now economically accessible reserves, oil production has increased. With increasing production comes an increase in water use and water purchases. The market for groundwater in the Permian Basin is assessed with special consideration of Groundwater Conservation District (GCD) policies on withdrawal and export.

Because of the groundwater policy system in Texas, discussed in Chapter 2, unregulated groundwater marketing leads to over-extraction of the resource. Use of alternative water sources, treated and marketed for use for oil and gas activities in the Permian Basin, could provide a potential remedy to this groundwater extraction. Use of non-fresh water resources could be achieved at a cost lower than the price paid for fresh groundwater, reducing the third-party effects of fresh groundwater use on aquifers in that region, including potential drawdown and increased energy costs for pumping.

6.2 Market Framework and Participants

6.2.1 Groundwater Policy: Rule of Capture and Groundwater Conservation Districts

The Permian Basin region is supplied mainly by fresh groundwater. In contrast to its governance of surface water, the State of Texas does not incorporate permitting or judgments on reasonable use of water into its groundwater policy. Groundwater in Texas follows the Rule-of-Capture, attributing the right to withdraw groundwater to the landowner residing above that water and providing that, absent malice or willful waste, landowners can withdraw as much water as they want without incurring liability, even if that withdrawal will inhibit access to water by neighboring landowners [47]. More discussion of the Rule of Capture, in context with other groundwater policies is included in Chapter 2.

Because groundwater is a property right, it can be bought, sold, or traded. However, no explicit allocation is attributed to these rights. Meaning, due to knowledge that neighbors might exploit or sell the shared water beneath their land, no single user has an incentive to conserve water for later use [49]. Landowners are instead inclined to over-exploit their groundwater resources [49].

A groundwater conservation district (GCD) authorized by the Texas Legislature can protect and manage groundwater resources to maintain supplies in the area [202]. These districts have the ability to require permits and to place reasonable restrictions on water withdrawals or well location [203]. Unless restricted by a GCD or other authority, landowners may withdraw as much water as they need.

Not all areas of the state have GCDs, nor are all areas of the Permian Basin regulated by GCDs, either. Moreover, water regulations vary by GCD. The Texas

Association of Groundwater Districts surveyed GCDs about their policies to determine the patchwork of regulations at GCDs across the state. Results show that ten GCDs set regulations for water use for hydraulic fracturing in the Permian Basin as of 2014. Four others were considering regulations at the time. Of the GCDs without regulations, five consider hydraulic fracturing operations within their district to be significant. Nine have what they consider to be minimal amounts of hydraulic fracturing. Some GCDs set limits on water production in volume per area per year. Other limitations might be beneficial use, reasonable use, or available water. Some have no limits. Eight GCDs in the Permian Basin set production limits between 0.18–1.24 cubic meters per square meter per year. GCDs in the Permian Basin set other limits. The remaining GCDs do not limit water production. Eleven GCDs limit groundwater export from their jurisdiction.

Regulations by GCDs allow water use and potential marketing while limiting over-exploitation. They can also limit a market by requiring permits or levy fees for water exported out of the district [204–206]. While statewide water trades are made more difficult, the rules do not inhibit market activity on the regional level within a district. The Edwards Aquifer Authority is an example of a functioning groundwater market [204]. To address third-party effects of groundwater transfers in the Edwards Aquifer, a groundwater right holder cannot sell or lease more than fifty percent of their irrigation rights [204]. This policy is not in effect in other groundwater conservation districts, meaning third parties could be impacted without options for recourse.

6.2.2 Market Participants

Hydraulic fracturing is common in the Permian Basin with some counties using between 10^8 and 10^9 gallons in 2011 and more estimated for later years. Water demands are supplied by landowners with groundwater rights. As discussed in Chapter 2, compared to the volume injected in hydraulic fracturing oeprations, a large volume of flowback and produced water (FP) returns to the surface in the Permian Basin. Treatment without removal of dissolved solids (clean brine), including clarification and dosing of chlorine dioxide has been shown to be applicable for reuse in oil and gas operations [207]. In addition, brackish groundwater and municipal effluent provide other alternatives to fresh groundwater in the area. As discussed in Chapter 2, some entities use already have contracts for use of municipal effluent.

6.3 Water Allocation Model: Location-Allocation

As mentioned in Chapter 2 and Section 3.2.3.3, groundwater is not allocated by any policy in Texas. Fresh groundwater and alternative resources are reallocated from sources based on price. To simulate this price-induced reallocation, a model of water supplies and demands is constructed within ArcGIS using the location-allocation network analysis for the Spraberry trend in the Permian Basin in Texas. An explanation of the algorithms used in location-allocation is included in Section 3.2.3.3. A discussion of the network, facilities, demands, and allocation scenarios in the location-allocation is included in this section.

6.3.1 Network

Assuming water moves by truck or pipe and pipes can be networked along the right-of-way of roads, the base network in this location-allocation problem set for water allocation is the system of roads in the State of Texas as reported by the Texas Department of Transportation (TxDOT) [26], as shown in Figure 6.2.

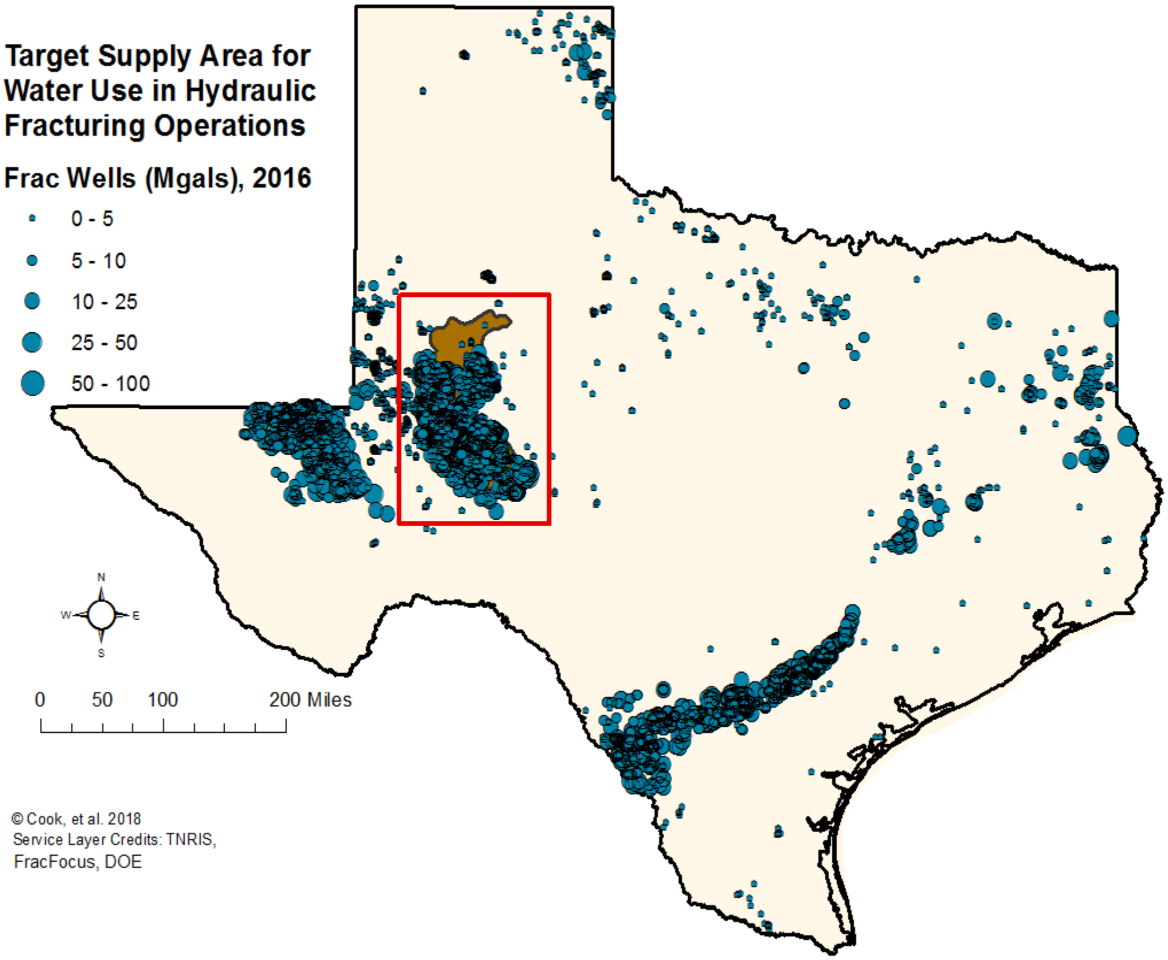

Figure 6.1: The target area for the location-allocation network analysis is the Spraberry trend in the Permian Basin. Wells shown in this figure are reported by FracFocus [24, 25].

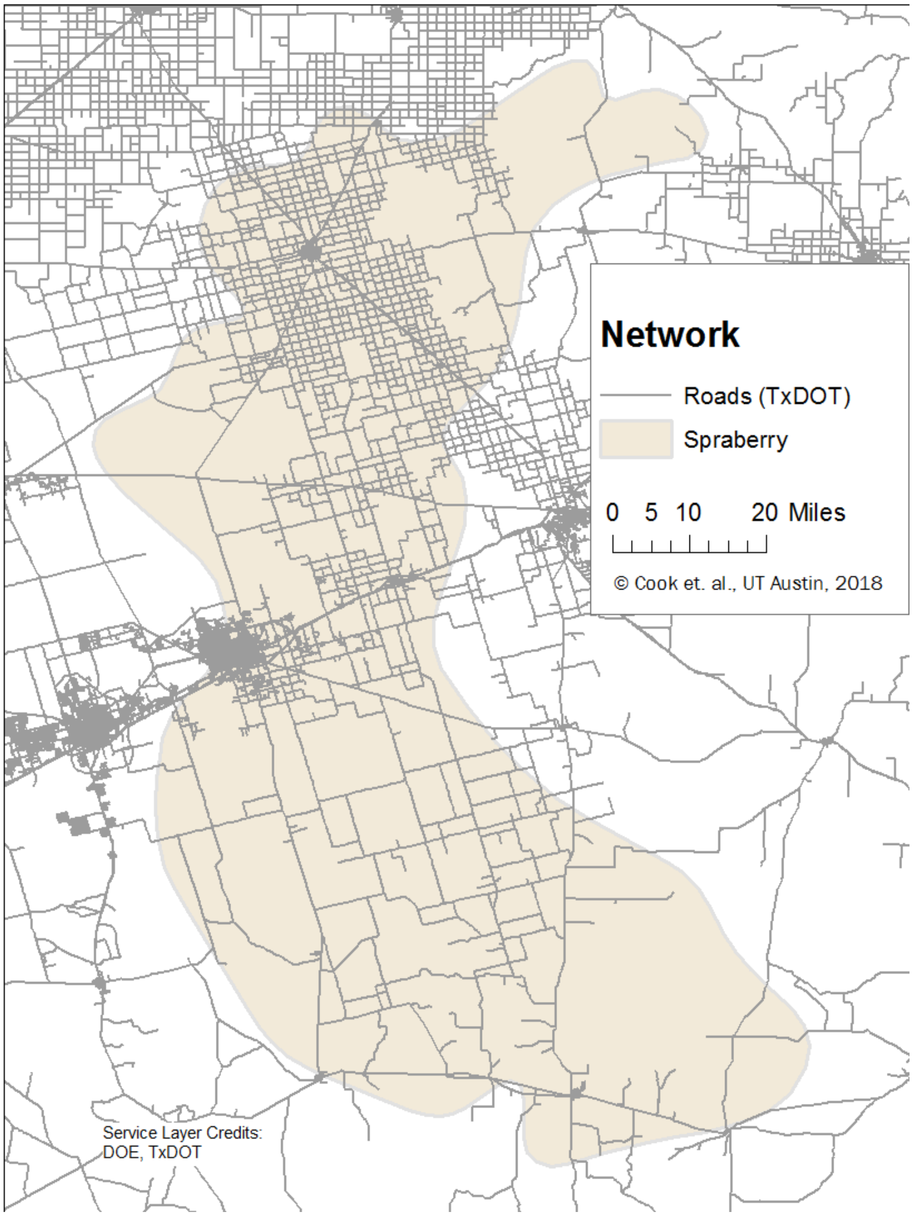

Figure 6.2: The base network for the location-allocation network analysis is the TxDOT road system [26].

6.3.2 Demands

Demands in this analysis are simulated from past water demands for hydraulic fracturing reported to FracFocus [24], as shown in Figure 6.3. Water demands are simulated using frac water demands from 2016 and are limited to the Spraberry trend in the Permian Basin of West Texas, an active location for oil and gas activity even during the reduction in activity caused by the low price of oil.

6.3.3 Facilities

This work depends on detailed facility information. Modeled facilities are sources of water including:

- fresh and brackish groundwater (locations collected TWDB [27]),
- municipal wastewater treatment plants (discharge information collected by [208], locations reported by [209], and
- supplies of oilfield wastewater injected into disposal wells (locations and supplies collected by the Railroad Commission and curated by DigitalH2O [28]).

Water is allocated from these facilities to demand sites. Simulation of price-induced water allocation assumes no existing contracts with landowners, which is not true in practice, and that companies can share water resources and treatment plants, which might or might not be true in practice.

Groundwater Supplies

Default fresh groundwater well capacities are set to be proportional to the modeled available groundwater (MAG) set forth to achieve the desired future conditions (DFC) for the aquifer within each groundwater conservation district (GCD). A

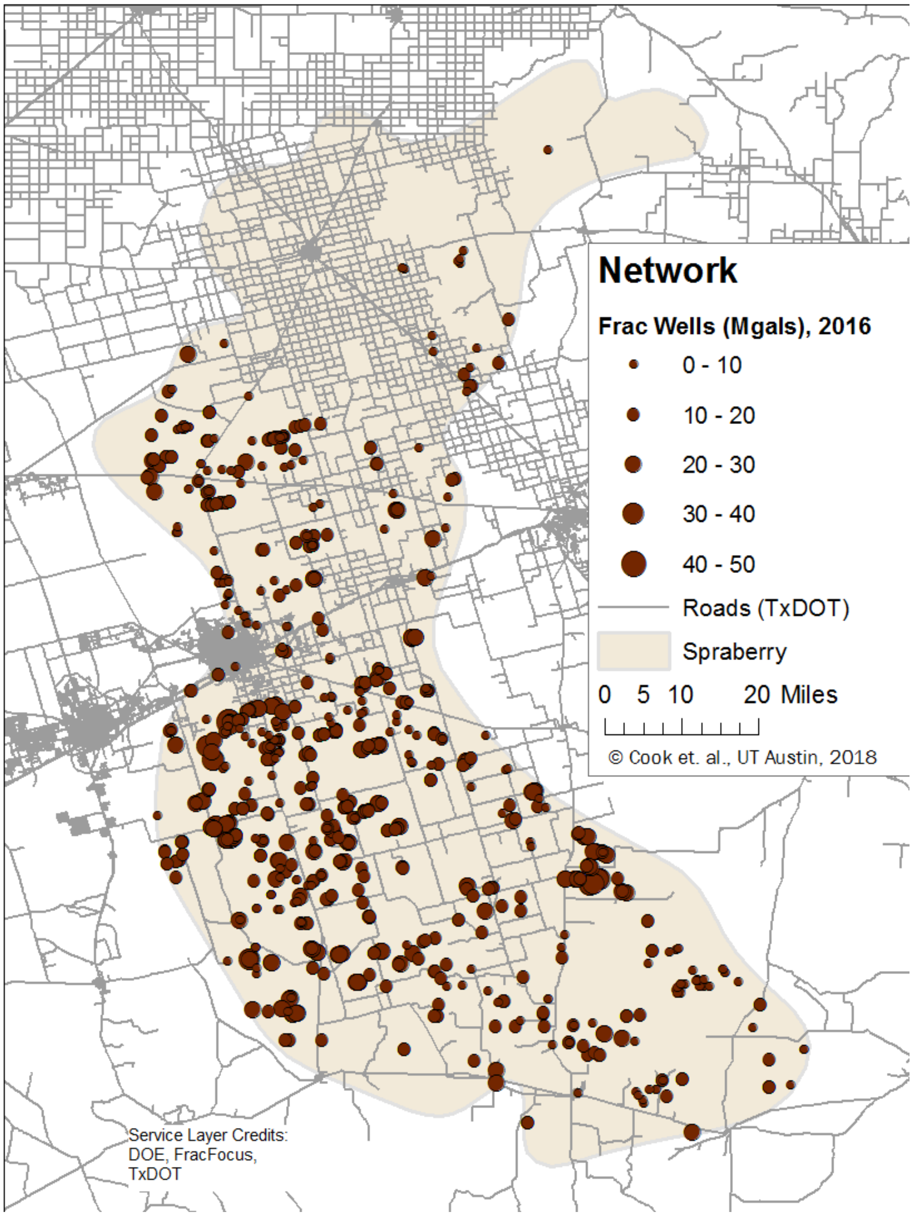

Figure 6.3: Water demands for wells hydraulically fractured in 2016 are used as a proxy for future demands in the location-allocation network analysis [24].

discussion of the DFC and MAG process is included in Section 3.2.3.3. However, in this analysis as in practice, groundwater wells are allowed to exceed capacity because there is no existing policy limit on the amount of fresh groundwater that can be withdrawn despite a common goal of conservation. Because of this condition, groundwater over-extraction compared to the MAG is analyzed later in this chapter.

Brackish Groundwater Supplies

Brackish water supplies are unknown in Texas but assumed to be abundant. Therefore, brackish groundwater supplies are assumed to be much larger than water demand and no capacity is set. Effluent supplies are assumed to be the permitted volume of effluent as reported by the Environmental Protection Agency.

Flowback and Produced Water Supplies

Oilfield operations produce wastewater, as discussed in Chapter 2. Supplies reported as disposed in 2016 are shown in Figure 6.6.

A multitude of options exist for recycling and resupplying flowback and produced water (FP) for use in oilfield operations. For this analysis, FP water is assumed to be sent to existing disposal well locations (receiving), treated, stored, and then sold for reuse in another hydraulic fracturing treatment. This analysis assumes construction of centralized oilfield wastewater treatment facilities, the cost of which is covered through payment of water and what would have been disposal. Receiving facilities are assumed to be able to transport to and from centralized treatment facilities. Treatment facility locations were chosen in a separate location-allocation analysis weighted to the disposal and frac volumes–those those would participate directly in use of treatment facilities, thereby reducing cost to transport water to and from treatment. Figure 6.7 shows the set-up of such a scenario.

A centralized treatment program was chosen because of the ability to treat and

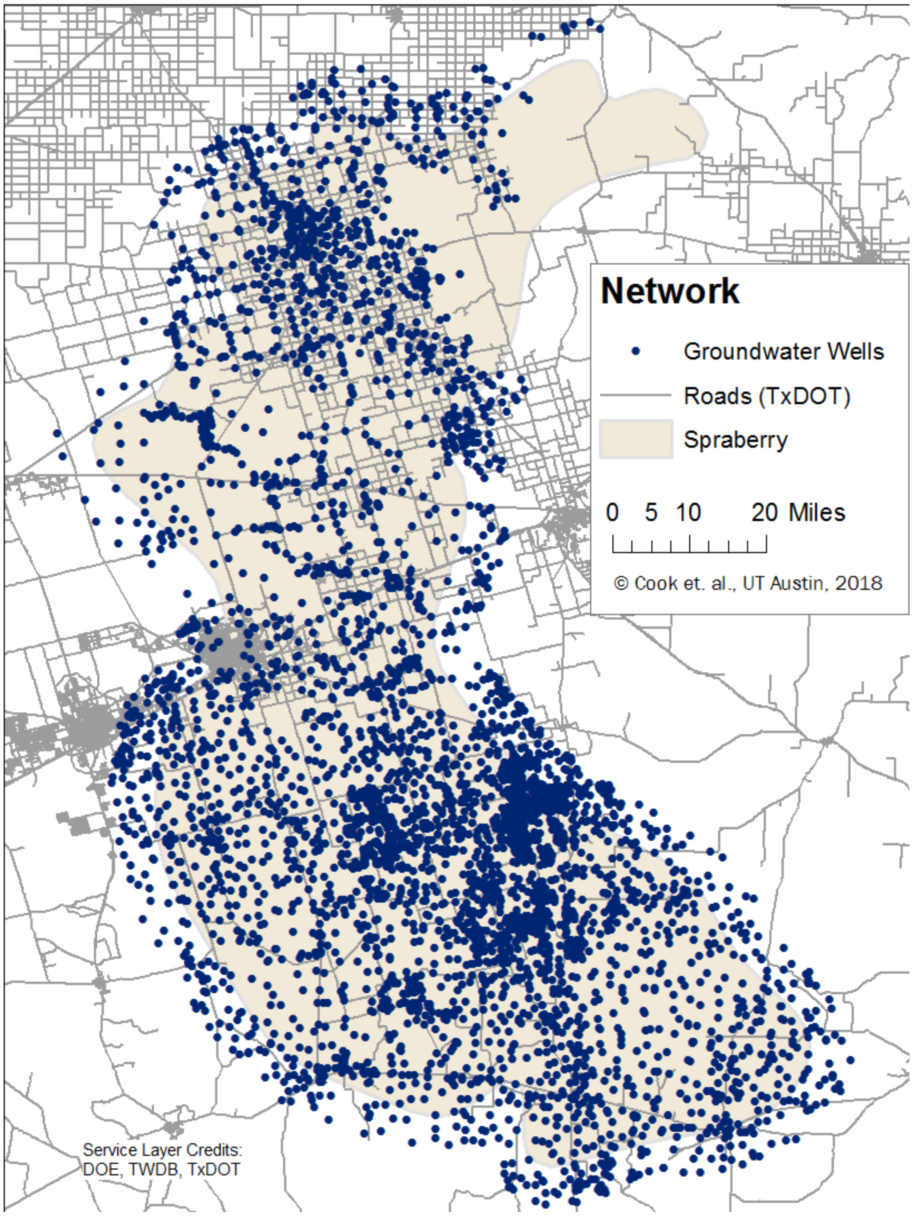

Figure 6.4: Fresh groundwater wells are common throughout the Spraberry trend, with a larger concentration in the southern portion of the region [27]. Wells are used as source facilities in the location-allocation network analysis.

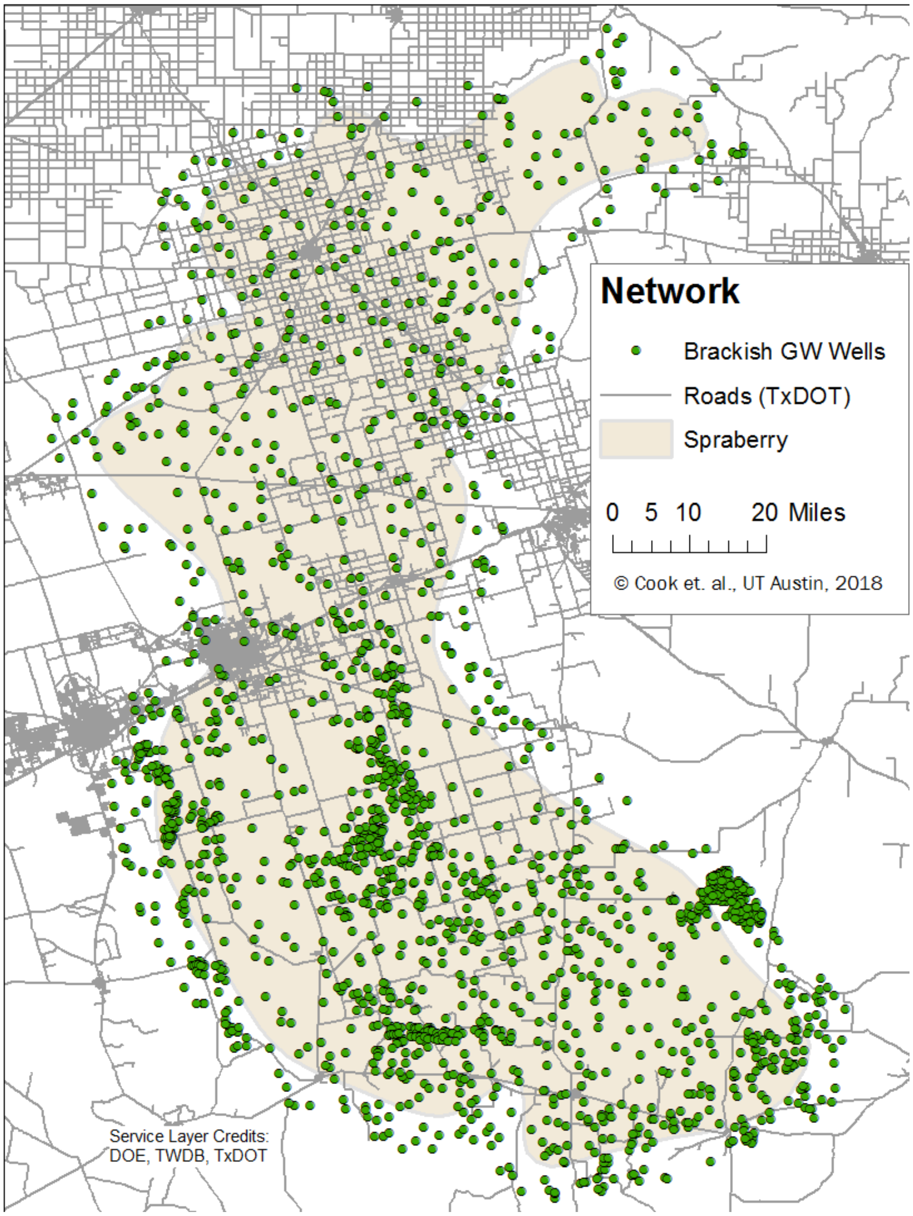

Figure 6.5: Brackish groundwater wells are common throughout the Spraberry trend, with a larger concentration in the southern portion of the region [27]. Wells are used as source facilities in the location-allocation network analysis.

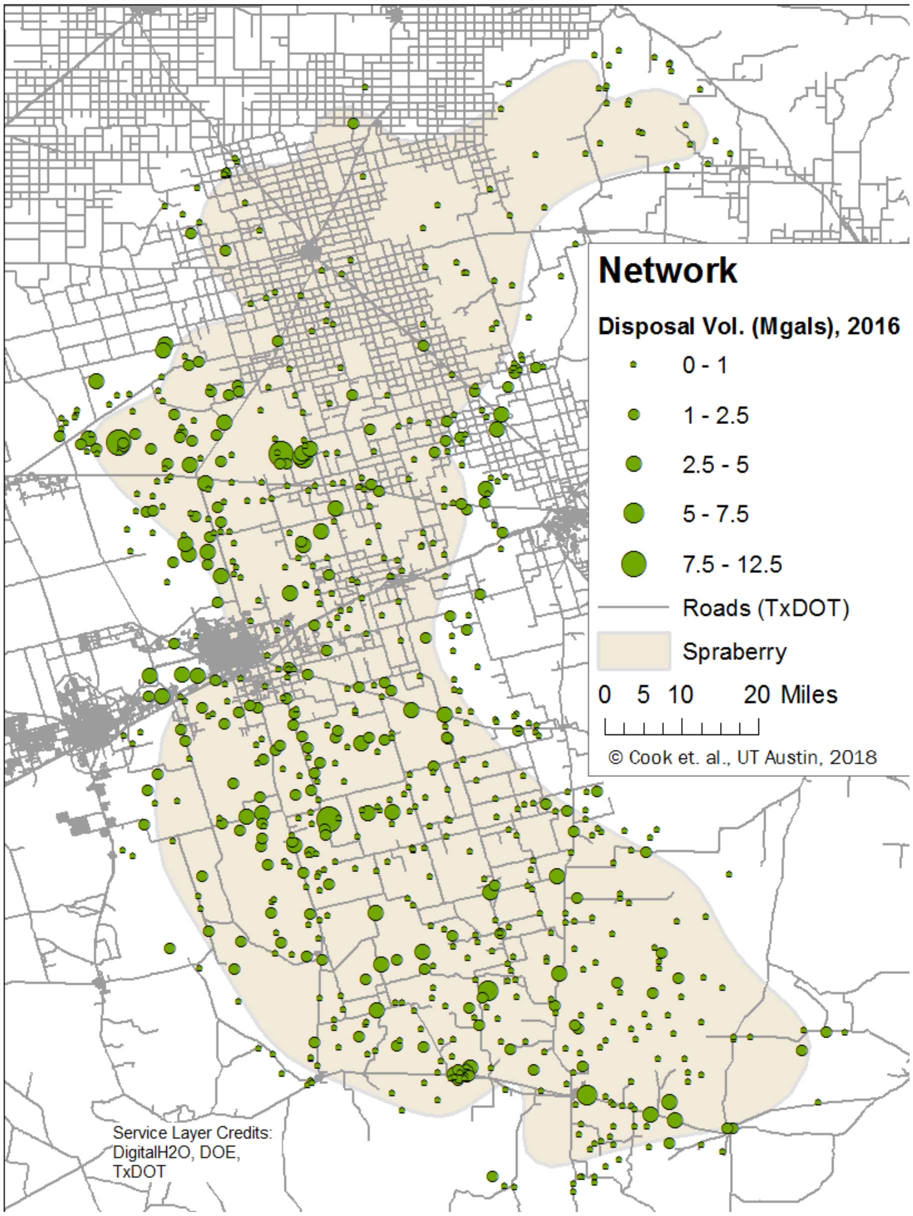

Figure 6.6: Disposal volumes received in 2016 are used as a proxy for future supplies in the location-allocation network analysis [28].

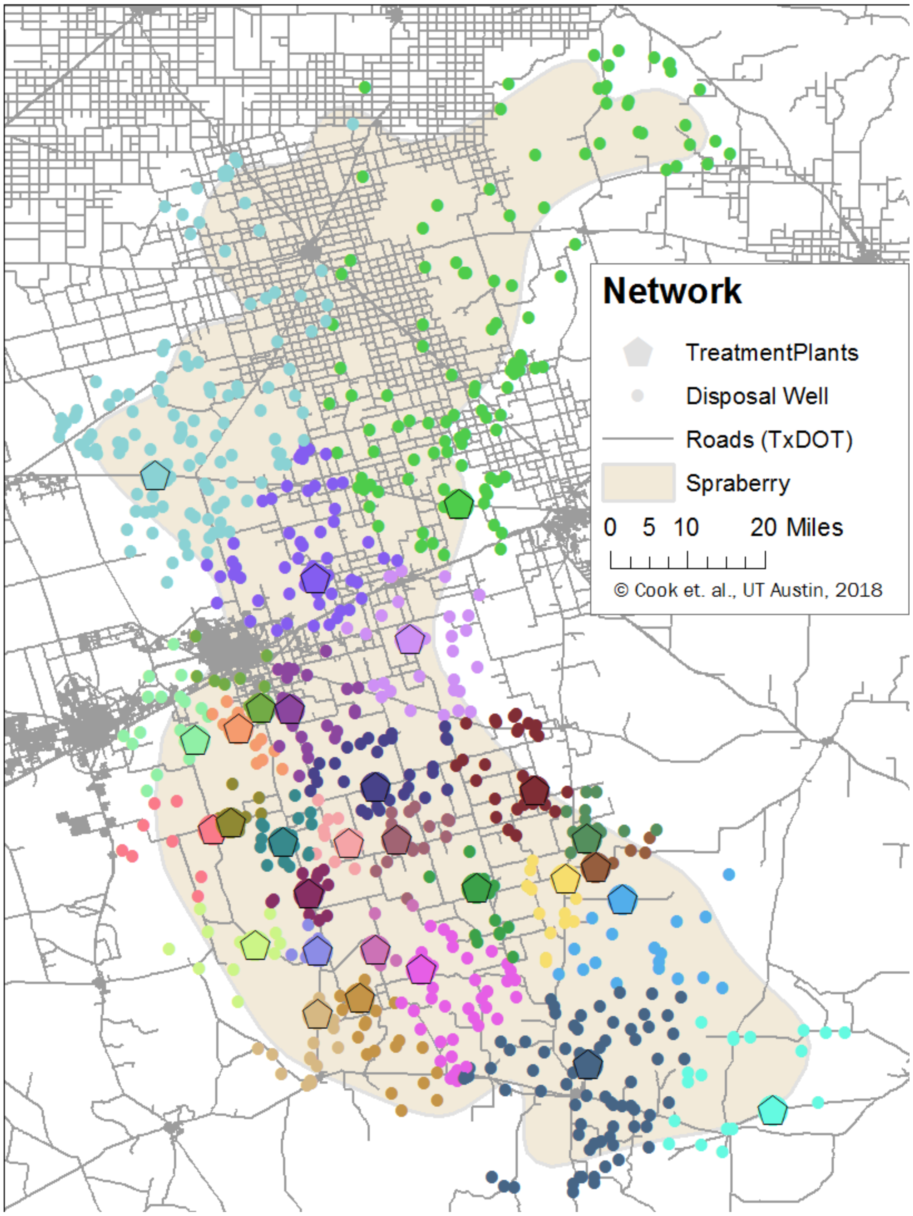

Figure 6.7: A system of centralized treatment with multiple receiving nodes and treatment facilities is used in the network analysis.

supply large amounts of water and save on economies of scale in that treatment and water transport process. Moreover, in the downturn in price of oil from 2014-2016, the facilities that operated at low prices and large volumes continued to operate while some companies that offered small well-to-well on-site treatment were pushed out of the market. A centralized system also benefits the smaller operators that cannot take advantage of economies of scale to treat and reuse FP water by collecting water from multiple users to supplement limited flows.

Scenario Analysis

Six scenarios were developed to allocate water by lowest impedance. Impedance used in these cases is the distance required to transport water. In general, transportation, whether by truck or by pipeline, is a high-cost component in the acquisition of water. The six scenarios allocate water of varying quality under varying competition, meaning some scenarios only allow one or two types of water sources to compete. The scenarios are intended to mimic an environment in which groundwater might be the preferred water source by users or alternative water sources (brackish water or treated produced water) might be required or encouraged. The scenarios allow for comparison of water choices as well as policy choices that might incentivize certain water choices. The six scenarios allocate water supplies in competition as follows:

1. Fresh groundwater only (GW)
2. Fresh groundwater, brackish groundwater, treated municipal effluent (GW/BW/Eff)
3. Brackish groundwater only (GW)
4. Brackish groundwater and FP water (BW/FP)
5. FP water only (FP)

6. All sources (All Sources)

Water demanded by frac wells within the Spraberry trend amounts to 13.4 billion gallons of water in 2016. Under each scenario, water is allocated to the closest facility along the road network. In limited cases, the program could not locate supplies or demands. The distance was added to the model manually for analysis in post-processing.

6.4 Assessing Potential Costs and Benefits

6.4.1 Water Deliveries

In the singular allocations of fresh groundwater (GW), brackish groundwater (BW), and flowback/produced water (FP), the entire volume allocated comes from each of these sources, respectively. In the competitive scenarios, some water is allocated from differing sources. No water is allocated from municipal treatment plants in this analysis as the transportation from such facilities is beyond that of the other competitors. Figure 6.8 shows the volume of allocated water from GW, BW, and FP sources under each of the six scenarios. While many companies in the Permian Basin use alternative water resources, most companies are still heavily dependent on fresh water [134]. A fresh groundwater or combination brackish groundwater/fresh groundwater (simulated by the GW and fresh groundwater/brackish groundwater/effluent (GW/BW/Eff) scenarios) is normal for many operators in the Spraberry trend. Allocating to lower-cost alternative resources could offset about 9 billion of the total 13.4 billion gallons of water demand (enough to supply the annual residential demand for 240 thousand people[1]).

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[1] The City of Midland's residential consumption was reported at 102 gallons per capita per day in 2016 [193].

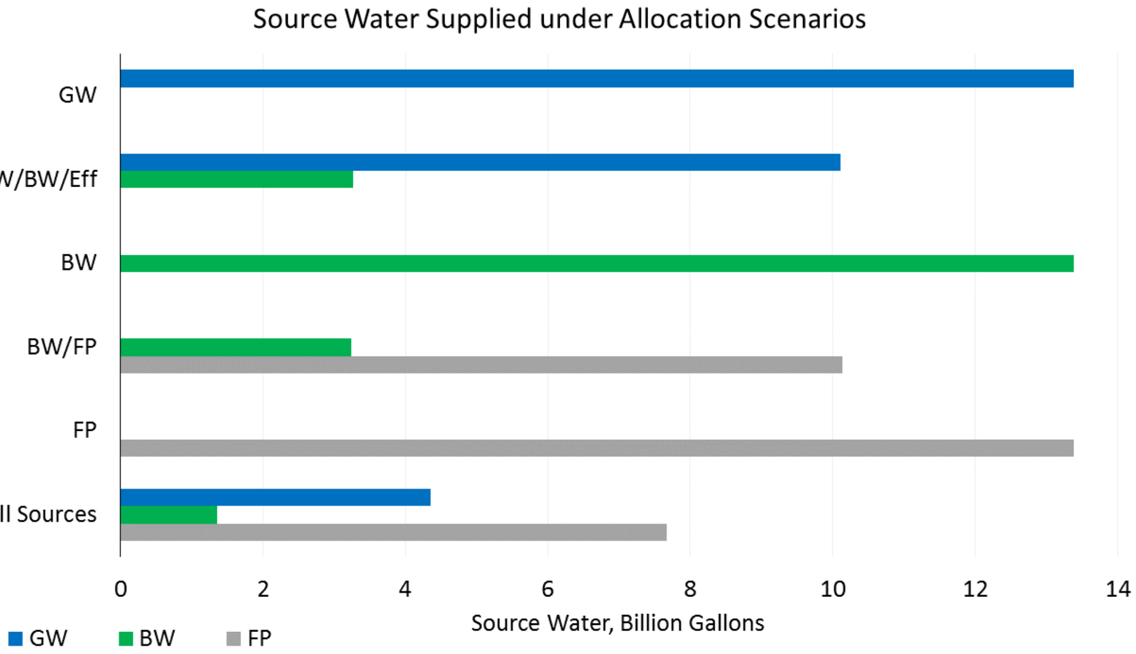

Figure 6.8: Results of the location-allocation network analysis show the volumes of source water allocated under each of the six scenarios. FP water is generally but not always the cheapest option.

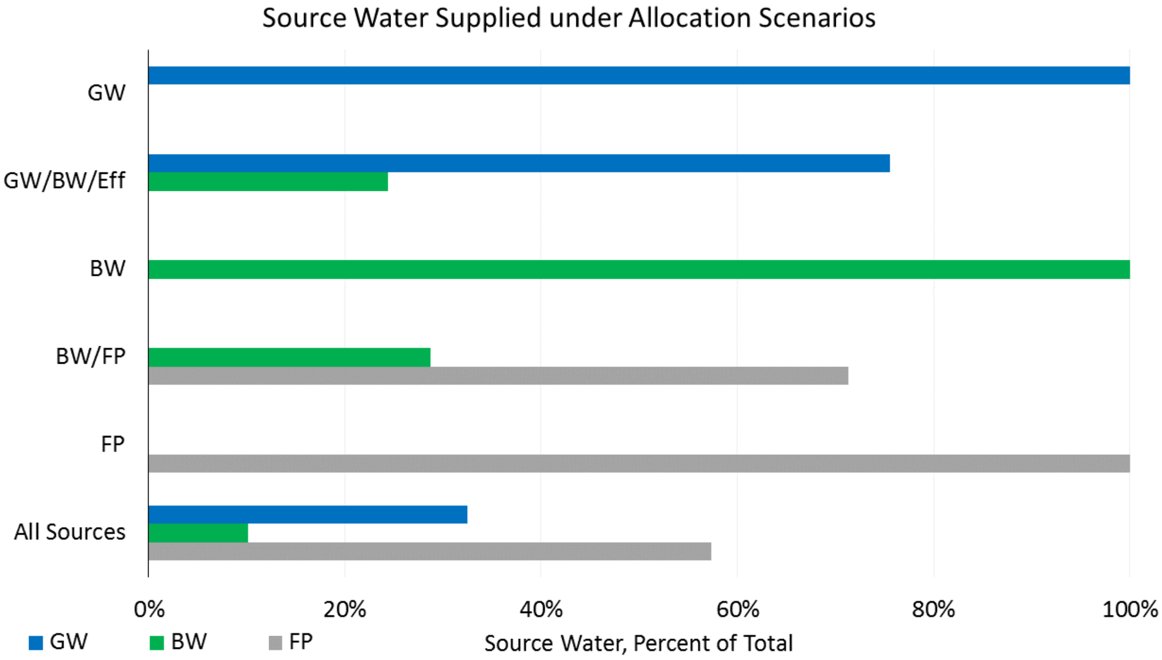

Figure 6.9: Results of the location-allocation network analysis show the percent of supply allocated under each of the six scenarios. FP water is generally but not always the cheapest option.

Figure 6.9 shows the same allocations as a percent of total allocated water from fresh groundwater (GW), brackish groundwater (BW), and flowback/produced water (FP) sources under each of the six scenarios.

In this analysis, water is allocated to minimize distance. Figure 6.10 shows the average distance traveled to allocate water from GW, BW, and FP sources under each of the six scenarios. Additionally, Figure 6.11 shows the average distance traveled to allocate water from all sources included in each of the six scenarios. Generally, more competition among water sources, particularly when including flowback and produced water sources, results in shorter transportation distances. However, this conclusion is a direct result of more water being available nearer to all sources due to the dispersion of supply. More competition at distances far from demands would not

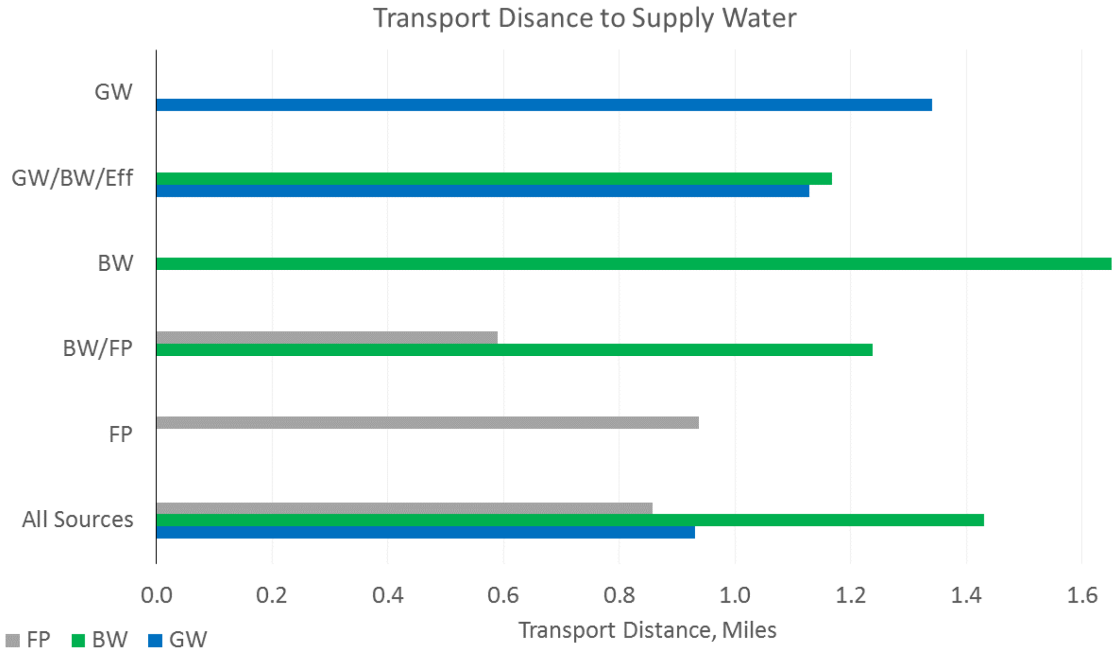

Figure 6.10: The location-allocation network analysis chooses supplies by closest distance. Average distance for each scenario's source water supply is shown.

result in shorter distances and shorter travel times.

6.4.2 Costs and Benefits of Water Sales

Distance traveled is important because of the cost associated with traveling long distances. As of 2018, water is often transported via truck and to a lesser extent through pipeline, including rented portable lay-flat pipe. Figure 6.12 shows the general price per well for water transfer via truck and lay-flat pipe for each of the six scenarios. Lay-flat pipe is a pipe that lays flat, so it can be quickly rolled or unrolled to lay or retrieve pipe for water transfer. The price assumes a rate of \$85 per hour for trucking and \$3 per foot per day for lay-flat pipe. Both prices were common in the Spraberry area as of 2014 (but might have reduced under the same conditions that reduced water price since 2014). Transportation speed is assumed to

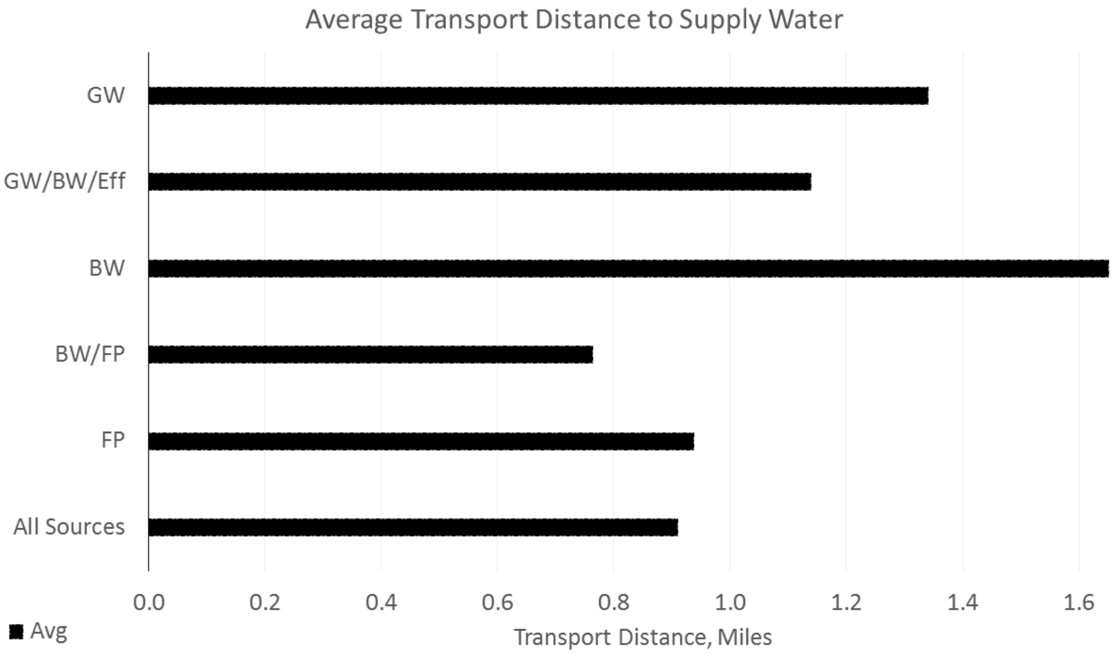

Figure 6.11: The location-allocation network analysis chooses supplies by closest distance. Average distance for all source water in each scenario is shown.

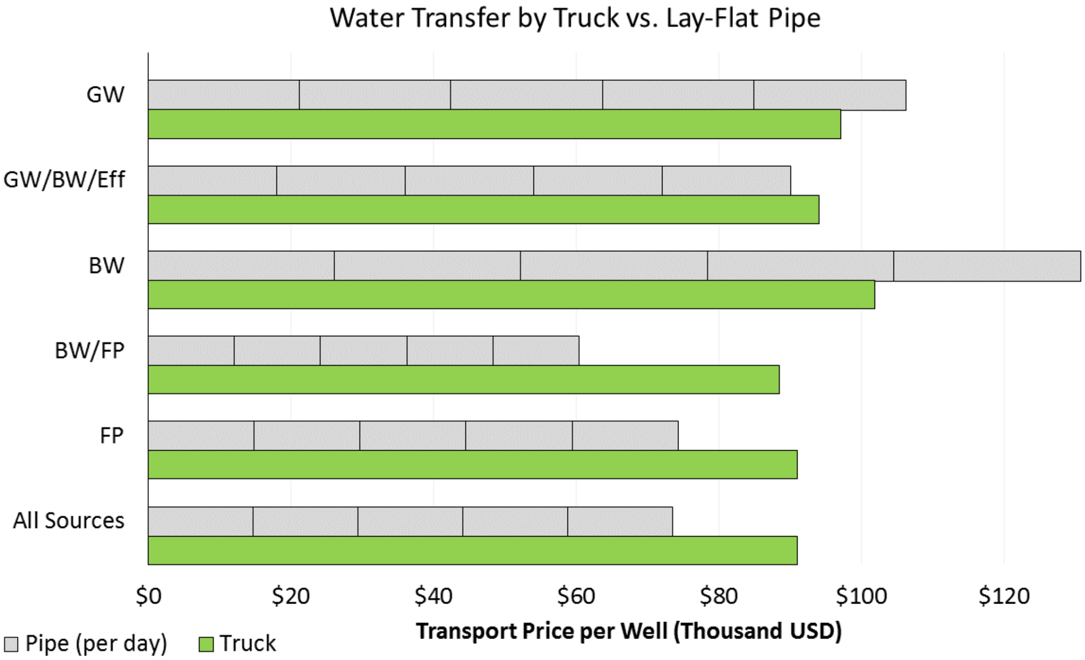

Figure 6.12: Cost to transfer water for each scenario is shown. Cost depends on choice of transfer equipment, distance, and time.

be 30 miles per hour (mph) and a wait time for site traffic, loading, and unloading of about 10 minutes is added for each truck trip. Truck trips are also assumed to be roundtrips. These assumptions might hold in some parts of the basin where prices were recorded but depend on variables like traffic and service company efficiency in operations. Sensitivity analysis on these assumptions is included below. The cost tradeoff between truck and pipeline transfer depends on distance as well as timing. In general, lay-flat pipe is the cheaper option, but a long rental term for pipe might make trucking the cheaper option, as shown in Figure 6.12.

Pipeline use might be complicated by weather, though; a pipeline transferring water might freeze. Moreover, using a pipeline involves acquiring permission to lay pipe along land that might not be owned by the operator seeking water. In this analysis, it is assumed that pipelines can access the public right-of-way (as per Texas Senate Bill 514), along the same stretch of road that a truck would use to transport water.

Sensitivity Analysis of Water Transfer Costs

Because water transfer costs can vary, a sensitivity analysis was conducted and is shown in Figure 6.13. A change in speed of 10 mph (to 20 mph instead of 30 mph, signifying higher traffic) would increase price by $5-10 thousand per well, depending on the scenario. A change in trucking rate of $5 per hour could change price by about $5 thousand. A change in wait time of 5 minutes (from 5 to 10 or 10 to 15 minute wait time for traffic, loading, and unloading) results in a change in cost of about $40 thousand. Meaning, reducing truck transfer times requires reducing wait times by making loading and unloading of trucks more efficient. If wait times are known to be long, lay-flat pipe is the cheaper option in under short-term multi-day contracts, but gets expensive under longer-term contracts.

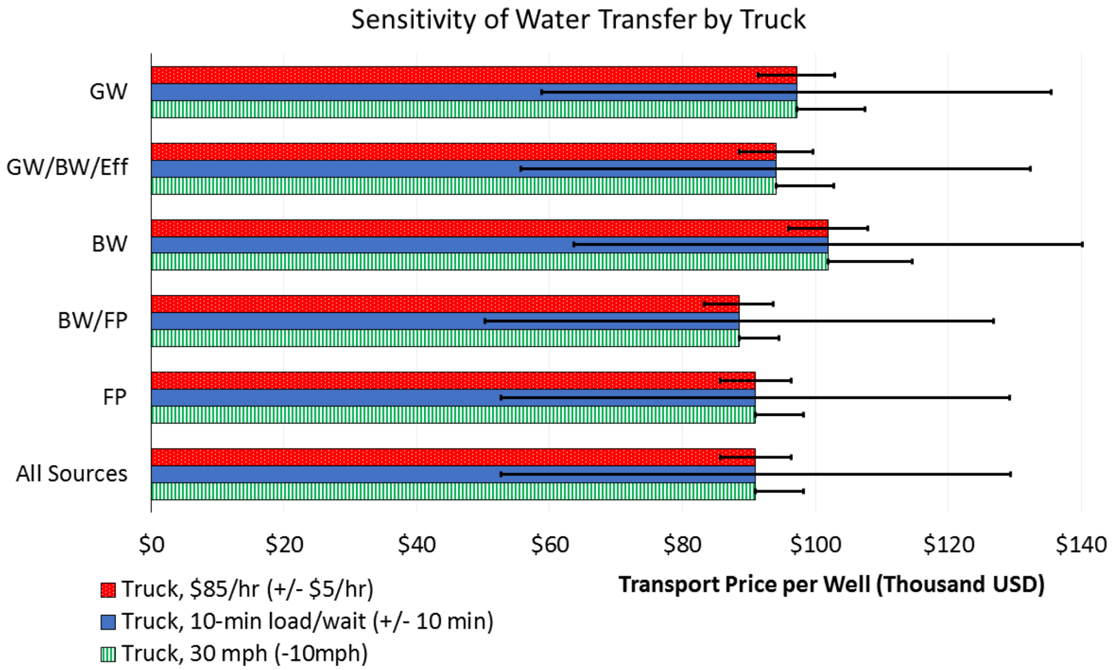

Figure 6.13: The sensitivity analysis for water transfer for each scenario shows variations in trucking cost, load time, and speed.

Comparing Costs Across Scenarios

Groundwater prices are reported by Cook and Webber 2016 [171]. However, those prices were collected at a high oil price. Under a lower oil price scenario, water prices will decrease. In this analysis, it is assumed that the low oil price scenario would result in a water price half that of the high oil price scenario. We evaluate groundwater at the low end of prices estimated by this 2016 study. Based on field estimates, brackish water is slightly less expensive than fresh groundwater. Price of using treated FP water is estimated from Barnes et al. 2015 [207] as a percent of fresh groundwater price.

Water acquisition, including purchase and transfer, becomes expensive as more water is used. Lowering this price is important for water users. Figure 6.14 shows water acquisition costs for each of the six scenarios. Table 6.1 includes the average and median costs for those scenarios. In this analysis, a transition toward alternative water sources in a market framework that incentivizes use of FP water (reducing fresh groundwater use from 100% to 30%) would see a change in cost of about $40 thousand per well on average as shown in Figure 6.14. Water acquisition costs are minimized in this analysis and thus, the range shown in the figure will be lower than the actual costs experienced in the field.

6.4.3 Reducing Potential Third Party Effects: Over-extraction of Fresh Groundwater

Groundwater in Texas is not allocated by any entity. However, the desired future conditions for the aquifer are evaluated and a modeled available groundwater is determined as discussed in Section 3.2.3.3. As a result of this planning process, modeled available groundwater is attributed to counties, as shown in Figure 6.15. Using the modeled available groundwater per county, this work then assigns a proportional

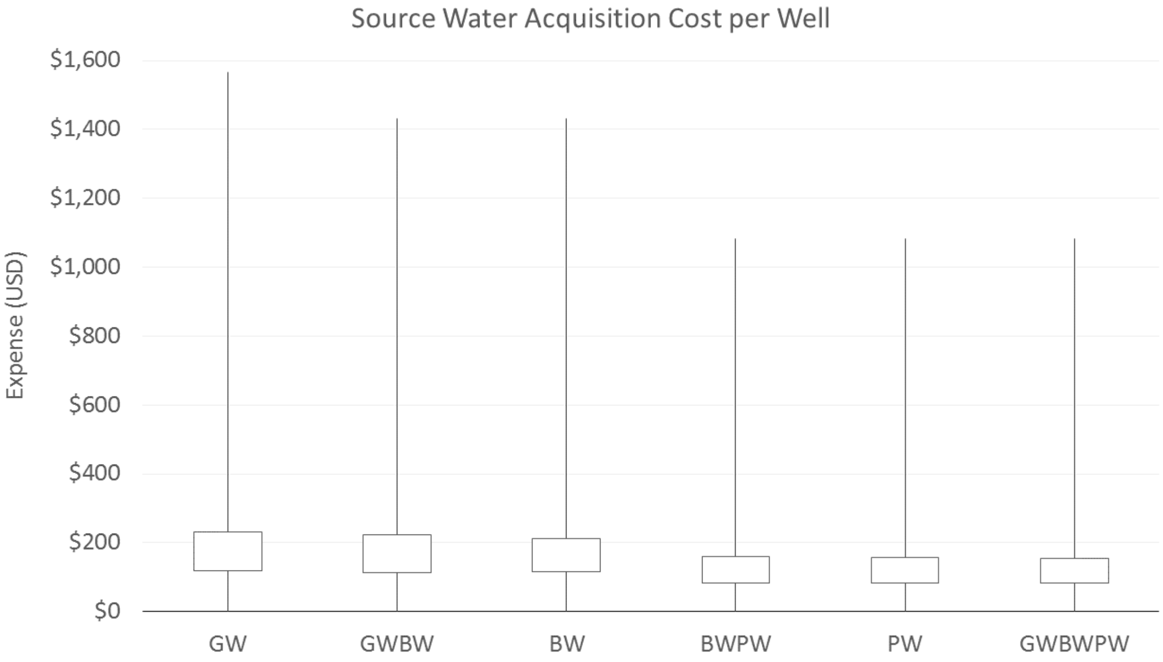

Figure 6.14: The variation of source water acquisition costs for all wells is reported for each scenario of the location-allocation network analysis. Water acquisition costs are minimized in this analysis and will be lower than actual costs experienced.

Table 6.1: Average and median source water acquisition costs per well are reported for each scenario of the location-allocation network analysis. Water acquisition costs are minimized in this analysis and will be lower than actual costs experienced.

	GW	**GW/BW/Eff**	**BW**	**BW/FP**	**FP**	**All Sources**
Average	$177,000	$169,000	$164,000	$125,000	$123,000	$122,000
Median	$182,000	$176,000	$174,000	$123,000	$123,000	$123,000

allotment to groundwater wells in each county, as shown in Figure 6.16.

The amount of groundwater allocated in the network analysis is then evaluated against the capacity assigned to a well to determine if groundwater is over-extracted compared to the MAG. Excessive extraction at a rate beyond that which the aquifer is refilled is considered groundwater mining. The aquifers in West Texas have been mined of their groundwater in the past and are still at risk of groundwater mining. Proportional over-extraction could lead to draw-down in certain areas of the aquifer that might be at risk of groundwater mining. Figures 6.17, 6.18, and 6.19 show the amount of potential over-extraction compared to the MAG at wells in the network analysis. As shown in the figures, the southern portion of the Spraberry trend experiences the most water use and the most over-extraction of groundwater resources. Using alternative water sources, as shown in Figures 6.18 and 6.19, reduces the singular instances of over-extraction and the collection of multiple instances of over-extraction into hot spots that could lead to groundwater mining. The location-allocation analysis chooses optimal groundwater wells for supply in each scenario (less when more alternative sources are available). However, in practice, the same wells might not experience the assigned withdrawals. Instead, similar nearby wells might provide groundwater. The existence of many wells extracting more than their share of water in the same area could cause draw-down in nearby wells and, on a grand scale, in regional aquifer levels. The actual level of draw-down is not measured in this analysis. However, viewing the general number of wells in an area exceeding the proportional modeled available groundwater, as well as the reduction of that count for alternative scenarios, gives an understanding of the impact on groundwater resources. Use of only alternative water sources would eliminate the associated over-extraction of groundwater (as no groundwater would be used).

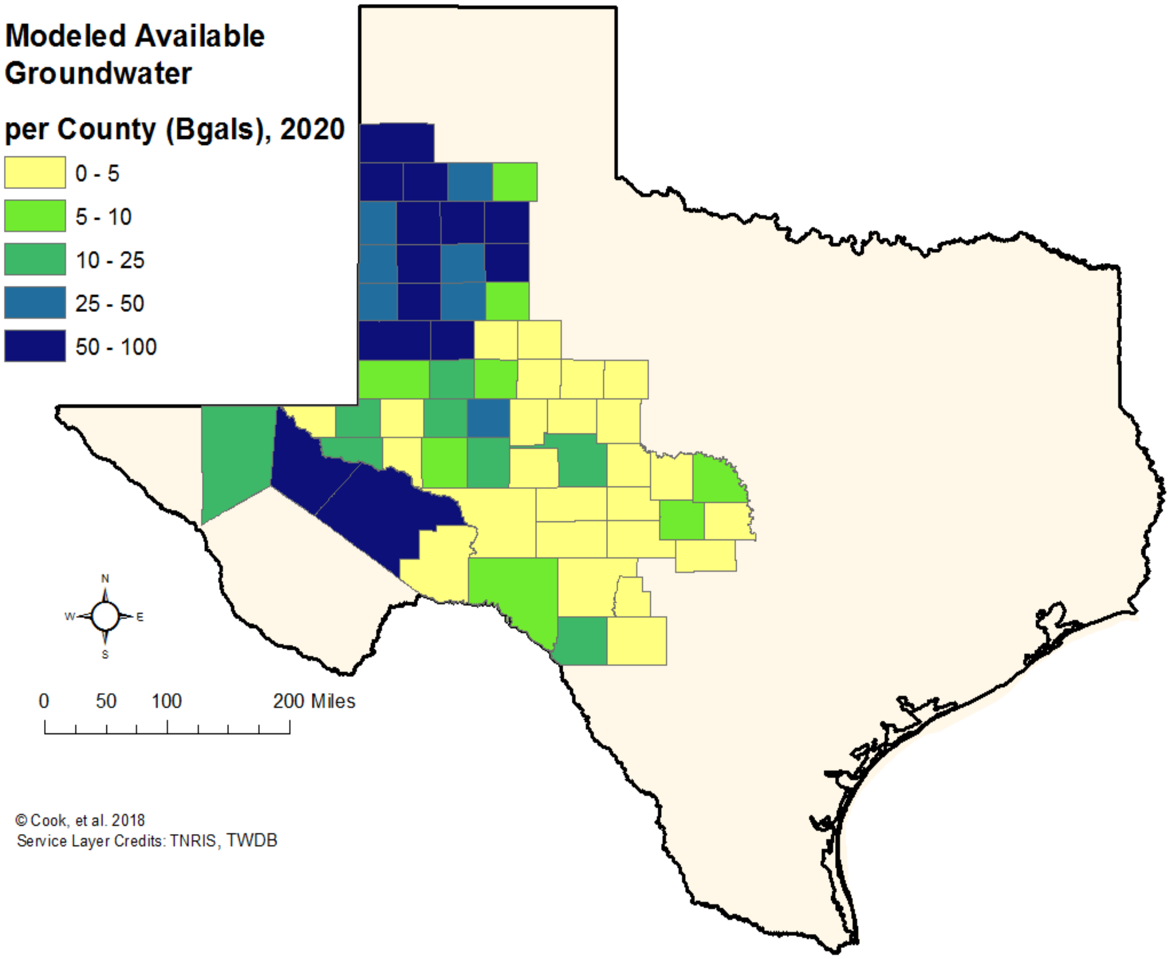

Figure 6.15: The figure shows modeled available groundwater per county in billion gallons collected and reported by TWDB [29–35]

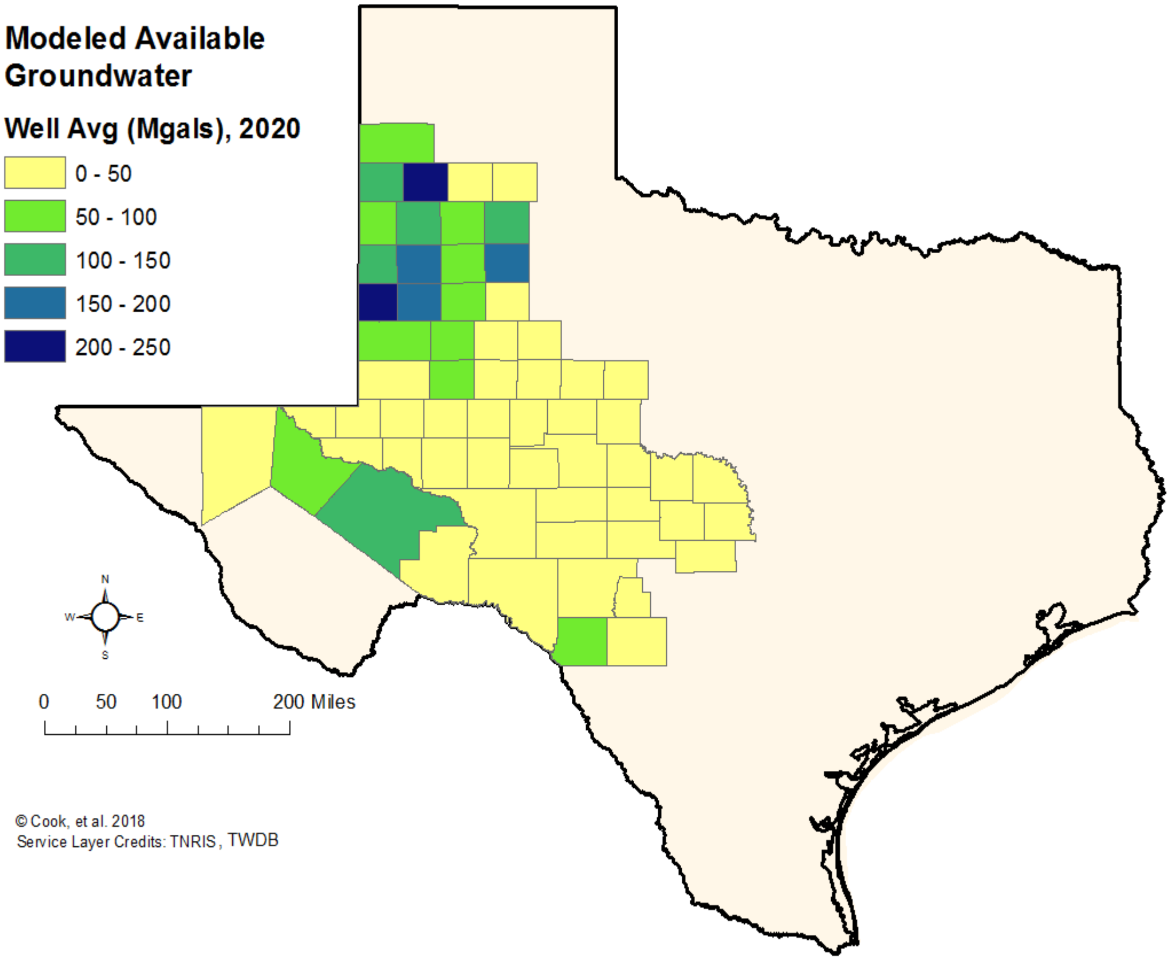

Figure 6.16: The figure shows reported modeled available groundwater per county allocated to wells producing water from aquifers in the county.

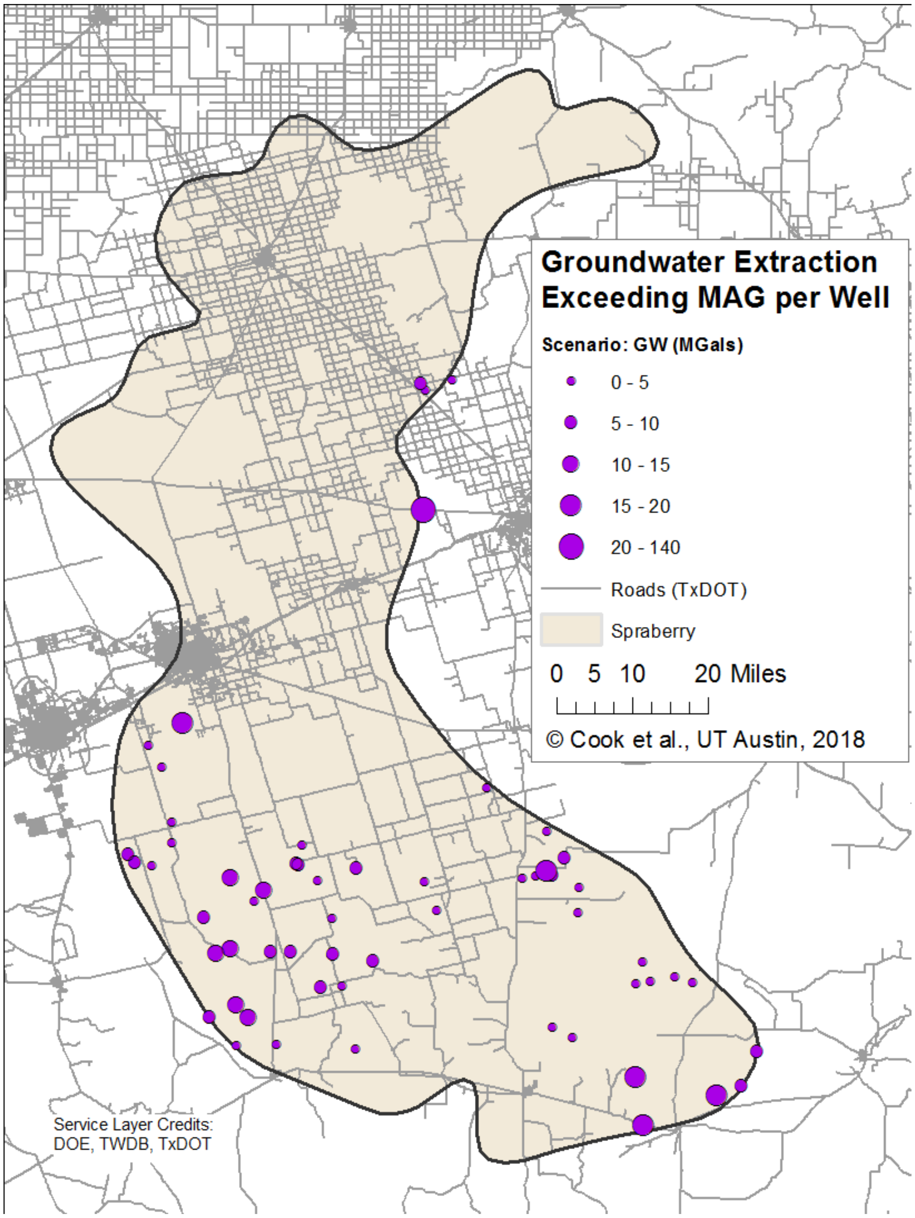

Figure 6.17: The figure shows potential over-extraction at groundwater wells for the scenario of fresh groundwater only (GW). Most groundwater over-extraction occurs in the southern portion of the Spraberry trend.

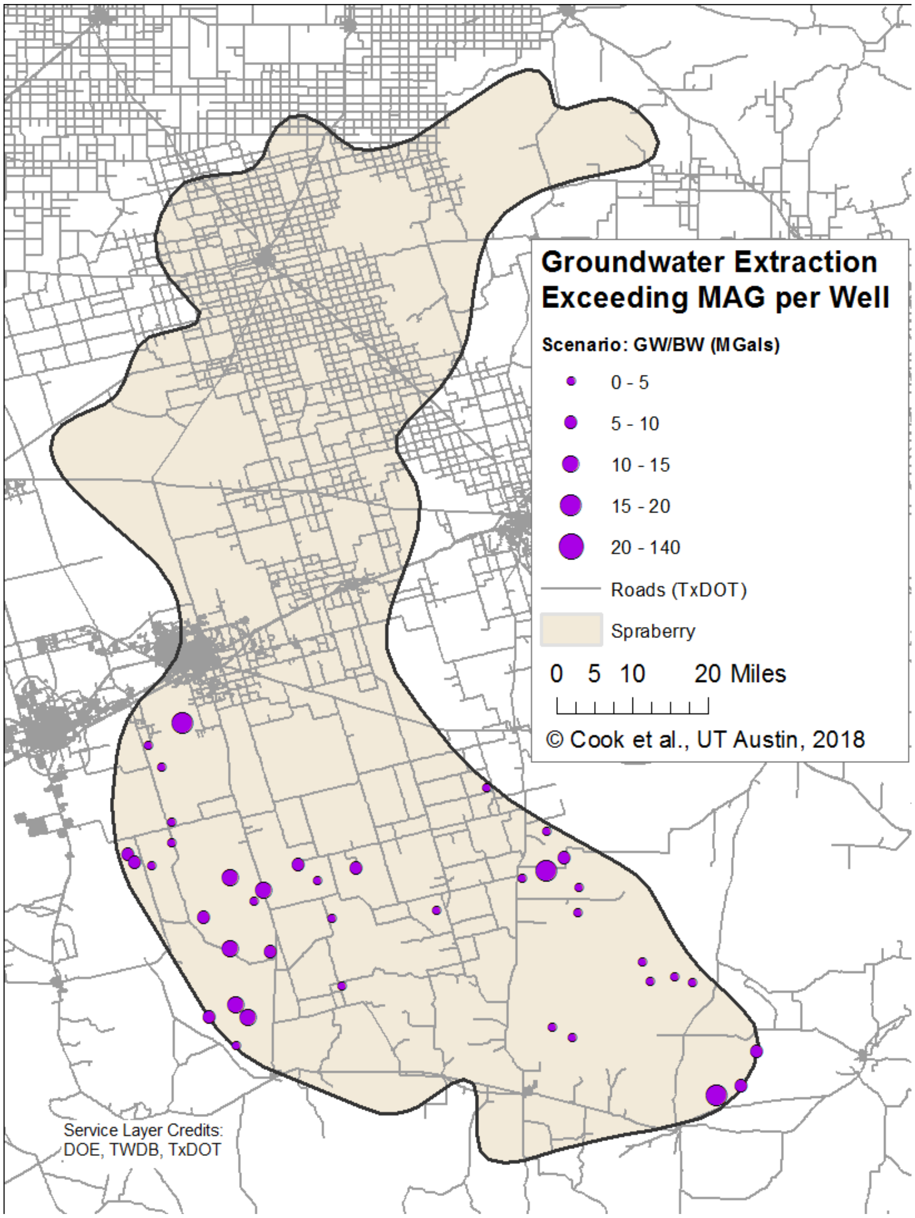

Figure 6.18: The figure shows potential over-extraction at groundwater wells the scenario of fresh and brackish groundwater (GW/BW). Less water is over-extracted under this scenario than under the groundwater only (GW) scenario.

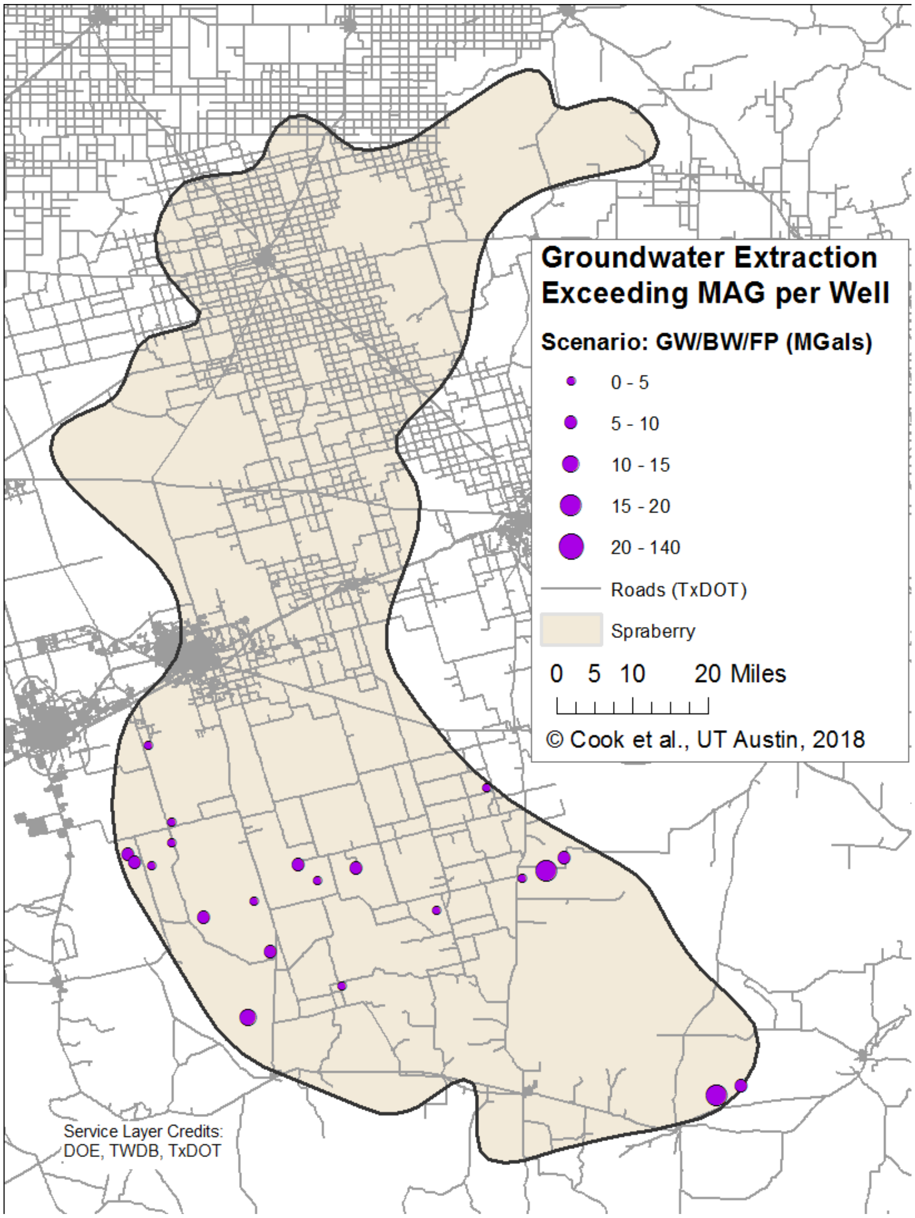

Figure 6.19: The figure shows potential over-extraction at groundwater wells for the scenario of a combination of fresh and brackish water and flowback and produced water (GW/BW/FP). As more alternative resources compete, less groundwater is used and less groundwater is proportionately over-extracted.

6.4.3.1 Feasibility of a Centralized FP Treatment System

Feasibility of using disposal wells from different companies work together might be questionable. This model makes the case for linking multiple receiving nodes to treatment systems. An operator or multiple operators with a sizeable footprint would be able to set up such a system. It is important to note that the larger the scale, the more collaboration potentially required between operators in water and cost sharing.

Transition costs are associated with building the plant and developing water sharing plans. The general lack of cooperation between companies on existing water sharing agreements shows that transition costs, though currently unmeasured are high. If the governing entity (in this case, the State of Texas or groundwater conservation districts at the regional level) would like to incentivize water sharing agreements for alternative water sources and construction of treatment plants, policy choices, such as increased fees on fresh groundwater or disposal or tax reductions associated with use of FP water, could help overcome transition costs.

Transaction costs are associated with transferring the water and mitigating leaks or spills in untreated or treated FP water. However, reducing groundwater extraction reduces third party effects and any costs that might have been applied to compensate those third parties.

6.5 Discussion

Of the four research questions laid out in Chapter 1, questions 1, 3, and 4 were explored in this chapter in the context of the Spraberry formation in the Permian Basin in West Texas. To summarize, (1) there are options available to reduce fresh water use in the Permian Basin, (3) a network of available treated flowback and produced water could economically supply oil and gas sector water demands, and (4) low cost alternative water resources could be supplied economically, offsetting billions of gallons of fresh groundwater demand for oil and gas operations.

In this analysis, six scenarios are analyzed to assess competition between water source types. Results show that use of non-fresh water resources could offset 9 billion gallons of water in the Spraberry formation (enough fresh water to supply the annual residential demand for 240 thousand people) at a cost lower than the price currently paid for fresh water. Costs for FP water treatment include capital and operations expenses. However, because transaction costs are not evaluated in this work, it is possible that current costs might be too high for many companies due to negotiations between various stakeholders (operators, service companies, and landowners). It should also be noted that this model includes one year of data and no forecasting of drilling plans. A decision-making process at the operator level could include more years of data and proprietary drilling forecasts.

Chapter 7

Discussion

7.1 Results of the Integrated, Geographically Resolved Hydrologic Process

The main aim of the work presented in this dissertation is to augment the existing literature by developing a process for evaluating water savings potential through incorporating existing methods, management, and technologies into an original water and cost model. Methods are integrated in an environment of previously unseen high marginal prices associated with energy extraction for three case studies in the Lower Rio Grande Basin, the Brazos River Basin, and the Permian Basin in Texas.

This work explores four research questions:

1. can reductions in fresh water consumption accomplished through improved water management make significant volumes of water available for other purposes,
2. which water use sectors (agriculture, municipal, or thermoelectric power) are best suited to conserve water with the intent to sell to other users,
3. could a network of available treated flowback and produced water economically supply oil and gas sector water demands, and
4. if the energy sector or other high-value water use sector makes cross-sectoral or intra-sectoral investments in fresh-water-lean systems, can their water demands be fulfilled at a cost offset by the price paid for that water?

Results vary, but in general, (1) there are options available to reduce fresh water use in each basin, (2) the low cost conservation options are in the agriculture and sometimes the municipal sectors, (3) the oil and gas sector could reduce its own fresh water use through flowback and produced water treatment, especially where wastewater volumes are significant compared to water demands, and (4) if the energy sector paid for water, the low-cost fresh water reduction methods available could be implemented economically and offset much of the water demand for oil and gas activity.

For example, in the Rio Grande Basin, results show that up to 900 million gallons per year could be made available through 15% conservation in watermaster area irrigation districts, enough to provide about 30% of the 3 billion gallons of water demanded per year in 2016 and 2017 for hydraulically fractured wells. In the Brazos River Basin, results show that agricultural and municipal users could increase profits by conserving consumptive uses and selling to oil and gas operations, and low cost conservation scenarios in the basin could provide up to 4.1 billion gallons of water per year. Finally, in the Permian Basin, results show that competition between all users that relies heavily on recycled FP water could offset 9 billion gallons of fresh or brackish water, that could be used for other purposes or remain in the aquifers. While hundreds of million to billions of gallons of water might not be significant for irrigation districts or municipalities, the volume is enough to provide a significant proportion of oil and gas water demands in each region. For each case, it is important to consider third party effects on reliability, resilience, and vulnerability of water supplies, as the water trade might benefit all direct users but have indirect impacts on water provided to other users. Similarly, existing conditions might have third party effects that are currently un-addressed but would be mitigated under a water trade. System evaluation of these changes would benefit all users and grant the opportunity to mitigate associated concerns.

7.2 Policy Considerations

The results presented in this dissertation illustrate some of the tradeoffs associated with water trading to achieve reallocation of resources without increasing fresh water consumption. To conduct this analysis in another basin, the modeler should first evaluate the functionality of the existent policy framework, any potential changes needed to encourage market activity, and whether those changes are feasible. Chapter 2 discusses water policy and basic principles of water markets. Here, some specific concerns are highlighted to emphasize their importance to the integrated, geographically-resolved hydrologic process and the case studies discussed within this dissertation.

Legacy Allocations and Price

Legacy allocations of water that give users rights to withdraw without paying for water give little incentive for users to conserve a supply to which they are essentially entitled. Similarly, ownership without a volume allocation gives little incentive to conserve as supply is virtually limitless for the user and, if they were to conserve a shared resource like water, another user would simply use the resource instead.

Capacity of Allocations

Setting capacities or permits to withdrawal as well as reasonable prices for water allows users to make judgments associated with their water use that incorporate the scarcity of the resource, the value of its current use, and the value of its sale for another use. For example, in the Rio Grande in Texas, water is more valuable when allotted to oil and gas activities than it is when allotted to irrigate certain types of agriculture because the market value of the final product is much higher. However, the impetus to sell water to oil and gas activities is not quite clear when water for agriculture is allocated and either inexpensive or free and water for oil and gas requires negotiation for trade.

Transparency in the Market

Water allocation policy in a system with the intent to encourage market trading should aim for transparency. In an active, transparent market with a water arbiter, surplus supplies available for trade, as well as prices of previous trades are determinable. Similarly, the potential to pay for increased surplus supplies could be made clear within this system, as well. In a less active environment with no transparency, finding surplus water would be difficult, posing a strong barrier to any potential trade and increasing associated costs. In addition, in each case, there are negotiation costs associated with ensuring that conservation occurs, the methods undertaken, and the payments required.

Policy Change

Where policies are not aligned to encourage markets but there is a desire to change, decision-making tools such as the process presented in this work could guide policy development by showing the benefits of price-induced water reduction under certain policy scenarios. As water resources become increasingly strained over time, understanding the available combinations of solutions could help inform the development and implementation of sustainable policy that encourages those solutions.

Encouraging Participation

Encouraging water users to participate in a water market to offset fresh water increases is a challenge. Encouraging conservation as a part of that participation adds additional difficulty. Market participation might be encouraged from multiple perspectives. For example, irrigators might wish to conserve but lack financial ability.

A market would provide that financial incentive to conserve and trade that surplus water. As an alternative, the water buyer might wish to encourage conservation. An oil and gas operator or set of operators might decide that public opinion warrants a campaign for net zero water use. One instance of such a campaign is that of Southwestern Energy operating in the Fayetteville Shale in Arkansas. The company mitigates the impacts of its hydraulic fracturing operations on the environment by rehabilitating lost wetlands or creating a new habitat in Arkansas [188]. In another instance of the buyer inducing changes in water management, in 2007, engineers for the City of Roma in Starr County decided to use grant funds they were awarded for water rights to instead make improvements to irrigation canal conveyance efficiency in Cameron County, Texas in exchange for excess water rights [158]. The trade provided necessary demands and resulted in excess savings. A third alternative of encouraging savings might come from the regulator in an attempt to ensure supplies are available for all demands. Incentives could be employed to encourage conservation decisions by the irrigator or operators. For example, capacity constraints could be implemented where they do not exist; subsidies, grants, or other forms of monetary encouragement could be attached to conservation plans; or taxes or tradable permits could be imposed on total water use. While this work does not go into detail about the potential incentives needed to encourage conservation and market participation, Section 8.2 describes the need to study the application of these options within the future work of the integrated, geographically resolved hydrologic process described in this dissertation.

7.3 Participant and Conservation Method Considerations

Model results for the Rio Grande and Brazos simulations show that there are options to reduce fresh water consumption through water conservation best management practices at costs offset by the price currently paid for water, specifically certain agriculture and municipal conservation methods. Focusing on these low-cost options to save water could be a goal for states or regions wanting to reduce fresh water consumption in an effort to reduce water stress. However, as noted in the previous chapters, it is important to address third party concerns associated with individual reductions in reliability (adequately meeting demand) and resilience (meeting demand after a shortage) of water supplies.

The goal of efficient conservation is to ensure that water use is reduced while production is able to continue at existent levels. If users conserve, but continue to operate at their current levels of productivity, and sell saved water, the total benefit to the user exceeds either option of not selling water to maintain operations or selling water but forgoing operations. For example, agricultural irrigators could (1) continue to farm at their current levels of productivity; (2) sell water and forgo farming as well as the income associated with that farming; or (3) conserve water to a point that does not damage their productivity, maintain their current levels of farming, and sell the new surplus associated with saving water. As another example, municipal water providers could (1) continue to provide water at their current levels of use; (2) reduce water use within their capacity (potentially for public areas) to benefit from selling water; or (3) reduce system water loss or increase system conservation, maintain current levels of customer satisfaction from water use, and sell the new surplus associated with saving water. In a market environment, the low cost agriculture and municipal water savings options become an economic choice for new users able to pay for that water at a benefit to the original user.

This work highlights best management practices (BMPs) that result in a benefit to the agriculture or municipal water user. Potential irrigation conservation opportunities that could benefit the irrigators are use of furrow dikes, which are small dams for each ridge between a planted row of crops; gated and flexible pipe to prevent seepage in irrigation channels and furrows; drip irrigation; center pivot sprinklers; surge flow; and brush management. Tailwater recovery and land leveling are more expensive methods that are sometimes offset by the price of water but not at a benefit to the irrigator over simply selling their water. Potential municipal conservation and efficiency opportunities included in this work that could benefit the municipality are reducing water losses, reducing turfgrass water use for public landscapes, or implementing rebate programs for home appliances. The cost of cash-for-grass programs that pay homeowners to replace their grass with Xeriscaping could be offset by the price of water but not at a benefit to the municipality over simply selling their water. A cash-for-grass program might still be valuable at the municipal level given other additional financing, though, if the end result meant less turfgrass demanding water in future decades. As another example, treating flowback and produced water (FP) at a network level could reduce total water costs for oil and gas operators and reduce total fresh water consumption. Conversely, neither selling water that would have been used to generate electricity nor switching cooling technologies to hybrid or dry cooling would be economic for the power company under current water and power prices. Finally, as noted in Chapter 2, improving system dynamics without the users intent to reduce water use does not reduce water use. Thus, those intending to trade saved water should ensure water users mindset is shifted to a low water use scenario.

Generally, cost is a major hurdle in implementing BMPs for water use in both the agriculture and municipal sectors. For example, as noted in Chapter 2, where cost of water is a small percent of total farm budget, investment is slow and capital for long-term investment in irrigation efficiency might not always be available. A major benefit of market-induced conservation is that payment for BMPs is part of the transaction, removing this particular hurdle. In addition, finances are not the only hurdle to BMP implementation. Education about BMPs (and newer technologies in general) leads to more adoption even under non-market conditions. More available BMP training within a market environment, including potential to trial new methods, would reduce both cost and education hurdles.

7.4 Hydrologic Model Choice Considerations

Chapter 3 discusses the considerations to address when choosing models and acquiring necessary data. It is sometimes possible to use an existing model that is already calibrated to the hydrologic conditions of the basin as well as the demands and discharges of water users and is employed within the basin for planning purposes, research, or both as with the studies in the Rio Grande and Brazos basins conducted in this work. Such a model is the best case scenario but not always available.

Instead, it might be necessary to develop an allocation model if one is not available. In such a case, it is important to choose a format that incorporates the necessary water supply, demand, and policy inputs. For example, WEAP, used in this work to evaluate the Rio Grande, is able to incorporate international treaties, allocations from user groups, and interconnections between surface and groundwater. It is also important to ensure that the period of analysis covered by the model is sufficient for decision-making.

The WEAP model for the Rio Grande includes 60 years of data. In another example in this work, the analysis for the Permian Basin in West Texas, the model of allocations between users was built specifically for that study and follows the road network traversed by water users in that area, but the model is a one-year approximation of current conditions. It is not built for nor should it be used for long-term planning in the region. However, the model is useful to evaluate semi-permanent solutions to water stress concerns in the near future. Ensuring the model choice incorporates the existing hydrologic conditions, the allocation data (supply, demand, and policy inputs), and an appropriate time period will lead to a robust backdrop for decision-making.

Uncertainty in Hydrologic Models

Chapter 3 discusses the error inherent in modeling water supplies. While approximations of error are not actually included in results reported in this analysis, it is important to understand that results are not exact. The WEAP, WAM, and Location-Allocation models used for regional analysis in this work carry their own technical errors associated with approximating flows, water allocations, and discharges. Optimizations, for example, are ideal, sometimes unrealistic approximations of actual activities. The inherent imperfection of model results underscores the need to reduce the error incorporated in the results by ensuring that aspects that are controllable (the data inputs, model choice, and period of study) are high quality.

In addition, each of the water models used in this work incorporates some aspect of human activity, which is generally unpredictable. For example, the model of water allocations in the Permian Basin assumes truck drivers transporting water will seek out the nearest source of water or wastewater disposal on the shortest path. In practice, drivers might choose a different water source, disposal well, or path for a number of reasons (for instance, the wastewater well is more convenient for their drive home) leading to non-optimal results for the oil and gas operator paying for truck transport. A good model could highlight the human error and make areas for improvement more apparent and potentially easier to address.

7.5 General Considerations

This work presents a process for evaluating water savings potential through incorporating existing methods, management, and technologies. To conduct such an analysis in another basin, water modelers should identify relevant policies, water users, and models. Agriculture conservation and flowback and produced water treatment for reuse in the oilfield are the low cost options identified in this analysis and might be the best water saving options for reallocation in other basins, as well. If hydrologic models need to be created, this work gives some direction for model design. In addition, if policy changes are needed, the process can be used to assess their usefulness in a market environment.

Although this methodology was applied to regions in Texas, the approach is applicable for other areas encountering or expecting additional water stress. As populations grow and demand more water, water resources are subject to stress and management challenges. Creating tools, such as this process can assist integrated function of water policy, technology, and economics to address water scarcity, now and in the future.

Chapter 8

Conclusions

The aim of the work presented in this dissertation is to augment the existing literature through the development of an integrated, geographically resolved hydrologic process for evaluating potential water savings and reallocation within a market environment. The Texas water market, like other water markets around the world, has historically been dominated by transactions within the agriculture sector and transactions between the agriculture and municipal sectors in local markets around the state. However, with the growth of unconventional oil and gas production, the market experienced an increase in demand for high-value water by the energy industry. The associated increased water price opens up the possibility for innovation and investments in management practices for water use efficiency in various sectors, spurring lasting changes in fresh water consumption in each basin. How regions have responded and continue to respond will affect future water supplies. Reduction in fresh water use through conservation of consumed unproductive water and use of alternative water sources is one option for meeting water needs. Incentives made clear through water markets could help finance investments in water fresh water reduction and link savings to new demands.

8.1 Summary of Results

This work lays out the methodology of evaluating water savings potential with an original water and cost model that is developed and demonstrated for three case studies in the Lower Rio Grande Basin, the Brazos River Basin, and the Permian Basin in Texas. The analysis adds to the existing literature by incorporating pricing, costs, water supply and allocations, and technological and management advances in an environment of previously unseen high marginal prices associated with energy extraction. Because water supplies around the world are expected to increase in stress in the future, it is important to analyze the effect of new, high paying users and the ability of regions to react in ways that preserve supplies for current and future users within existing policy frameworks.

By implementing a combination of improved conservation, efficiency, and management mechanisms, current water users and their economic partners (for example, oil and gas companies) could optimize their water use and achieve more water availability for themselves and/or the environment. In a partnership, this increased water availability would augment the ability to hydraulically fracture more wells, for example, and maintain the same amount of productivity in the original water sector, while possibly increasing environmental flows. In the ideal situation, this water market could solve water needs for multiple industries, result in more water for ecosystems, and create a more water resource-friendly environment in the process.

Results vary, but generally, water can be saved in a market environment at a price paid by high value water users. The water saved in the study areas analyzed within this document could provide a significant proportion of oil and gas water needs. The low cost options are agriculture conservation, treatment of flowback and produced water for reuse in oil and gas operations, and some municipal water loss reduction or conservation. While thermoelectric power and turfgrass are significant water users In Texas, the value associated with that water use generally exceeds the ability to pay for conservation strategies in a water market. Attention should be paid to low cost options and remedying third party impacts such as reductions in reliability and resilience or increases in vulnerability associated with those trades.

In the Rio Grande Basin, scenarios are analyzed for trading irrigation savings for use by oil and gas operations. Results show that up to 900 million gallons per year could be made available through 15% conservation in watermaster area irrigation districts at a cost much lower than the price paid for water used in oil and gas operations. The savings are enough to provide about 30% of the 3 billion gallons of water demanded per year in 2016 and 2017 for hydraulically fractured wells. Irrigation districts would increase profit and experience an increase in reliability of their supply. Moreover, use of saved fresh surface water rather than fresh groundwater for oil and gas operations leaves slower-to-replenish groundwater in place, a positive effect on third parties in the area.

In the Brazos Basin, scenarios are analyzed for trading water savings from irrigation, municipal, and thermoelectric power for use by oil and gas operations. Results show that scenarios could provide up to 4.1 billion gallons of water per year, depending on the user and conservation method. However, costs of conservation vary. Generally, irrigation conservation methods are the least cost choice, followed by municipal conservation, and then water conservation in thermoelectric power. Under water trading scenarios, agricultural and municipal users could increase profits by conserving consumptive uses and selling to oil and gas operations. However, third party users might experience positive or negative changes in their reliability and resilience. Capturing these effects is important to addressing externalities. Additionally, as in the Rio Grande Basin, use of saved fresh surface water rather than fresh groundwater leaves groundwater in place, a positive effect on third parties in the area.

In the Permian Basin in West Texas, six scenarios are analyzed to assess competition between water source types. Results show that competition between all users that relies heavily on recycled FP water could save operators money and offset 9 billion gallons of water (enough water to supply the annual residential demand for 240 thousand people[1]). However, it is possible that current transition costs might be too high for many companies.

To conduct such an analysis in another basin, consideration should be given to existing policy structure, water users' potential to conserve, and availability of existing models and data. In evaluating policy choices, the modeler should analyze the efficacy of the current policy framework and the feasibility of implementing changes when needed. In considering users' potential to conserve, it is possible that the low cost options in Texas will also be the low cost options in other areas. Therefore, cross-sectoral participant analysis should focus on agriculture users and some municipal users, followed by intra-sectoral focus on reducing consumptive use, for example, through recycling contaminated water. Finally, in choosing a model to assess the effect of trades between users in the current or altered policy environment, the modeler must aim to include existing hydrologic conditions, allocation data, a time period adequate for decision-making, and uncertainty.

8.2 Future Work

Future work should include better estimation of transaction costs and methods for reducing those costs that could be the main barrier to reallocation of saved water. Rio Grande basin transaction costs are similar to those seen in other basins (about 21% compared to 8–34% in other basins [166–170]). However, calculation of

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[1] The City of Midland's residential consumption was reported at 102 gallons per capita per day in 2016 [193].

transaction costs was not exhaustive of all potential costs that exist and thus could be higher than the estimated amount. Moreover, the Rio Grande market is thought to be a relatively efficient market compared to the less active groundwater and surface water markets in other parts of the state. Meaning, the unquantified transaction costs in the Brazos Basin and the Permian Basin could be much larger than the 21% seen in the Rio Grande Basin. Quantifying and reducing these costs should be a priority before engaging in large-scale water trading in either basin.

A water market with incentives to encourage consumptive water use reduction strategies is one policy tool of many and can be used in tandem with others or in place of less economically efficient policies. Future work should include policy analyses aimed at determining gradual, iterative reforms that could improve market efficiency in the varied water management systems included in this analysis or in other systems that might experience an influx of high-priced demand. In the Murray-Darling Basin in Australia, iterative reforms, including informal trading, diversion limits, water rights reform, and adaptation, took hold over three decades [168]. To take full advantage of improving water supplies, regions could streamline their regulated water markets and incorporate basin-, region-, or state-wide incentives that promote consumptive water reductions in favor of supplying other beneficial uses including oil and gas activity or environmental flows.

In addition, estimations of the uncertainty in the hydrologic models should be included in future use of the integrated, geographically-resolved hydrologic process. Uncertainty is inherent in the technical and human aspects of the model, as well as water conservation, allocation, and use. Discussion of the impact of uncertainty is included in Chapters 3 and 7, but estimates are not included. The accuracy of the integrated process would be improved with inclusion of uncertainty.

Finally, site-specific engineering analyses are needed to actually implement water consumption reductions properly. Each entity participating in a saved water market should conduct its own water audit to ensure that the saved volume estimated in this work is “real water” rather than “paper water” as described in Chapter 2. It is also important to note that while best management practices analyzed in this work might save water, water users might be unwilling to implement them. Many factors affect adoption of water efficiency mechanisms, particularly water price and finances, education, policy, and water availability. Partnership with oil and gas companies could eliminate the financial hurdle. However, it is also important to ensure water users are educated, policies are favorable, and water availability concerns are managed.

Appendices

Appendix A

Interest Rates and Terms

Because systems have different lengths of effect, before comparing costs between systems, we assess the net present value, NPV , and recurring yearly payment, R_t, of each system so comparisons can be made on equivalent values. Calculation of NPV and R_t are included in Chapter 3. The discount rate is the rate that could be earned on an investment and is assumed to be the market interest rate for agricultural loans as reported by TWDB, 3.15% [22]. Examples of the cost of irrigation and municipal conservation varied by common payment periods and interest rates reported by TWDB are shown in Chapter 3. Additional example figures are included here in Figures A.2 and A.1.

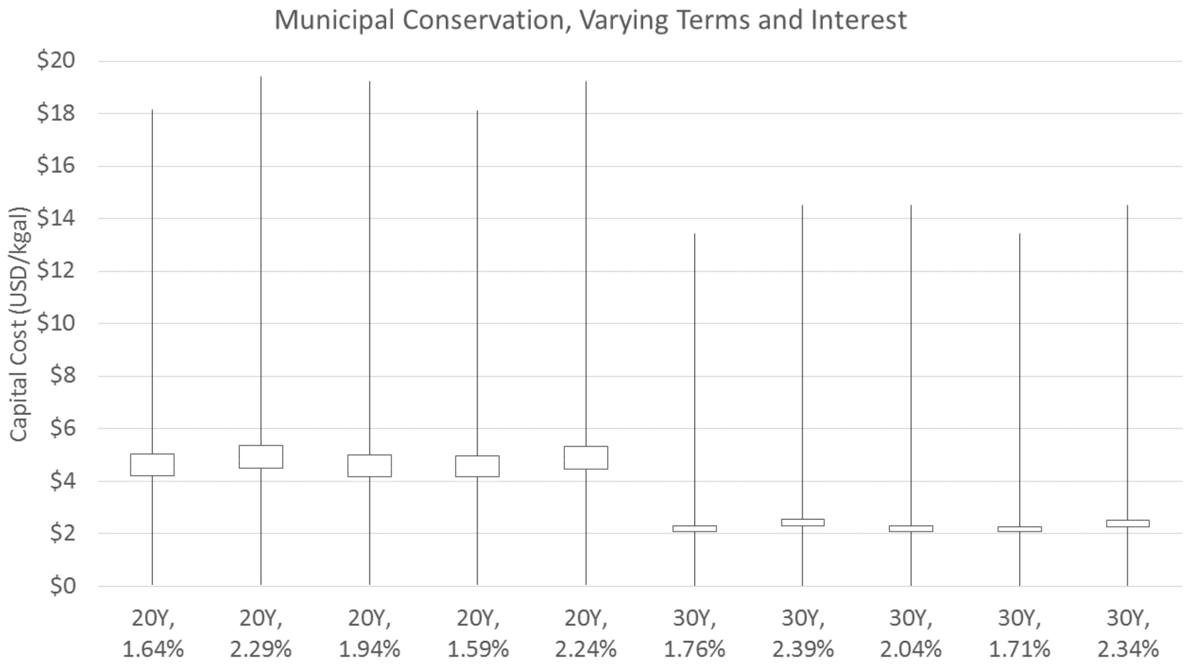

Figure A.1: The capital cost of municipal water conservation reported by TWDB [21] is shown using interest rates and loan lengths offered by TWDB or the market and reported by TWDB [22].

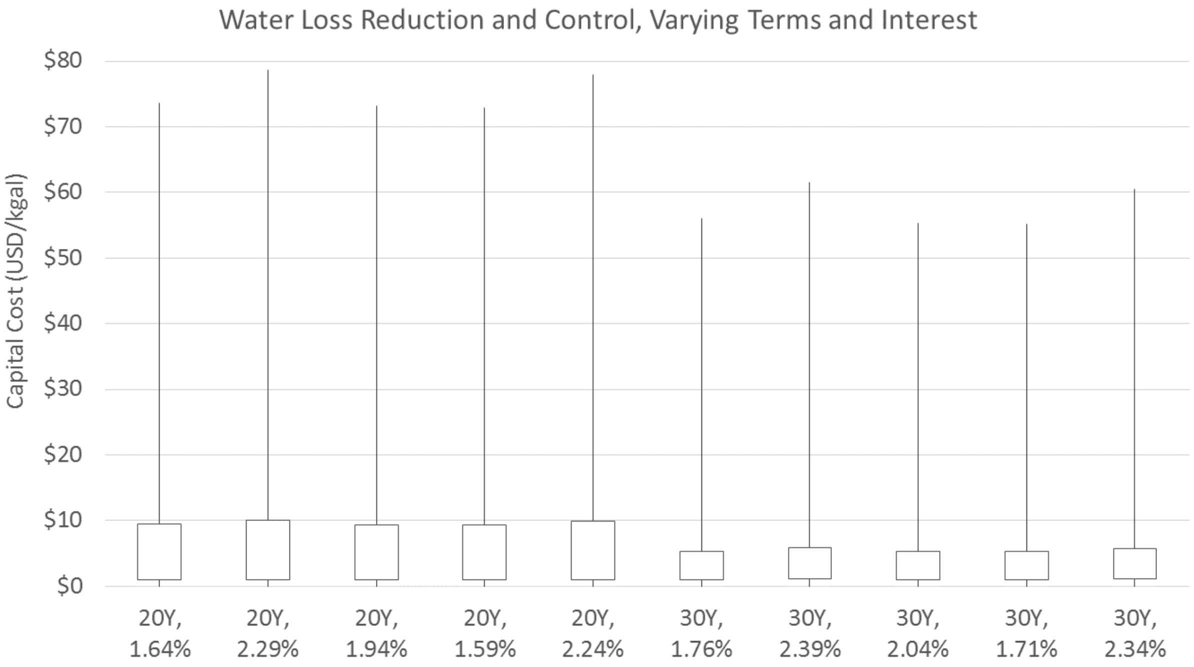

Figure A.2: The capital cost of municipal water loss reduction and control reported by TWDB [21] is shown using interest rates and loan lengths offered by TWDB or the market and reported by TWDB [22].

Appendix B

Reliability, Resilience, and Vulnerability for Trades on the Rio Grande

B.1 Reliability

Figure B.1 displays the reliability of water supplied to oil and gas operators for each of the water saving scenarios: 1%, 5%, 10%, and 15% from each of the watermaster sections saving water. As Figure B.1 shows, reliability is unchanged across scenarios at approximately 60–62%, depending on the watermaster section providing saved water.

Figure 4.5 in Chapter 4 shows reliability of water supplied to irrigators in watermaster sections after saving water under each scenario: 1%, 5%, 10%, and 15% water savings. Reliability for all irrigation sections is shown to increase from baseline in all scenarios of conservation and trade.

B.2 Resilience

Figure B.2 displays the resilience of water supplied to irrigators in watermaster sections after saving water under each scenario: 1%, 5%, 10%, and 15% water savings. For most watermaster groups, resilience improves under increasing conservation levels. For one watermaster section, 13A, resilience decreases from baseline, but increases for increasing conservation levels.

Figure B.3 displays the resilience of water supplied to oil and gas operators for each of the water saving scenarios: 1%, 5%, 10%, and 15% from each of the

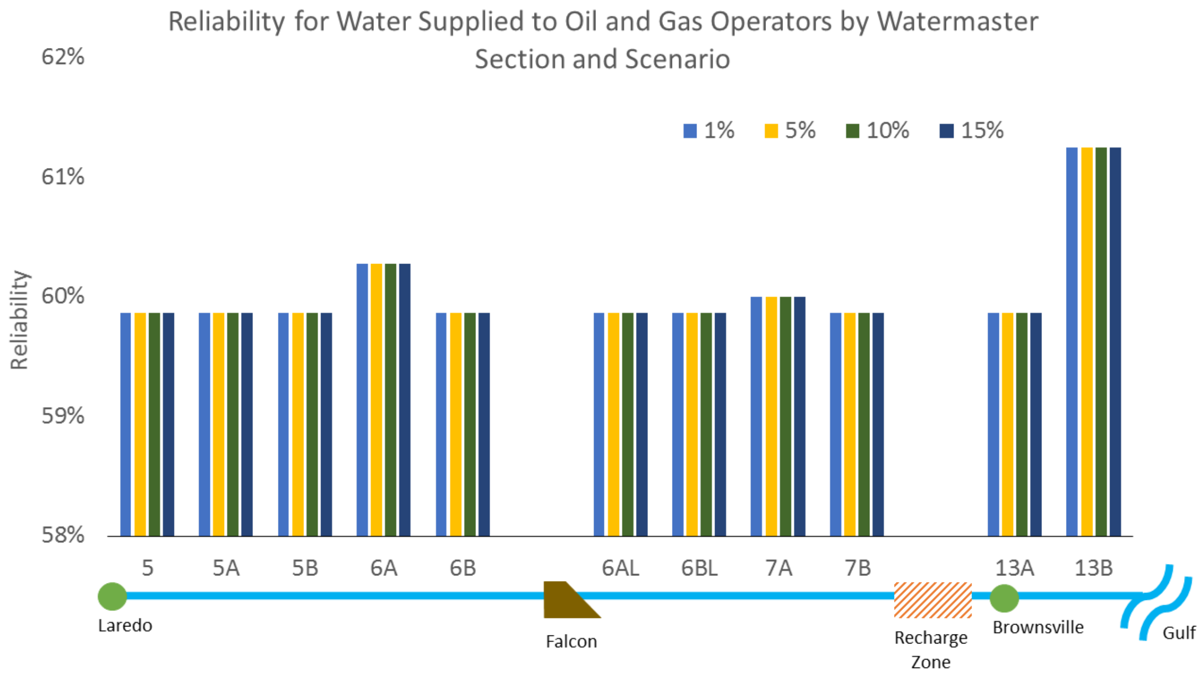

Figure B.1: Reliability for oil and gas operators following trades of varying amounts of saved water, shown by watermaster group.

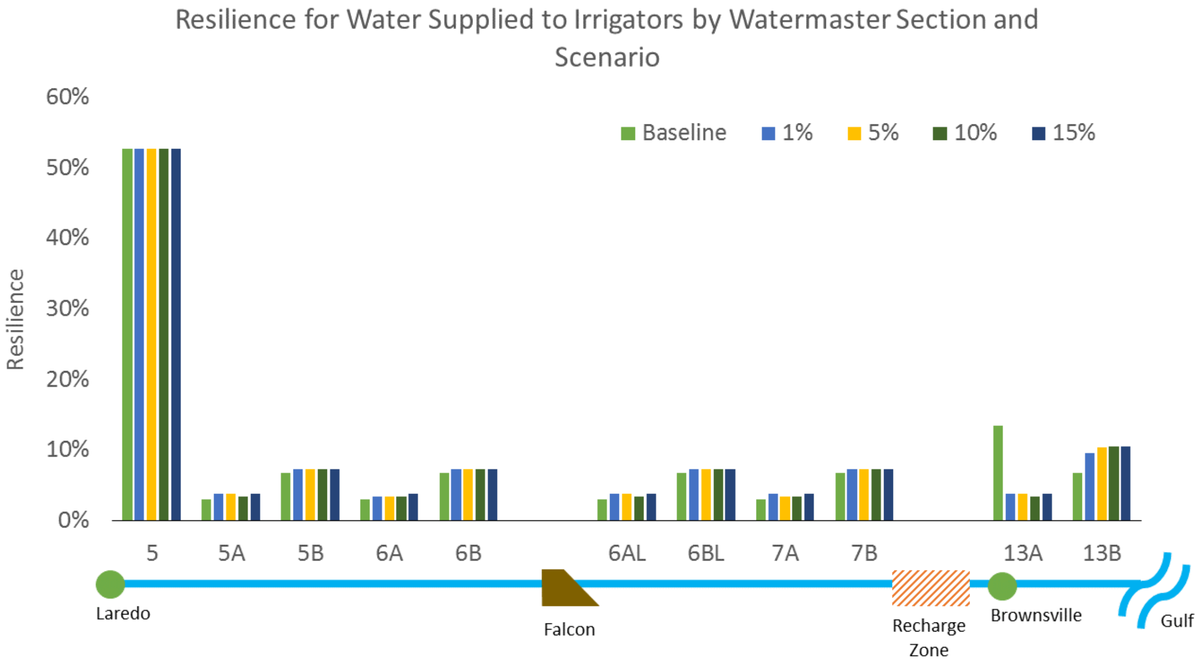

Figure B.2: Resilience for irrigators following trades of varying amounts of saved water, shown by watermaster group.

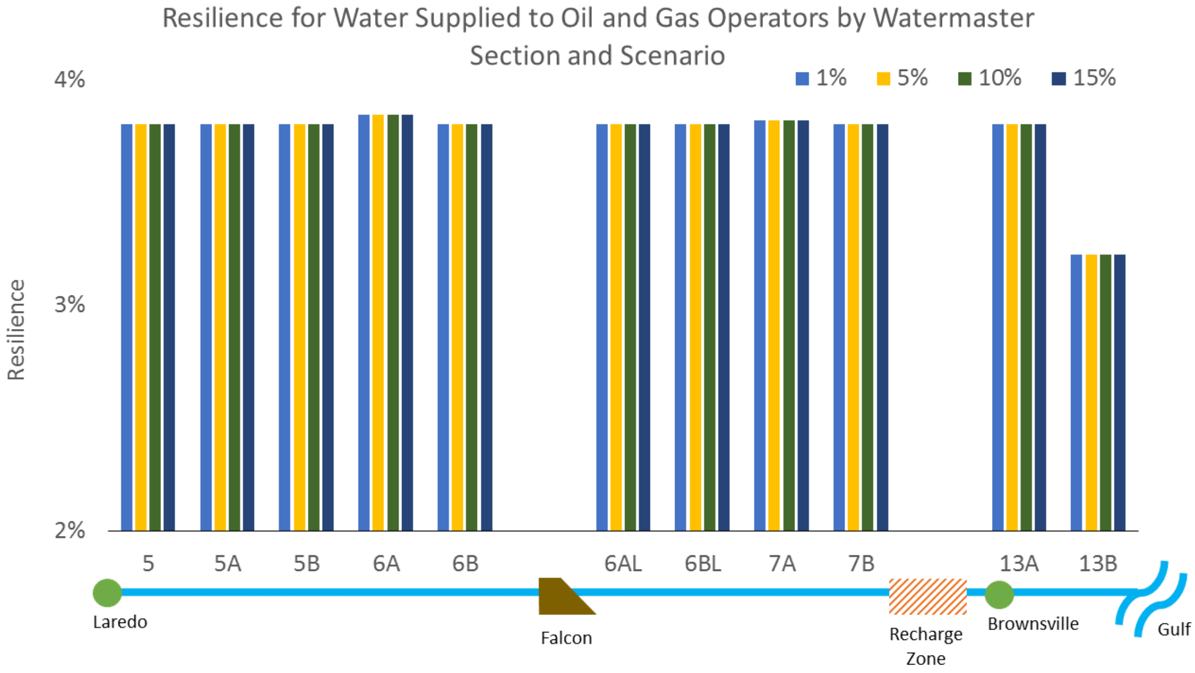

Figure B.3: Resilience for oil and gas operators following trades of varying amounts of saved water, shown by watermaster group.

watermaster sections saving water. Resilience is constant across scenarios at approximately 4%. This low resilience indicates a general inability to recover from drought in consecutive years.

B.3 Vulnerability

Figure B.4 displays the vulnerability of water supplied to irrigators in watermaster sections after saving water under each scenario: 1%, 5%, 10%, and 15% water savings. Vulnerability for irrigators saving water is low, varying between 0.04% and 0.12% depending on the watermaster section.

Figure B.5 displays the vulnerability of water supplied to oil and gas operators for each of the water saving scenarios: 1%, 5%, 10%, and 15% from each of the

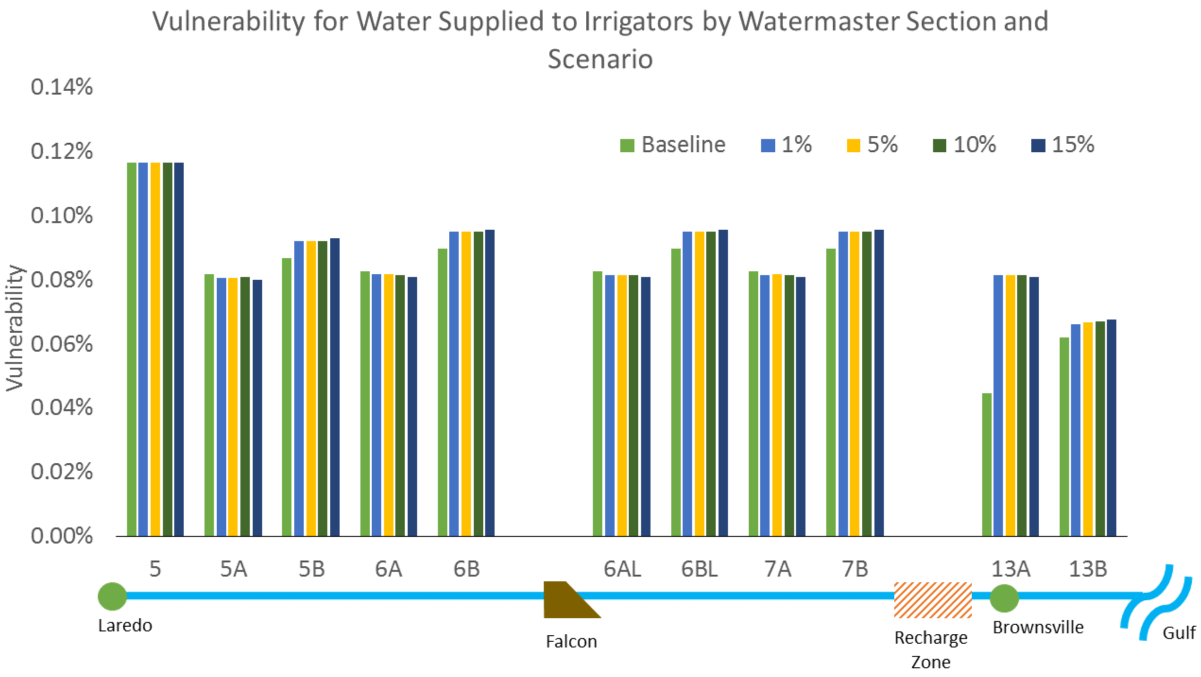

Figure B.4: Vulnerability for irrigators following trades of varying amounts of saved water, shown by watermaster group.

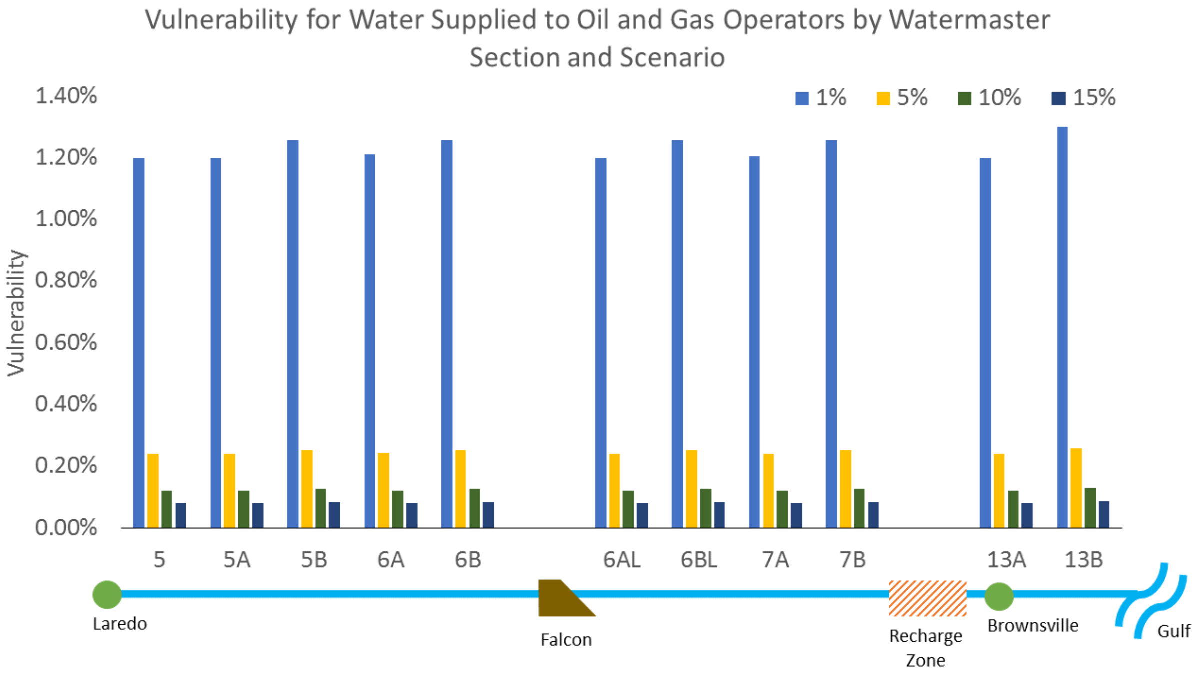

Figure B.5: vulnerability for oil and gas operators following trades of varying amounts of saved water, shown by watermaster group.

watermaster sections saving water. Vulnerability for oil and gas operators receiving saved water is low, decreasing as water conservation increases.

Appendix C

Reliability, Resilience, and Vulnerability for Trades on the Brazos

C.1 Reliability

Figures in this section display the effects of water trading scenarios on reliability for users throughout the Brazos Basin. Figures C.1 and C.2 show reliability for agriculture case 1 and 2, respectively. Figures C.3, 5.6, and C.4 show reliability for municipal cases 1, 2, and 3, respectively. Figures C.5, C.7, C.9, C.11, and C.13 show results for thermoelectric power hybrid cooling cases. Figures C.6, C.8, C.10, C.12, and C.14 show results for thermoelectric power dry cooling cases.

Reliability is measured as the frequency of a system to receive its full demand (frequency of non-deficit periods). The figures show a change reliability for individual users in the basin. Some of the cases shown have minimal third party effects (for example, Figure C.12). Some cases affect many users, but most effects are beneficial (for example, Figure C.2). Conversely, some cases affect many users negatively (for example, C.6). It is important to determine individual changes in reliability (third party effects) in response to a reallocation of water in a trade to be able to mitigate them at the watermaster level.

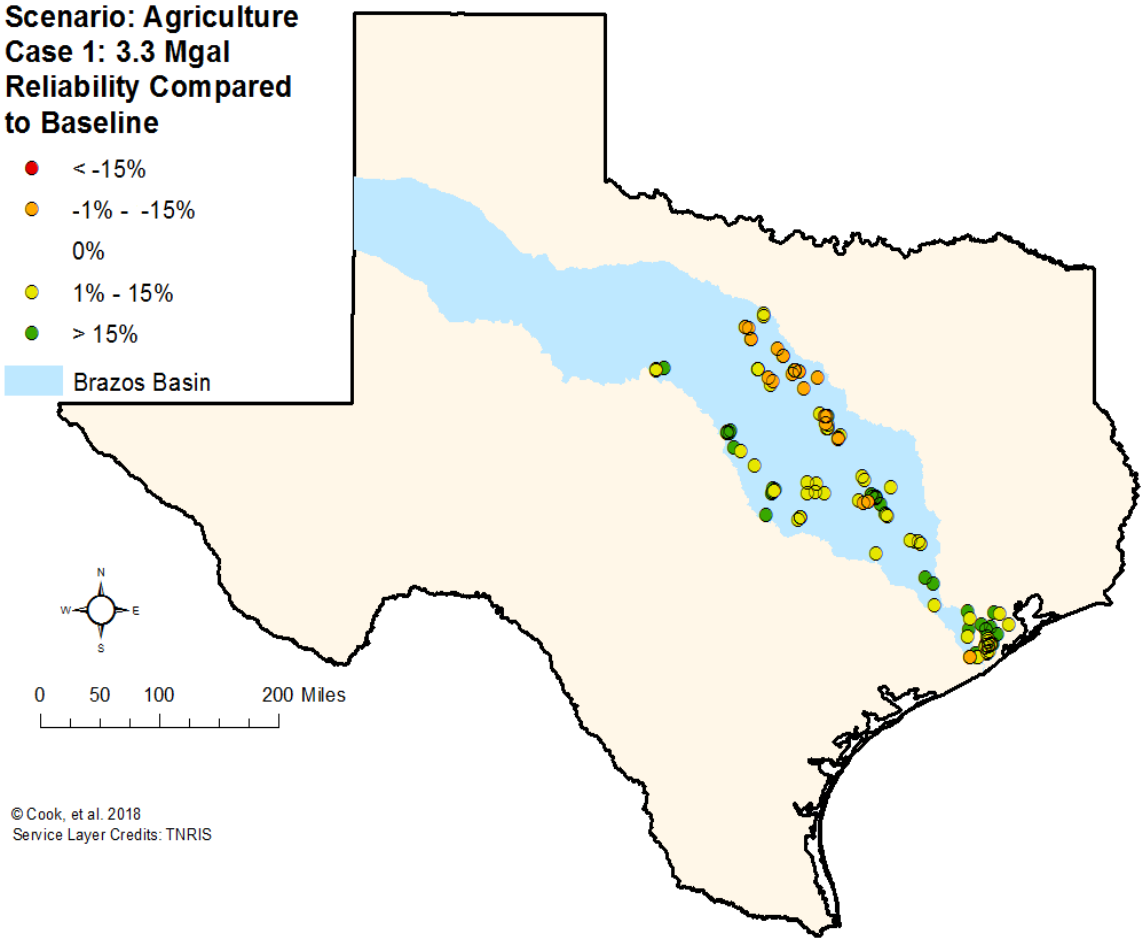

Figure C.1: After trading for saved water under Agriculture Case 1, many users benefit from improved reliability and some users experience reduced reliability. All decreases in reliability are under 15% compared to the baseline.

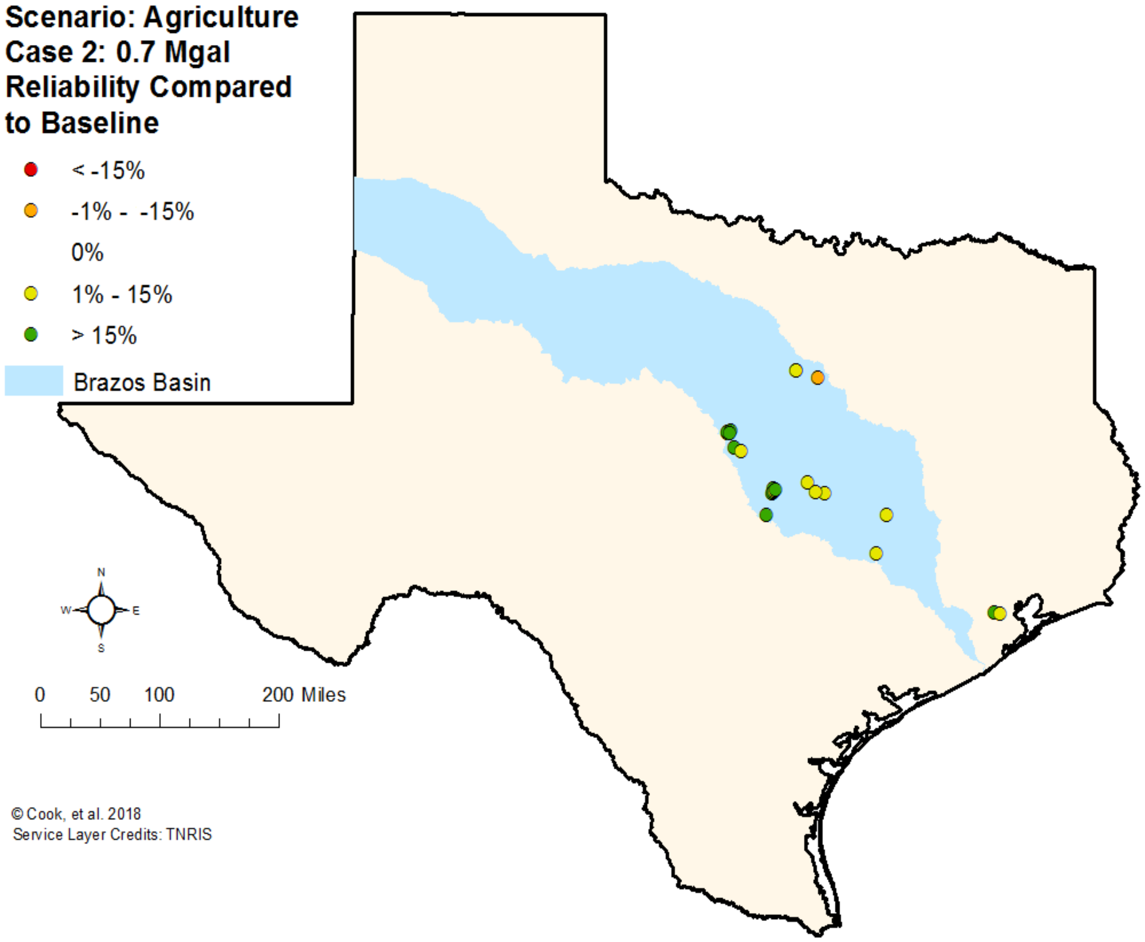

Figure C.2: After trading for saved water under Agriculture Case 2, many users benefit from improved reliability and one user experiences reduced reliability. All decreases in reliability are under 15% compared to the baseline.

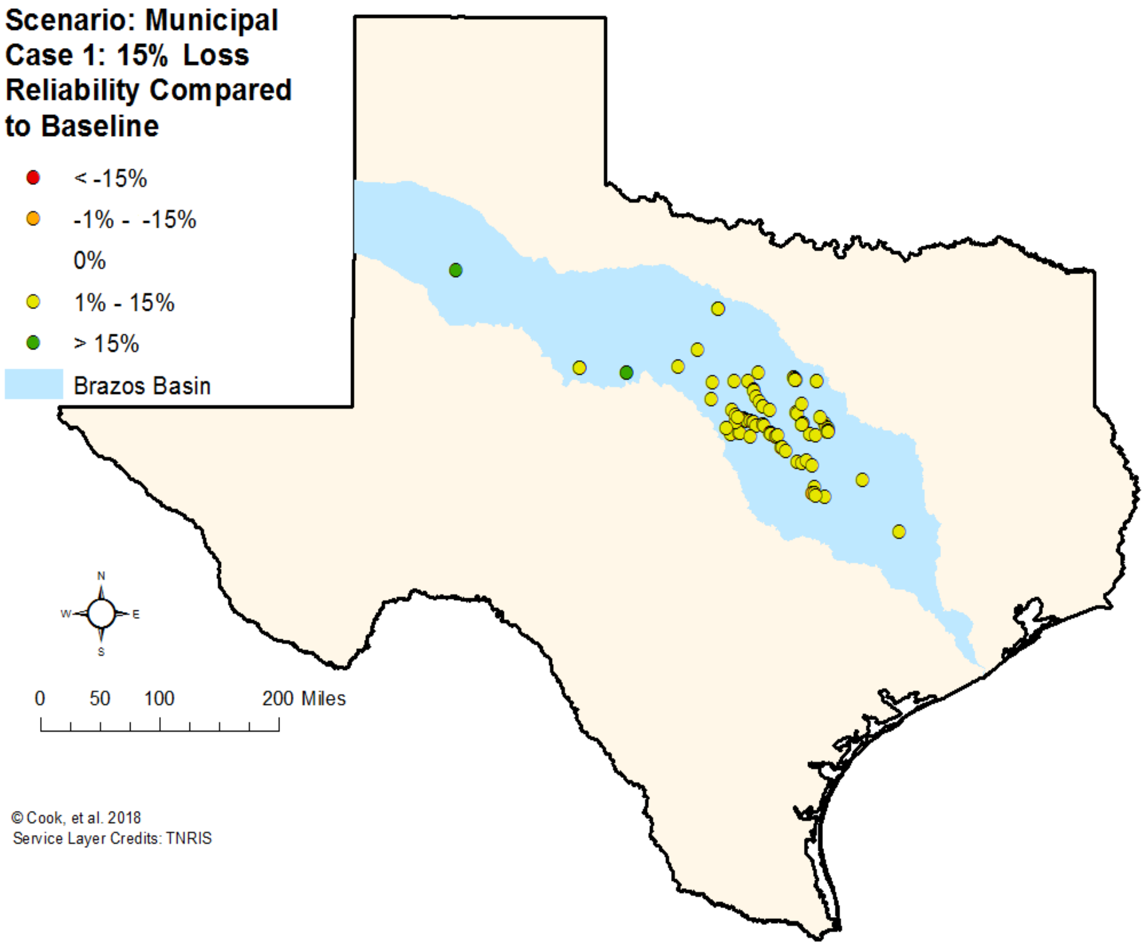

Figure C.3: After trading for saved water under Municipal Case 1, many users benefit from improved reliability. All decreases in reliability are under 15% compared to the baseline.

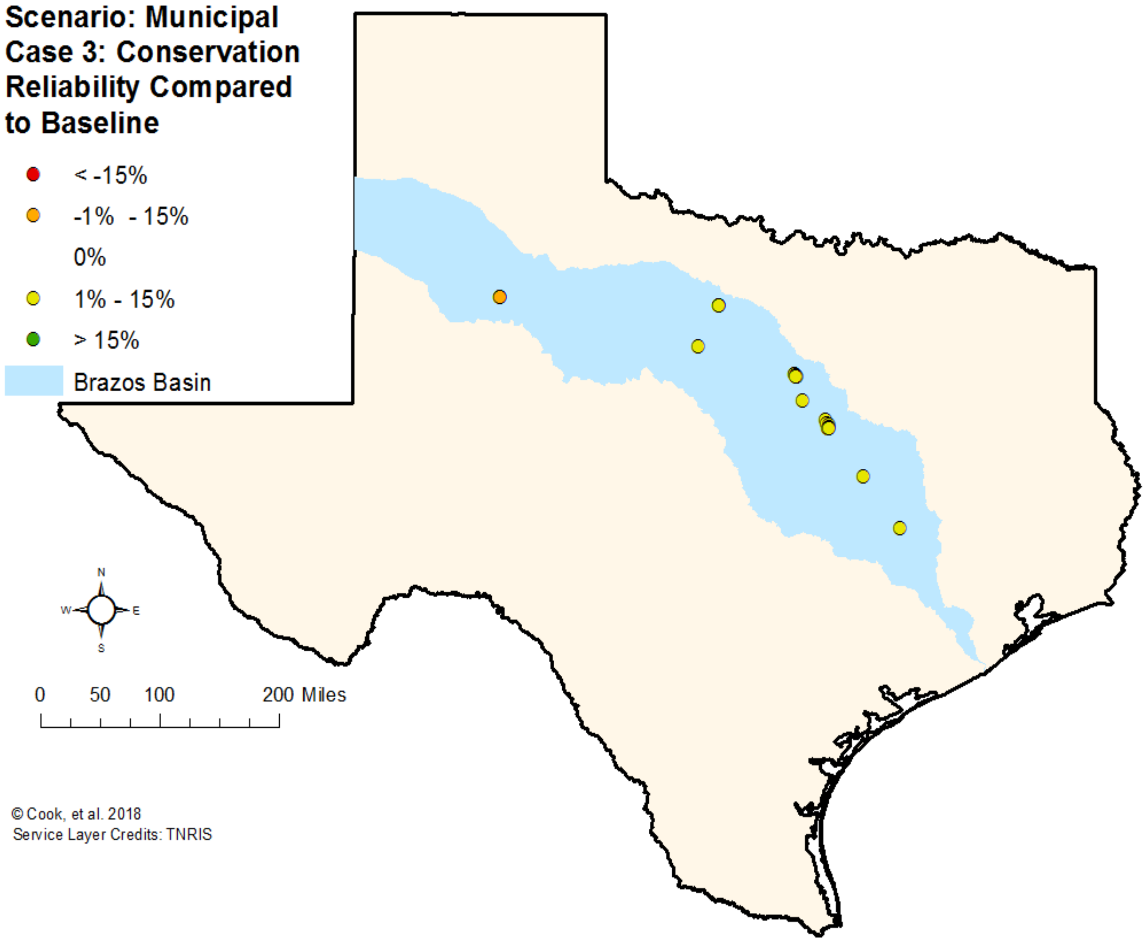

Figure C.4: After trading for saved water under Municipal Case 3, many users benefit from improved reliability and one user experiences reduced reliability. Changes in reliability are under 15% compared to the baseline.

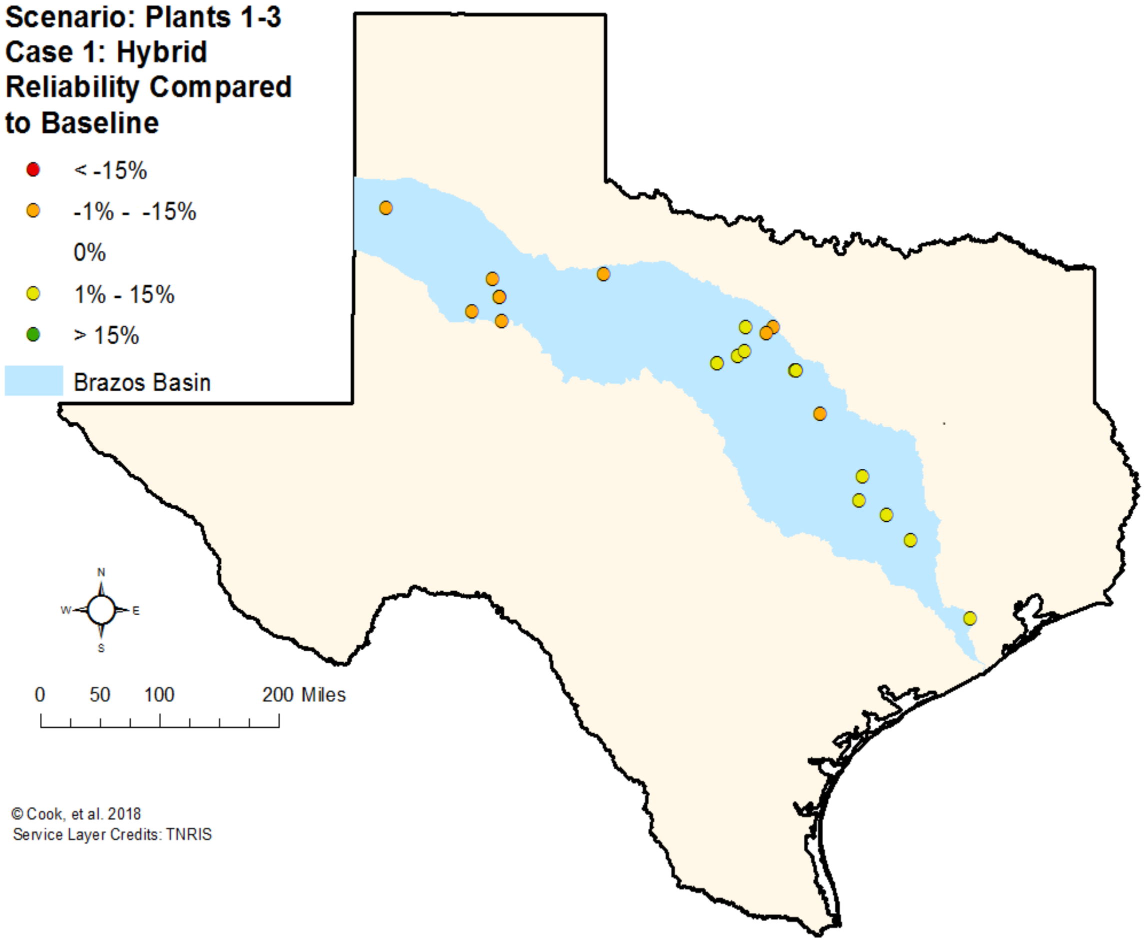

Figure C.5: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 1–3, some users benefit from improved reliability and some users experience reduced reliability. Changes in reliability are under 15% compared to the baseline.

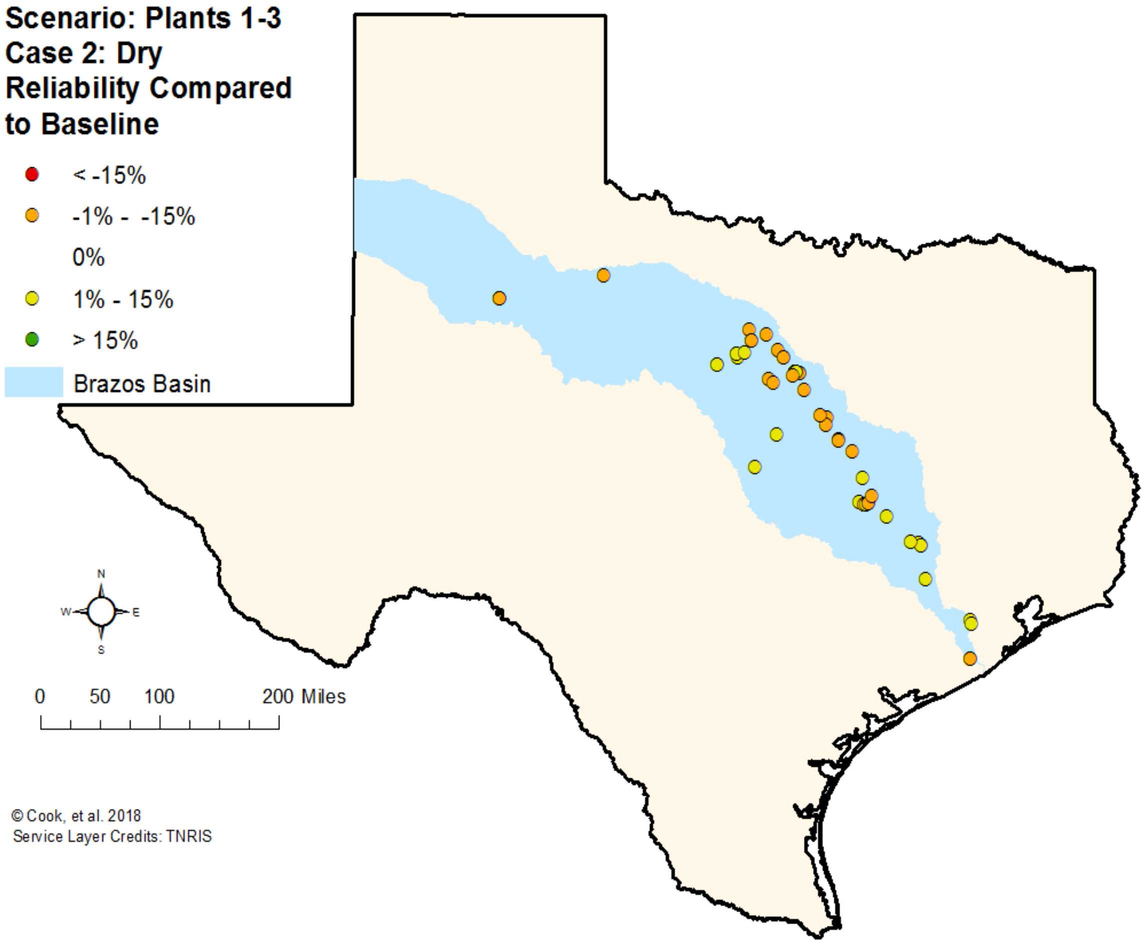

Figure C.6: After trading for saved water under a Dry Cooling Scenario for Power Plants 1–3, some users benefit from improved reliability and many users experience reduced reliability. Changes in reliability are under 15% compared to the baseline.

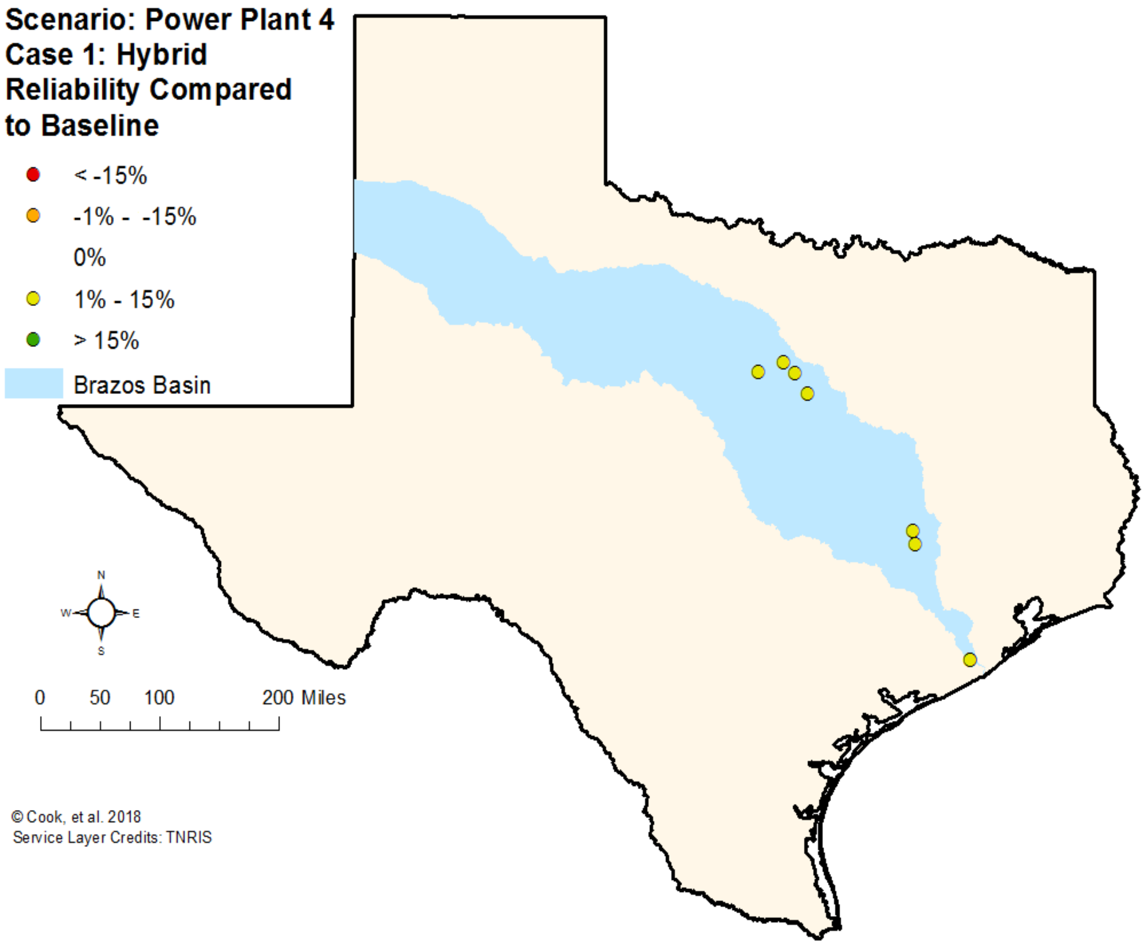

Figure C.7: After trading for saved water under a Hybrid Cooling Scenario for Power Plant 4, some users benefit from improved reliability. Increases in reliability are under 15% compared to the baseline.

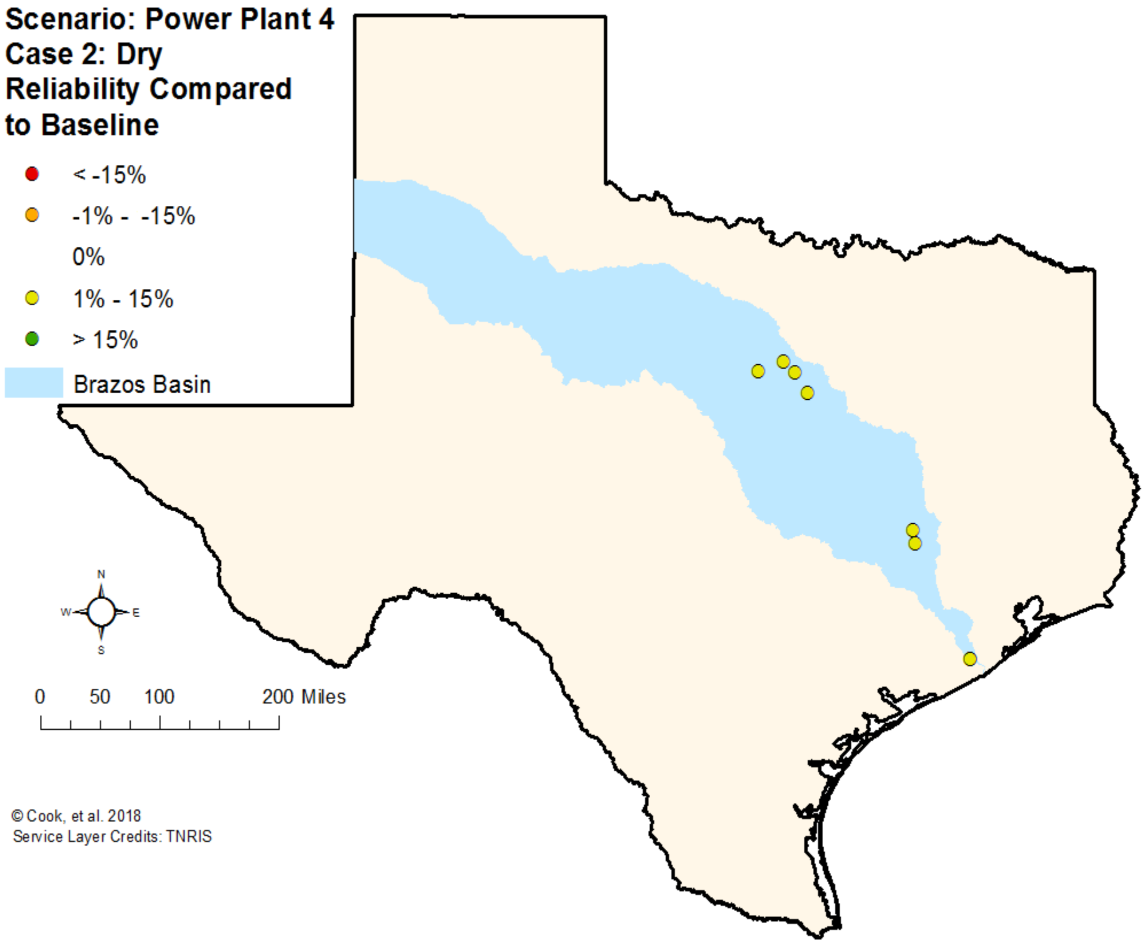

Figure C.8: After trading for saved water under a Dry Cooling Scenario for Power Plant 4, some users benefit from improved reliability. Increases in reliability are under 15% compared to the baseline.

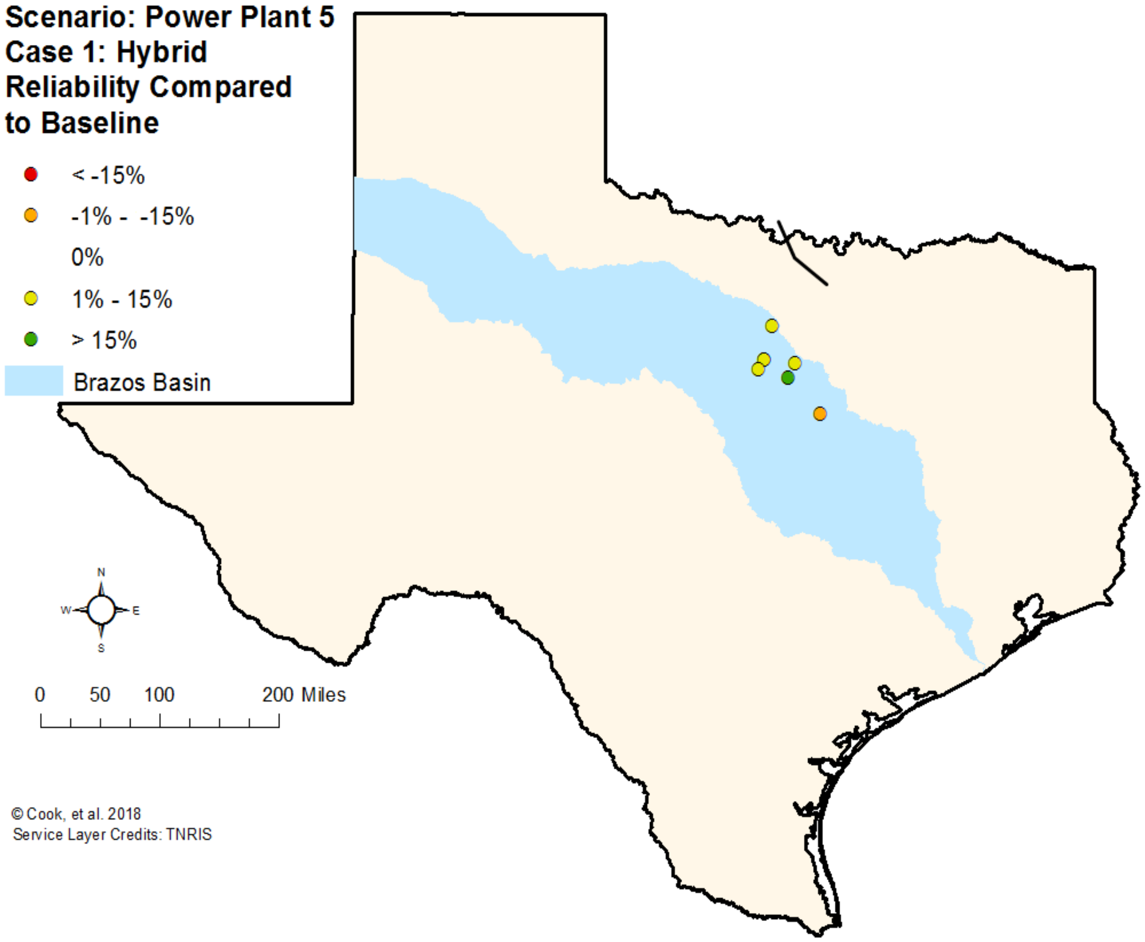

Figure C.9: After trading for saved water under a Hybrid Cooling Scenario for Power Plant 5, some users benefit from improved reliability and one user experiences reduced reliability. The decrease in reliability is under 15% compared to the baseline.

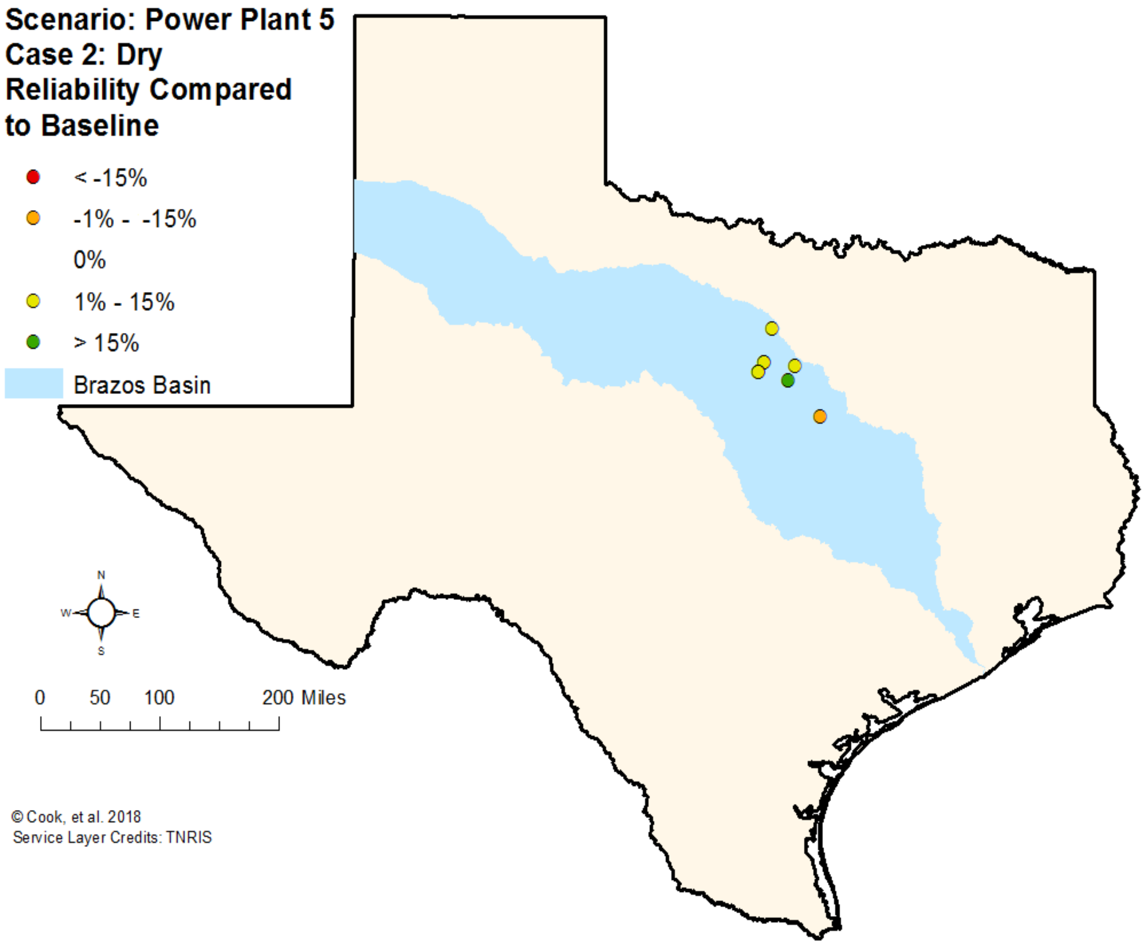

Figure C.10: After trading for saved water under a Dry Cooling Scenario for Power Plant 5, some users benefit from improved reliability and one user experiences reduced reliability. The decrease in reliability is under 15% compared to the baseline.

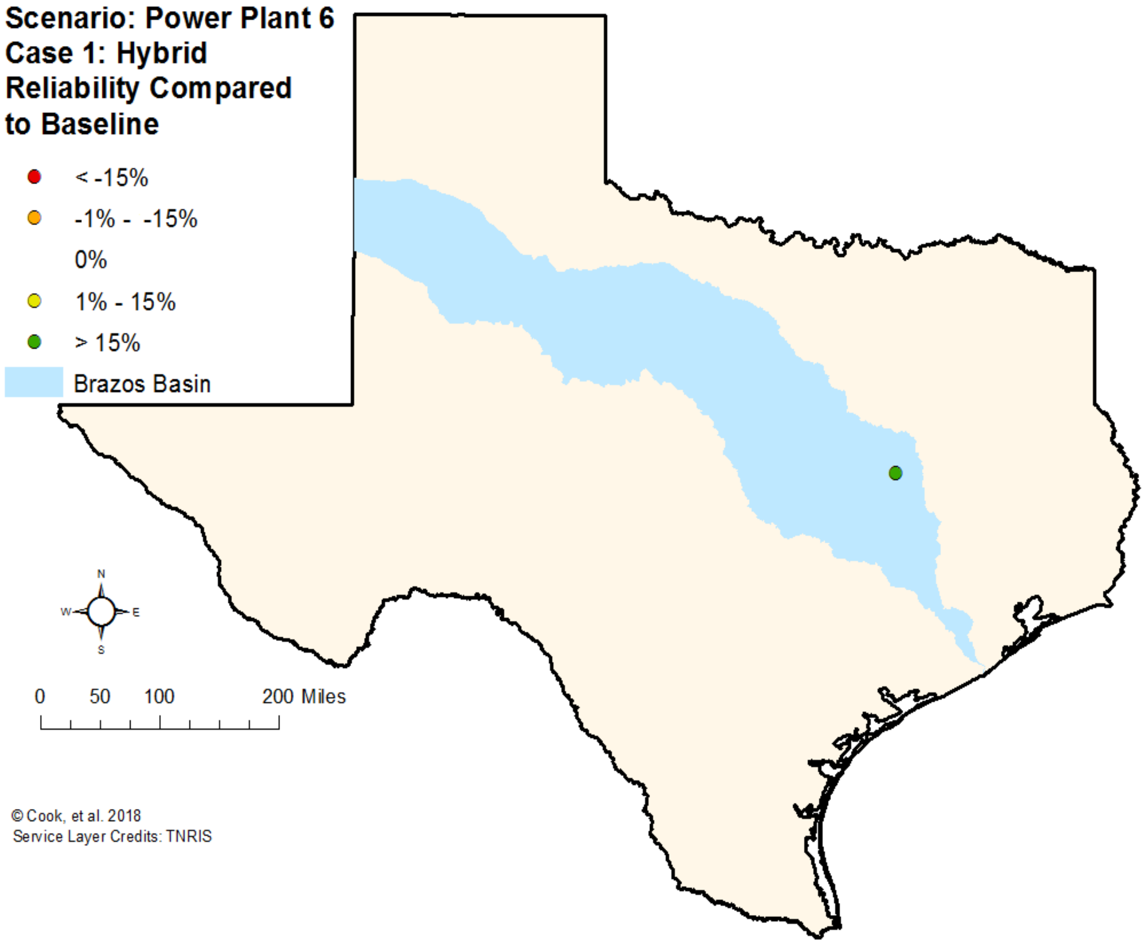

Figure C.11: After trading for saved water under a Hybrid Cooling Scenario for Power Plant 6, one user benefits from improved reliability above 15% compared to the baseline.

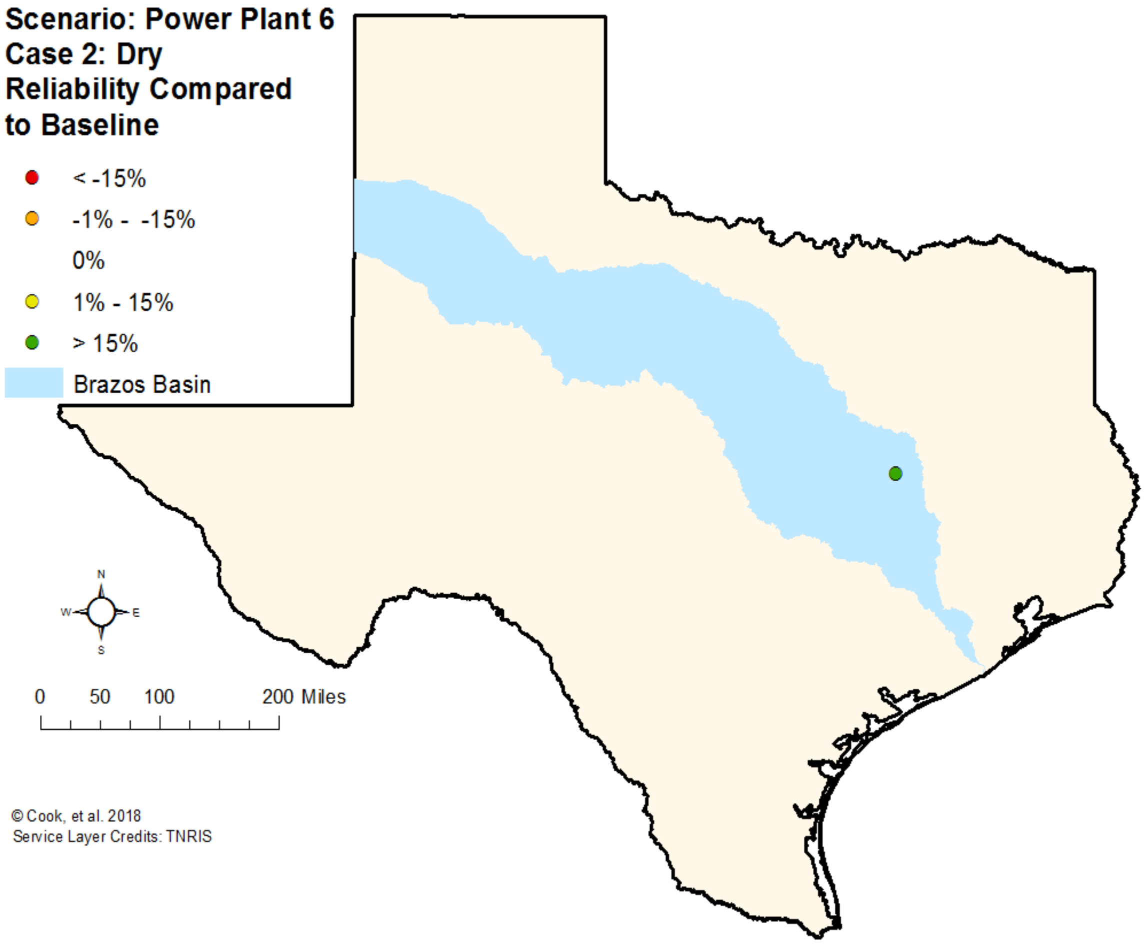

Figure C.12: After trading for saved water under a Dry Cooling Scenario for Power Plant 6, one user benefits from improved reliability above 15% compared to the baseline.

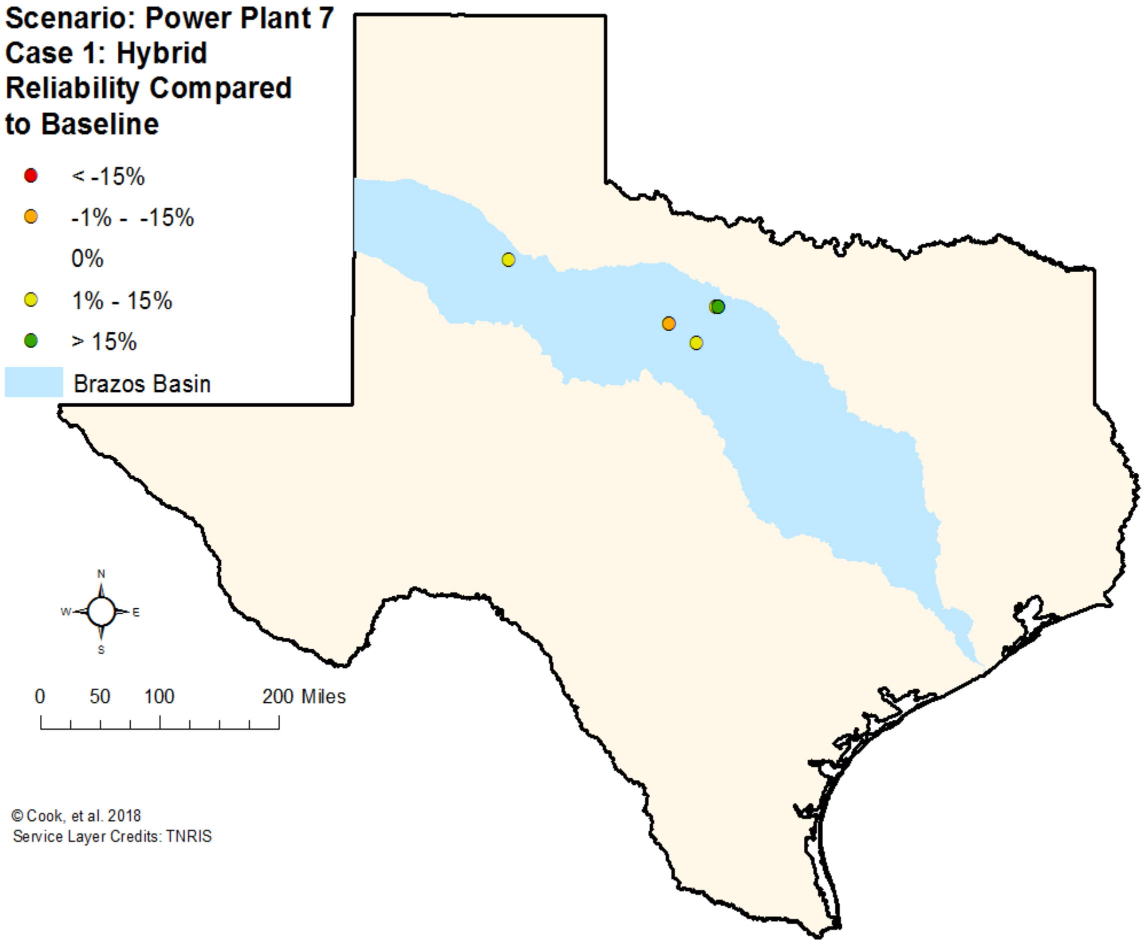

Figure C.13: After trading for saved water under a Dry Cooling Scenario for Power Plant 7, some users benefit from improved reliability and one user experiences reduced reliability. The decrease in reliability is under 15% compared to the baseline.

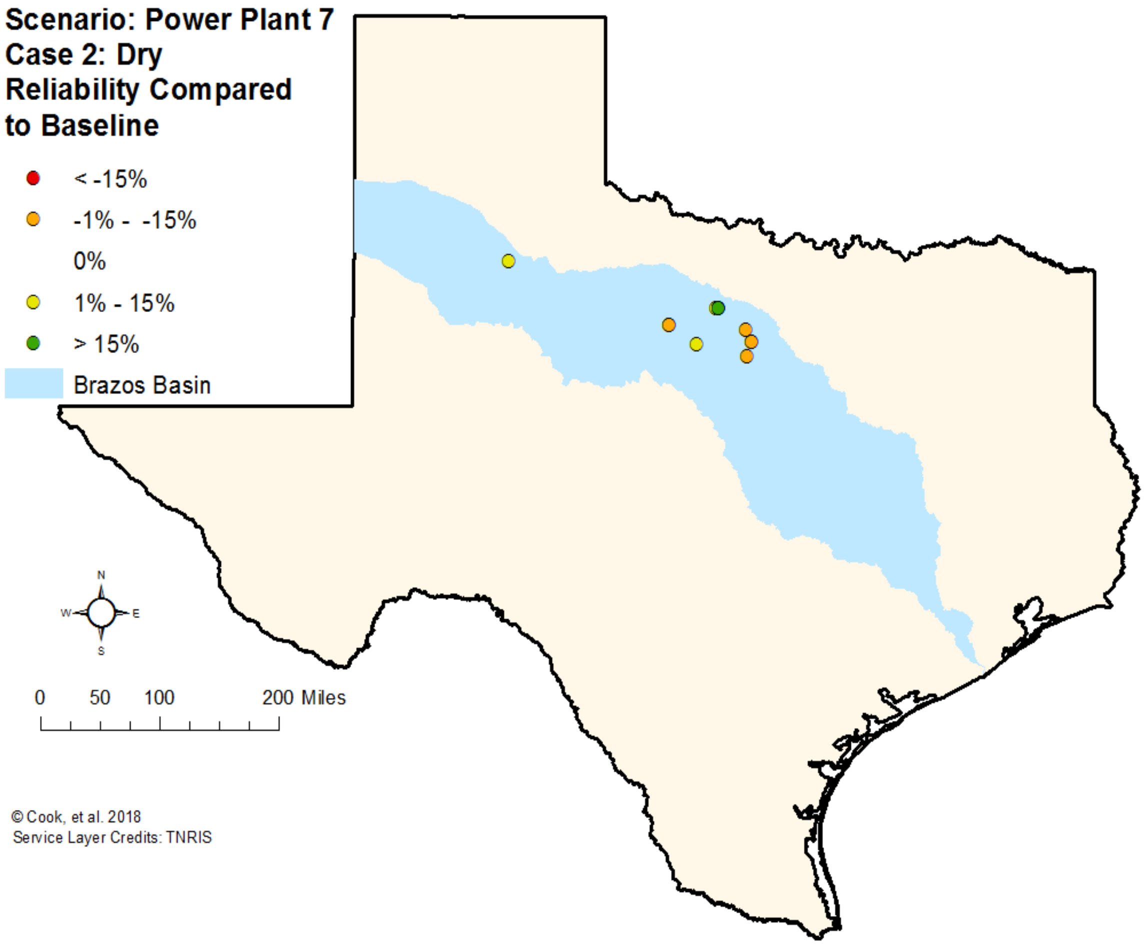

Figure C.14: After trading for saved water under a Dry Cooling Scenario for Power Plant 7, some users benefit from improved reliability and some users experience reduced reliability. Decreases in reliability are under 15% compared to the baseline.

C.2 Resilience

Figures in this section display the effects of water trading scenarios on resilience for users throughout the Brazos Basin. Figures C.15 and C.16 show resilience for agriculture case 1 and 2, respectively. Figures C.17, 5.7, and C.18 show resilience for municipal cases 1, 2, and 3, respectively. Figures C.19, C.21, C.23, C.25, and C.27 show results for thermoelectric power hybrid cooling cases. Figures C.20, C.22, C.24, C.26, and C.28 show results for thermoelectric power dry cooling cases. Scenarios not shown experienced no change in resilience compared to the baseline.

Resilience is measured as the ability to recover after a deficit. The figures show a change in the ability to recover from deficit for individual users in the basin. Some of the cases shown have minimal effects on resilience (for example, Figure C.26). Some cases affect many users, but most effects are beneficial (for example, Figure C.15). Conversely, some cases affect many users negatively (for example, C.17). It is important to determine individual changes in ability to recover from deficit in response to a reallocation of water in a trade to be able to mitigate them at the watermaster level, if possible.

C.3 Vulnerability

Figures in this section display the effects of water trading scenarios on vulnerability for users throughout the Brazos Basin. Figures C.29 and C.30 show vulnerability for agriculture case 1 and 2, respectively. Figures C.31, 5.8, and C.32 show vulnerability for municipal cases 1, 2, and 3, respectively. Figures C.33, C.34, and C.35, show results for thermoelectric power dry cooling cases. Scenarios not shown experience no change in vulnerability.

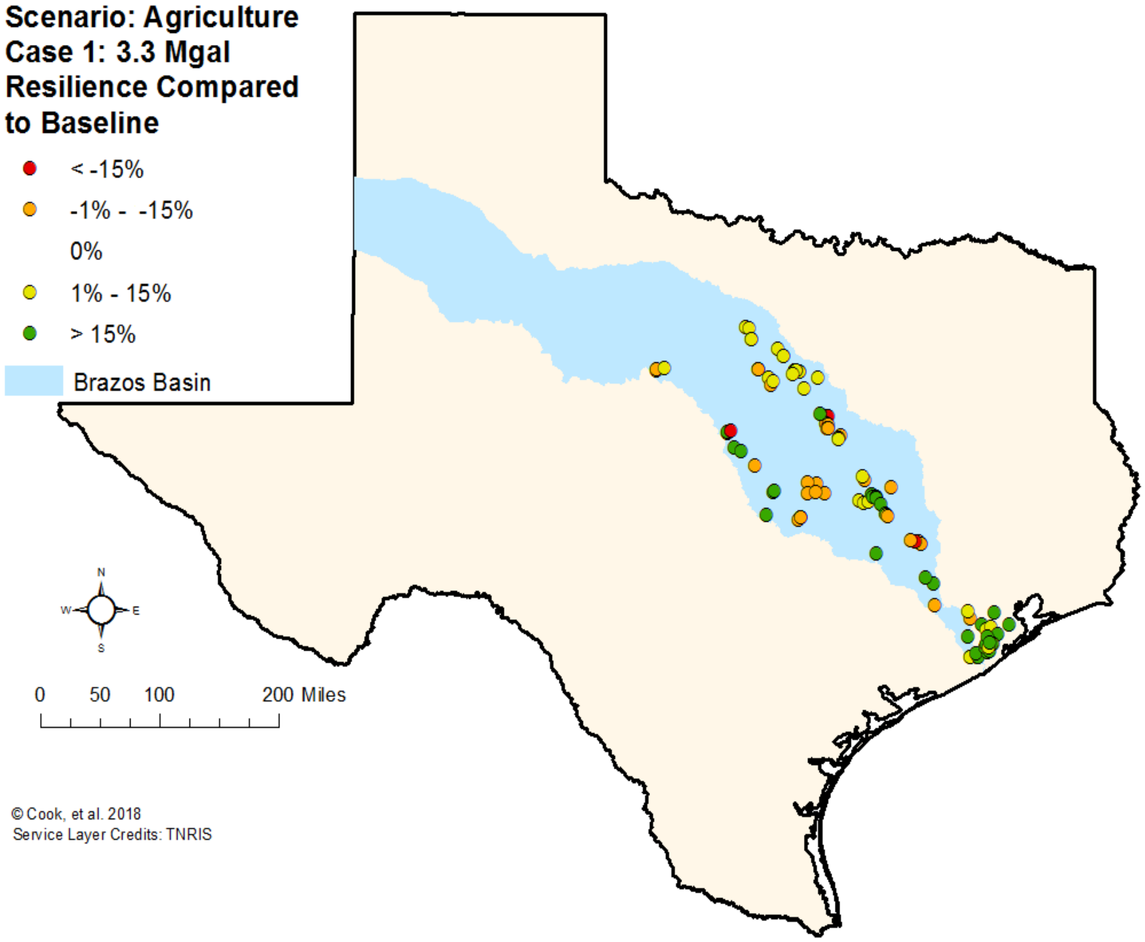

Figure C.15: After trading for saved water under Agriculture Case 1, many users benefit from improved resilience and some users experience reduced resilience. Two users experience large reductions in resilience (more than 15% compared to the baseline).

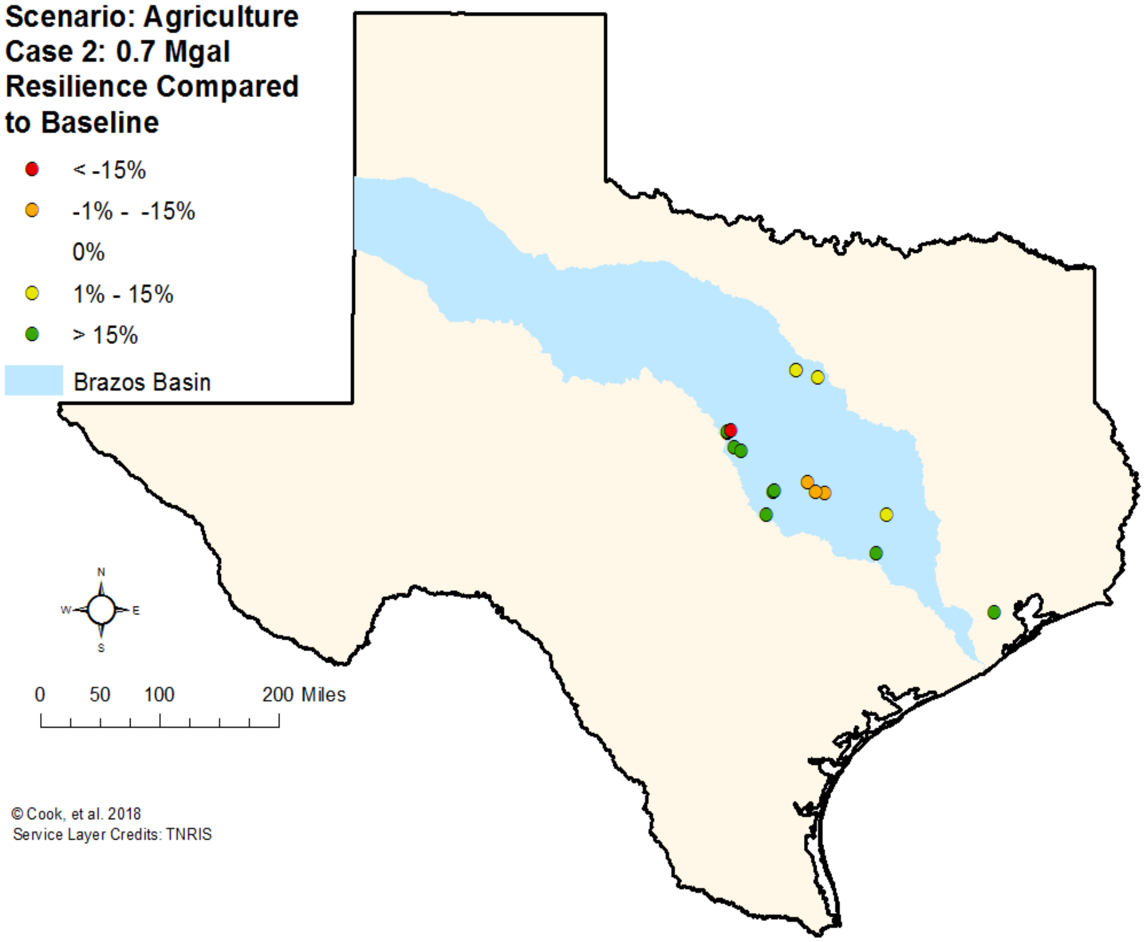

Figure C.16: After trading for saved water under Agriculture Case 2, many users benefit from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (more than 15% compared to the baseline).

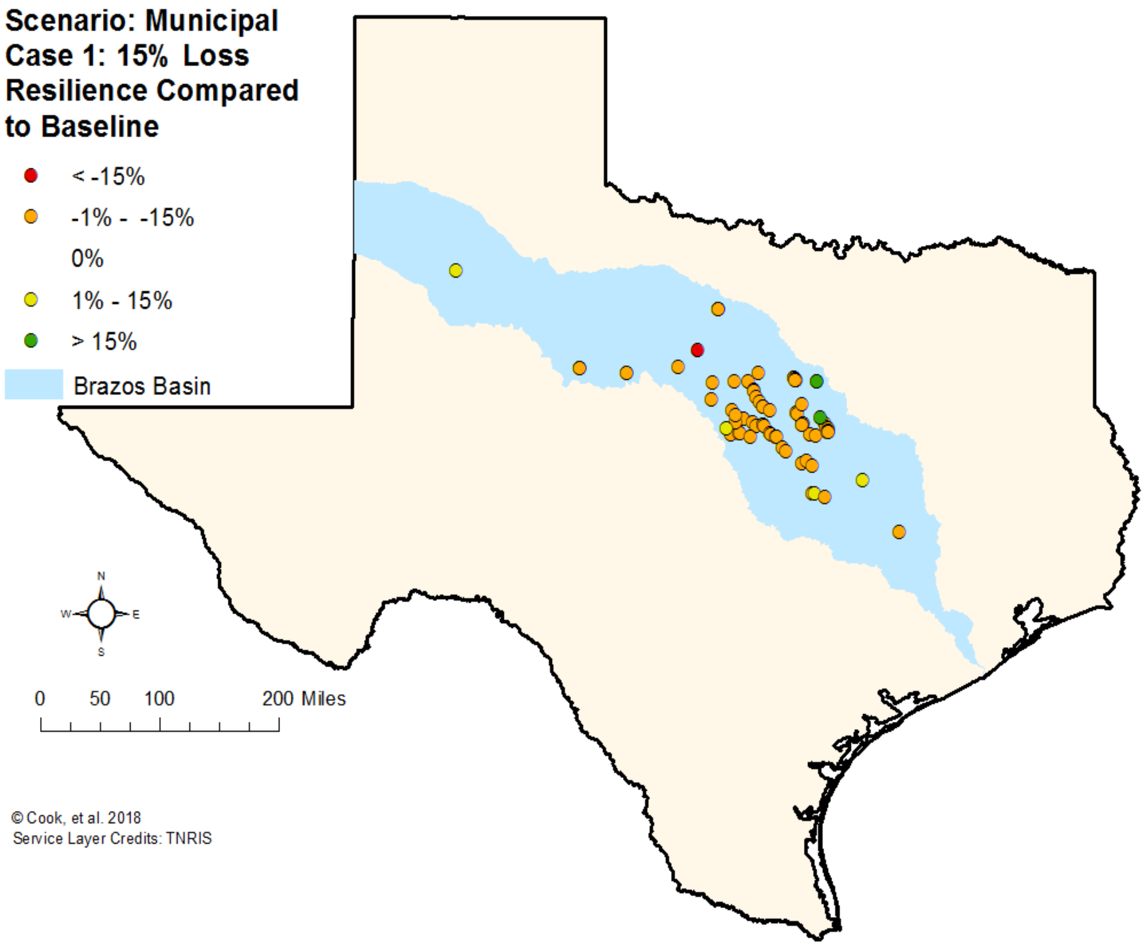

Figure C.17: After trading for saved water under Municipal Case 1, many users benefit from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (more than 15% compared to the baseline).

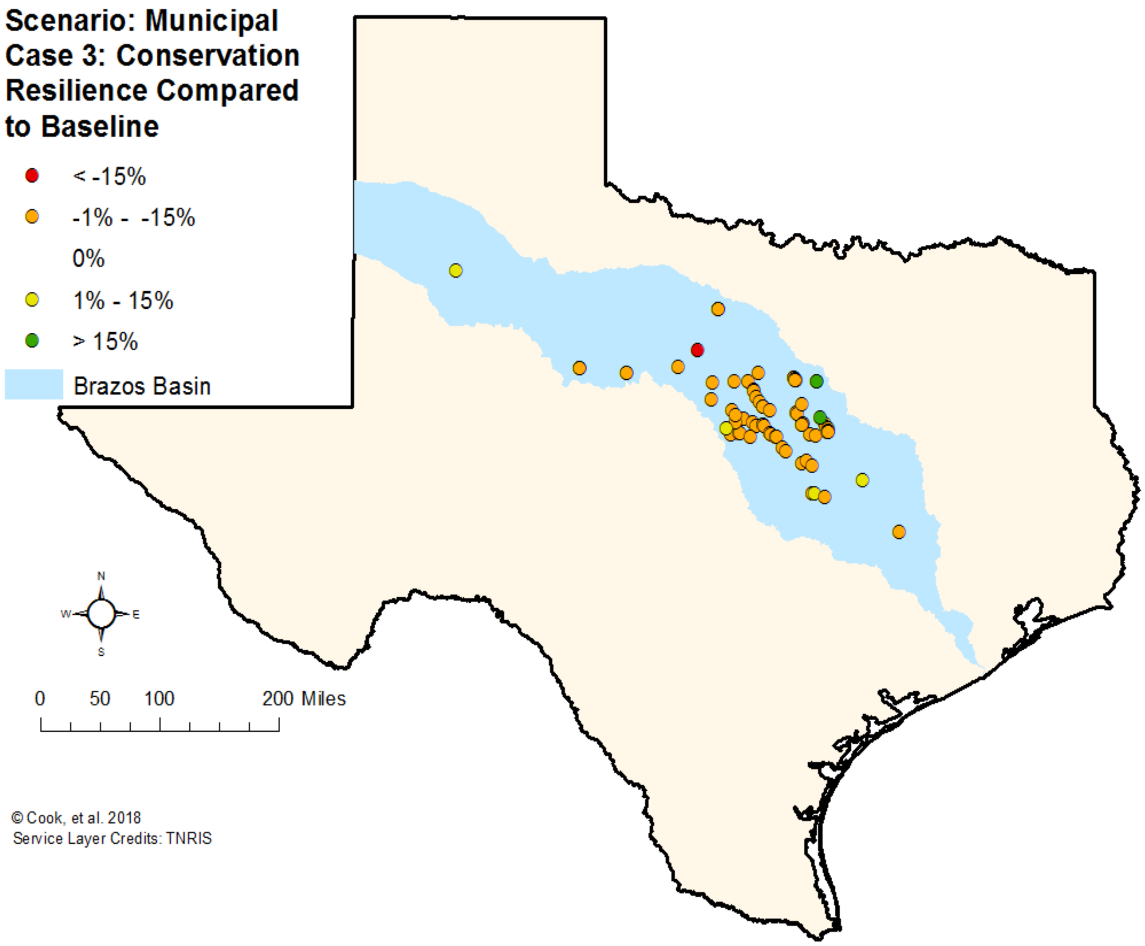

Figure C.18: After trading for saved water under Municipal Case 3, many users benefit from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (more than 15% compared to the baseline).

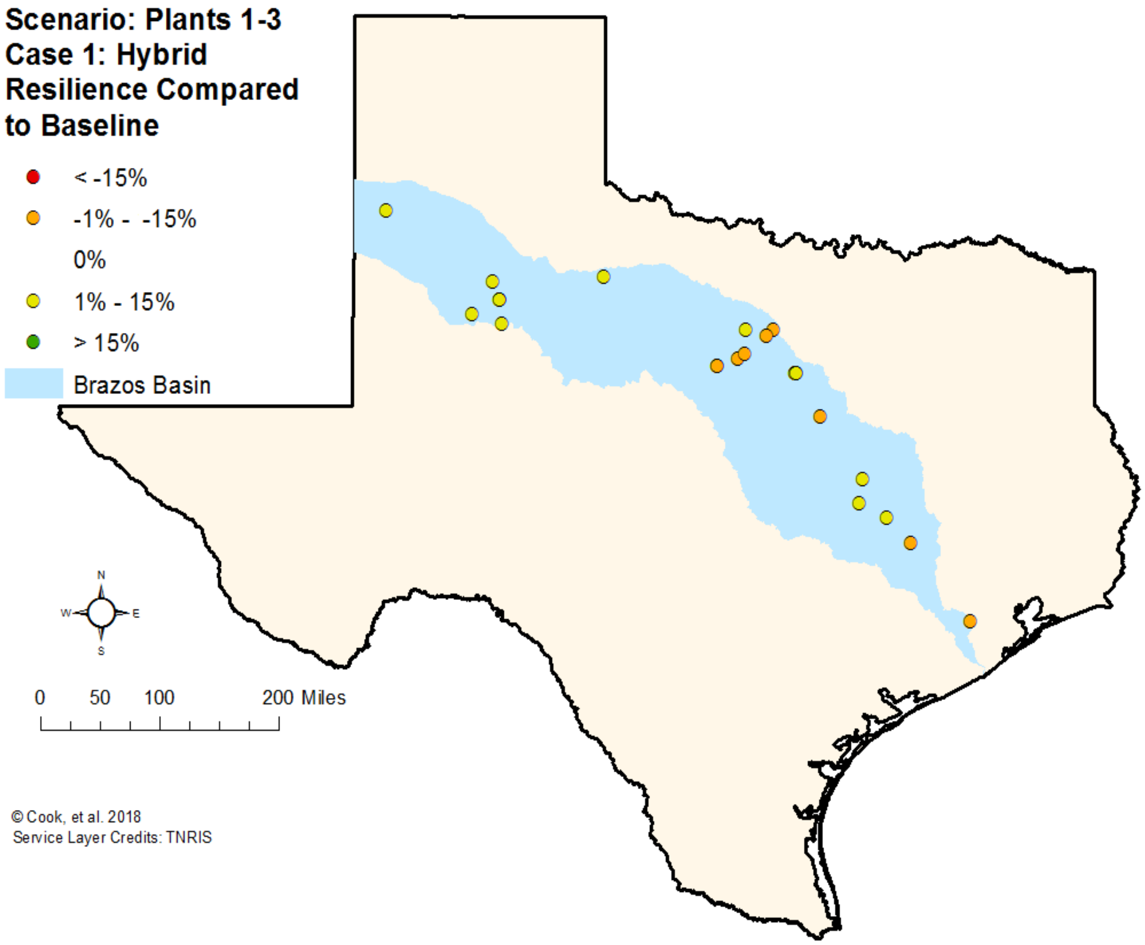

Figure C.19: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 1–3, many users benefit from improved resilience and some users experience reduced resilience. Changes in resilience are under 15% compared to the baseline.

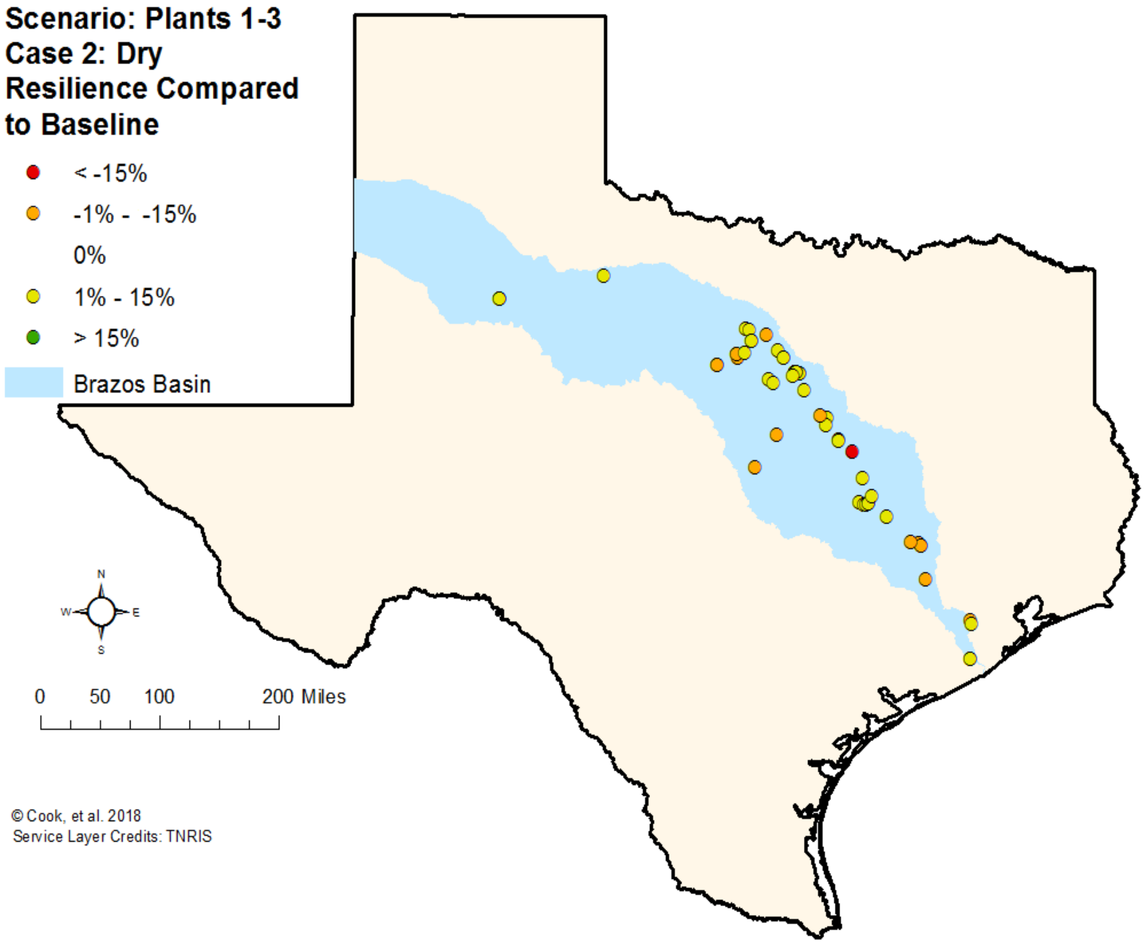

Figure C.20: After trading for saved water under a Dry Cooling Scenario for Power Plants 1–3, many users benefit from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (more than 15% compared to the baseline).

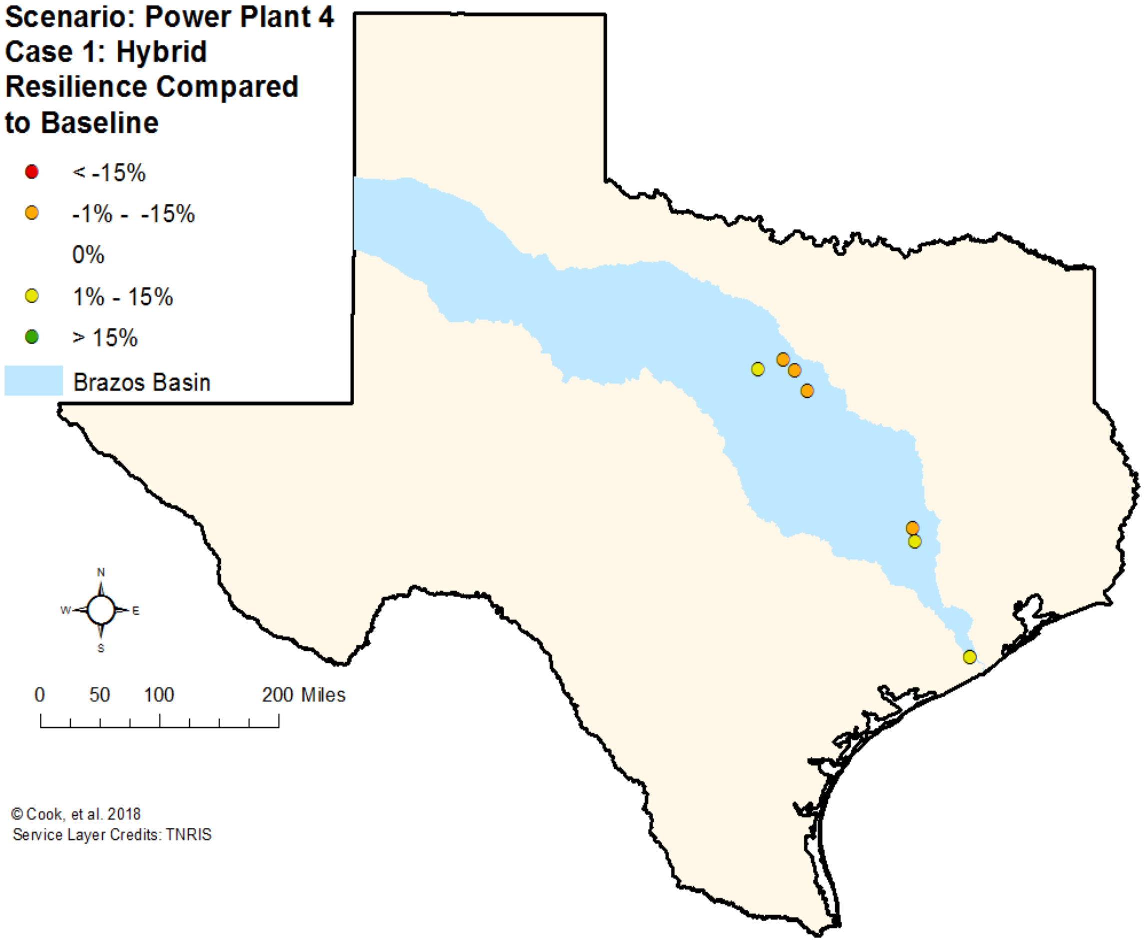

Figure C.21: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 4, some users benefit from improved resilience and some users experience reduced resilience. Changes in resilience are under 15% compared to the baseline.

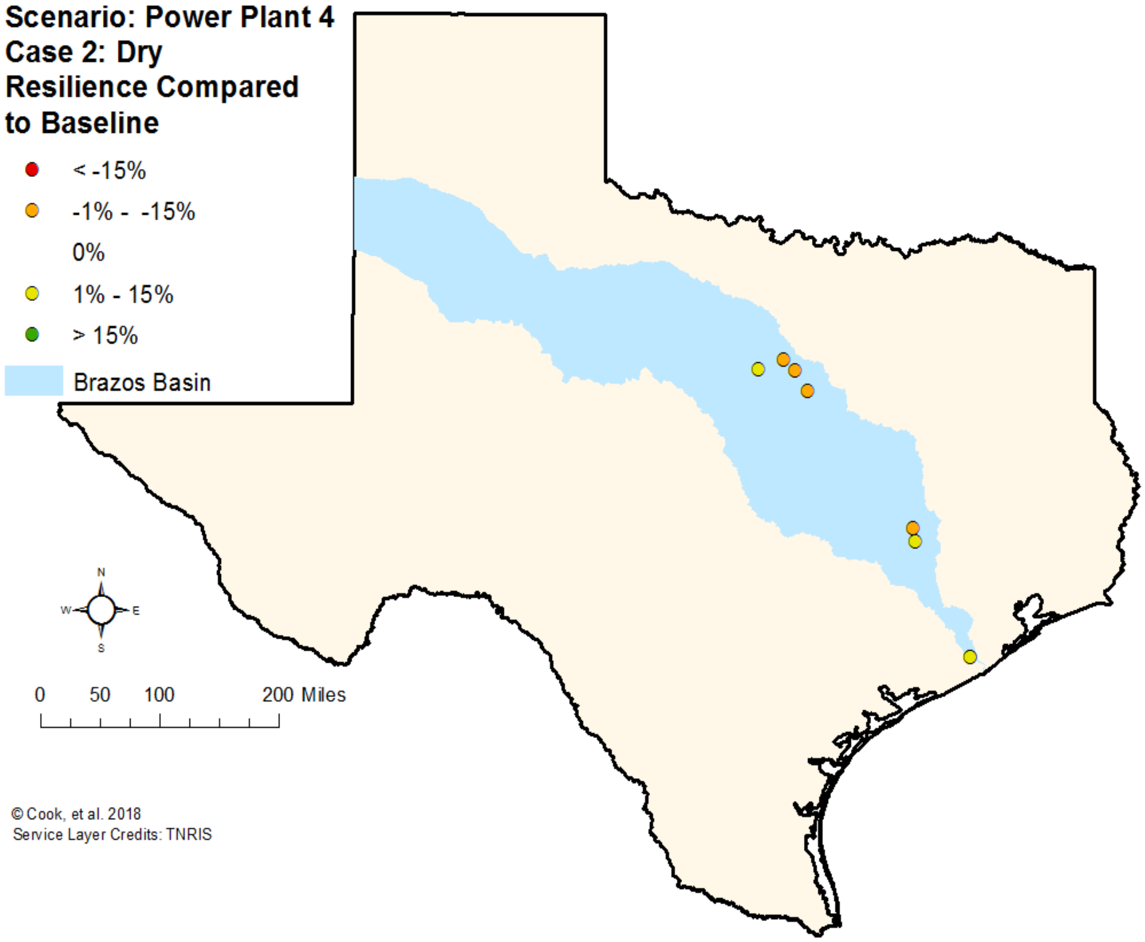

Figure C.22: After trading for saved water under a Dry Cooling Scenario for Power Plants 4, some users benefit from improved resilience and some users experience reduced resilience. Changes in resilience are under 15% compared to the baseline.

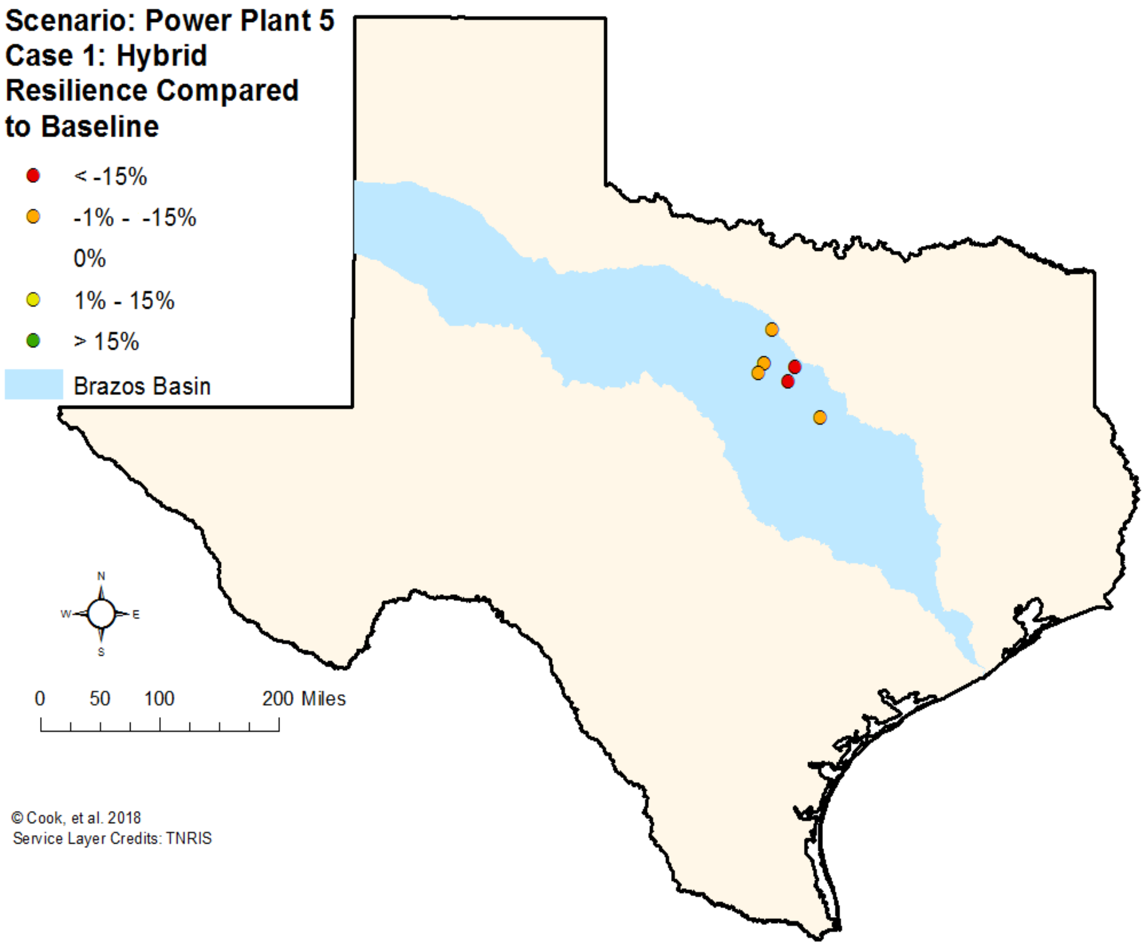

Figure C.23: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 5, no users benefit from improved resilience and some users experience reduced resilience. Two users experiences a large reduction in resilience (more than 15% compared to the baseline).

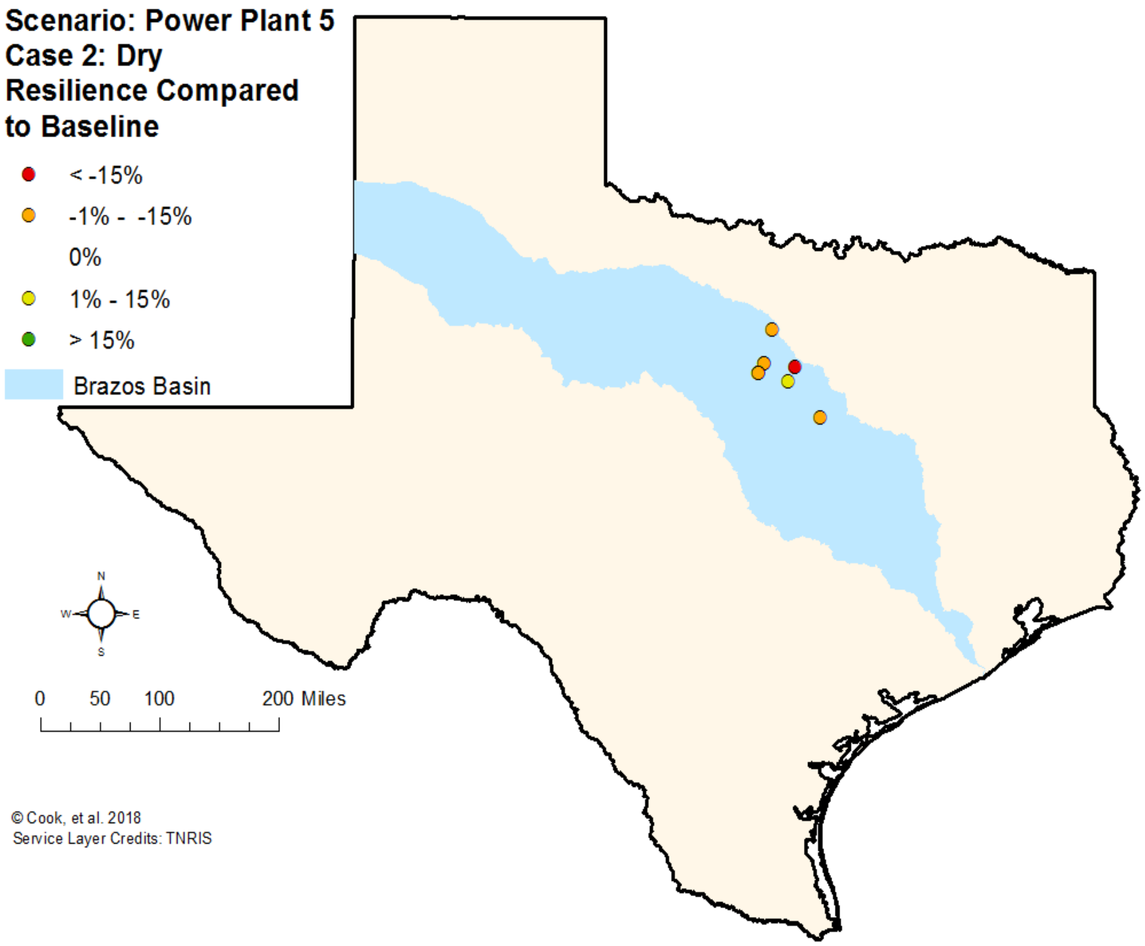

Figure C.24: After trading for saved water under a Dry Cooling Scenario for Power Plants 5, one user benefits from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (more than 15% compared to the baseline).

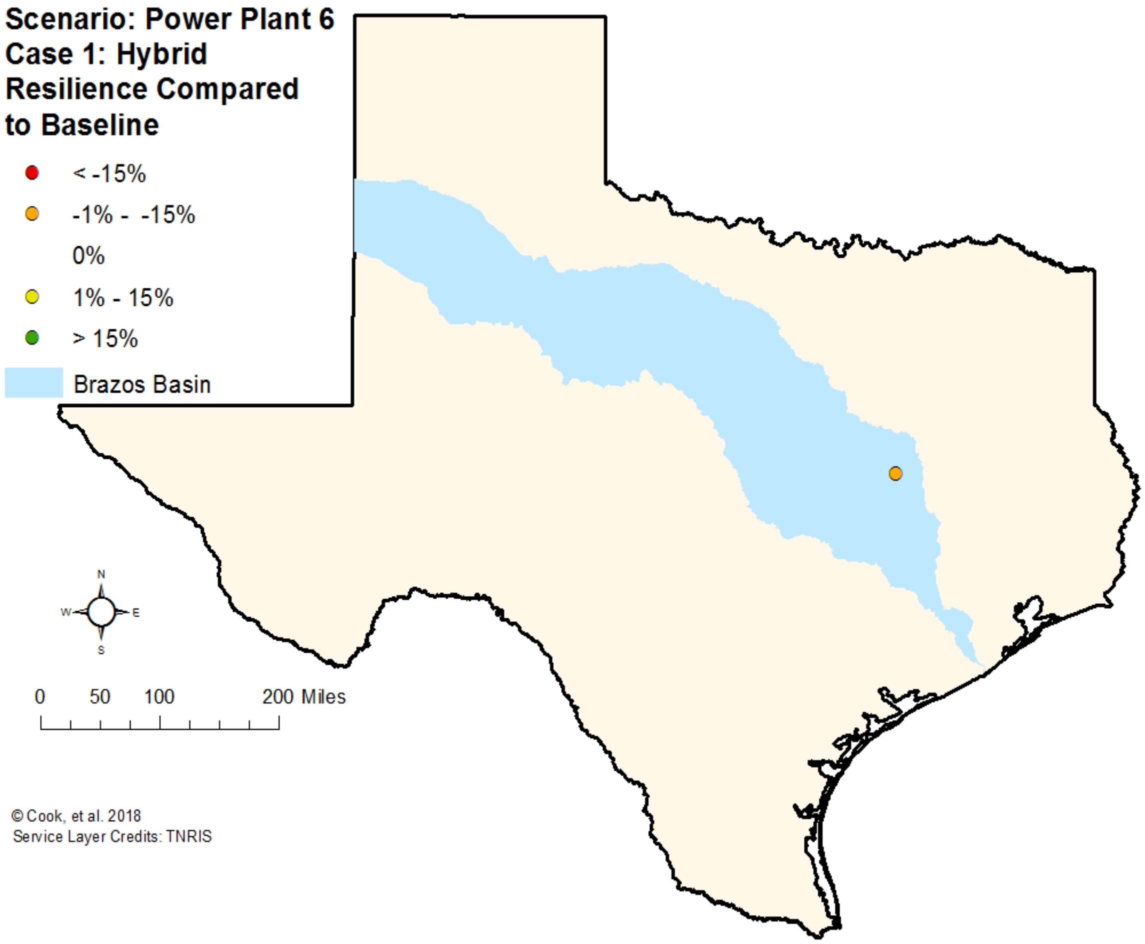

Figure C.25: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 6, most users' resilience is unaffected. One user experiences a small reduction in resilience.

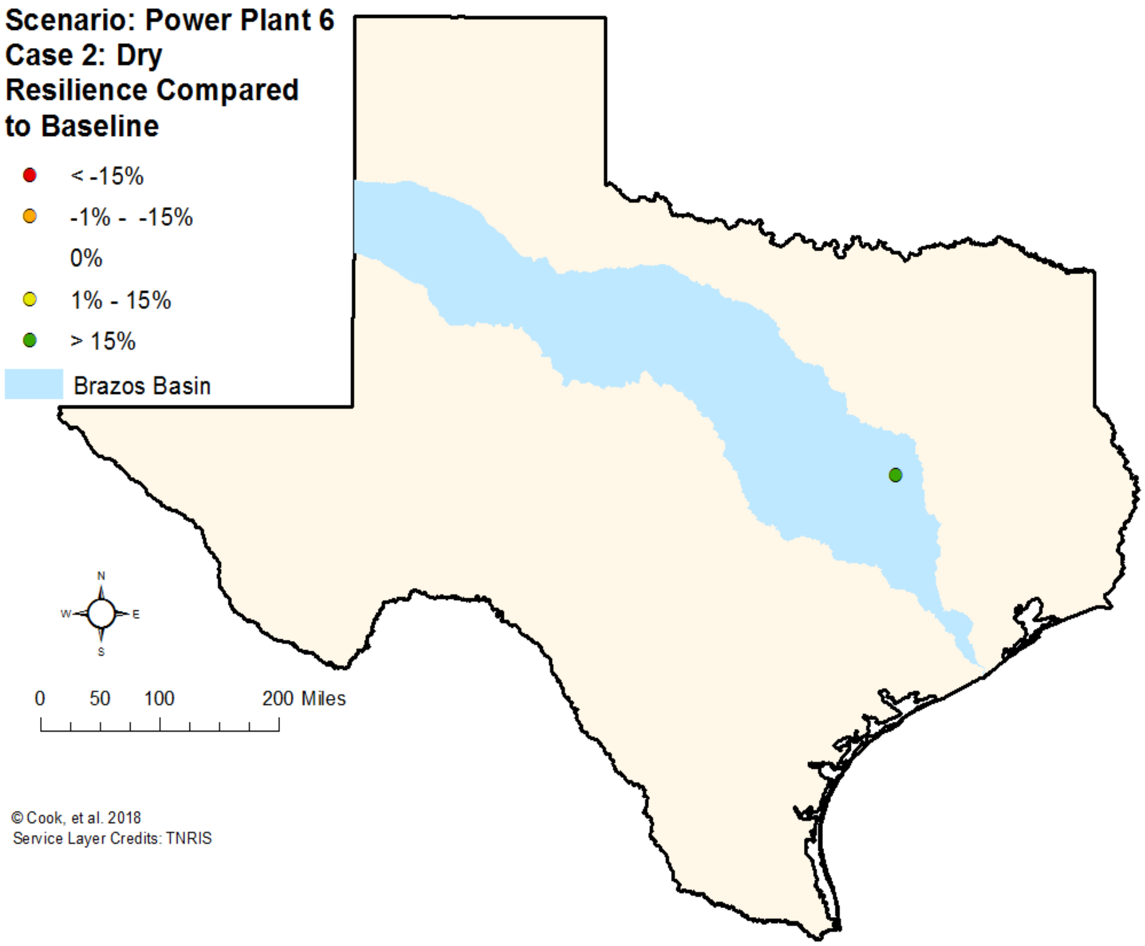

Figure C.26: After trading for saved water under a Hybrid Cooling Scenario for Power Plants 6, most users' resilience is unaffected. One user experiences an increase in resilience.

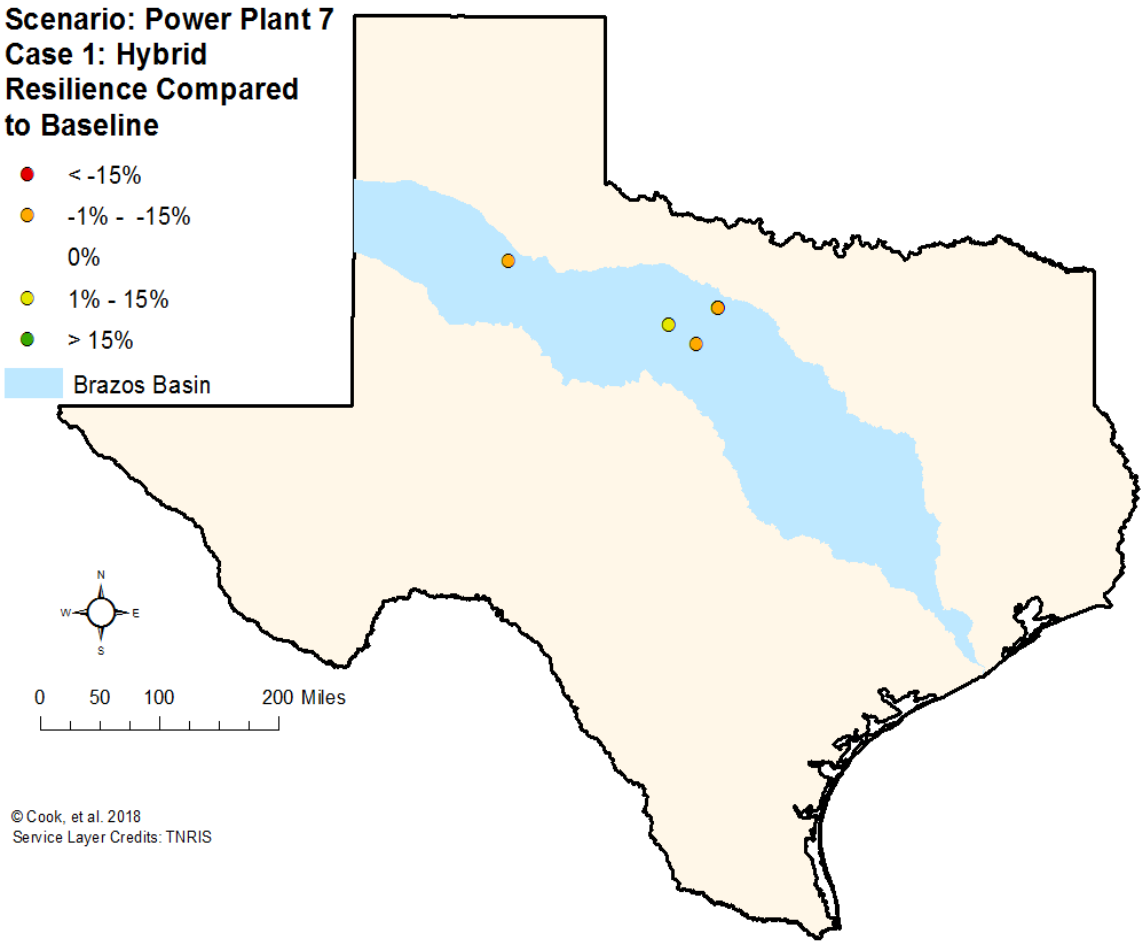

Figure C.27: After trading for saved water under a Dry Cooling Scenario for Power Plants 5, one user benefits from improved resilience and some users experience reduced resilience. Changes in resilience are under 15% compared to the baseline.

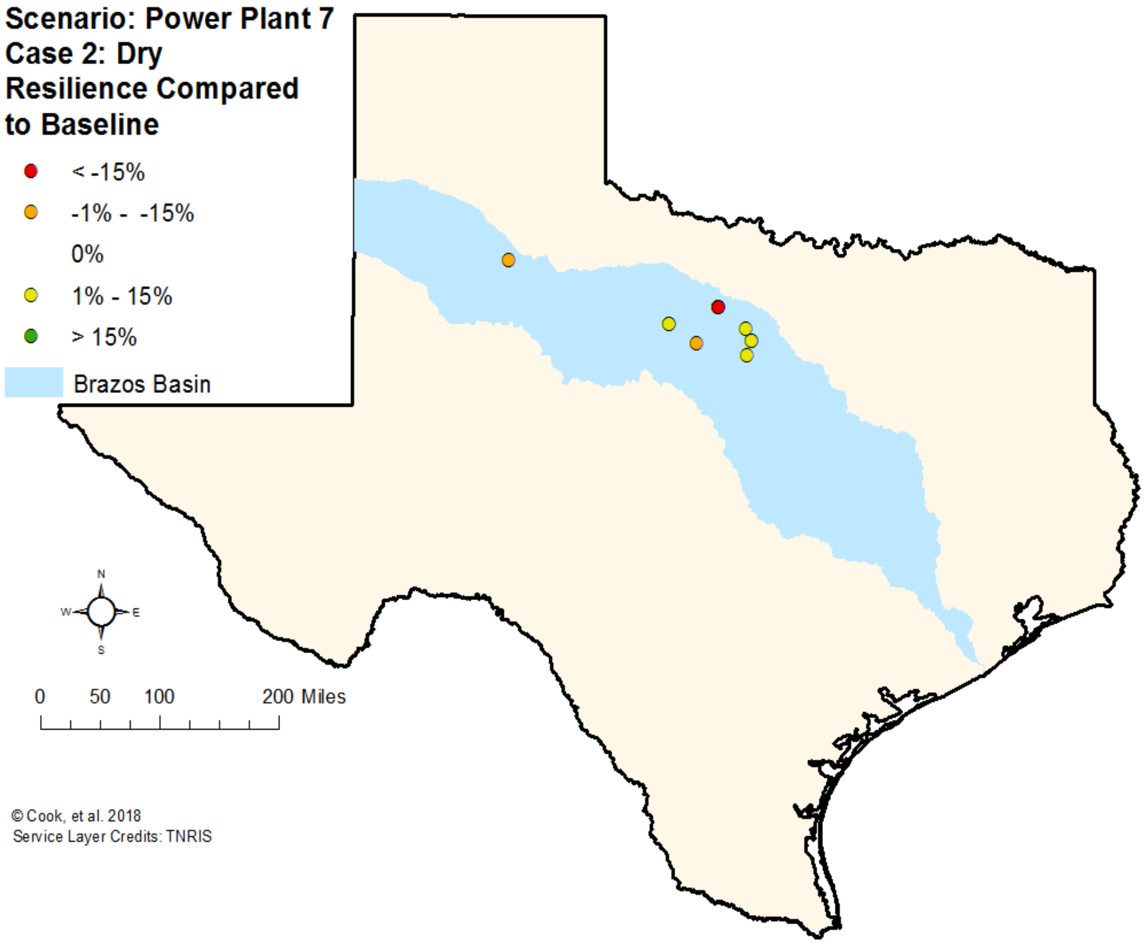

Figure C.28: After trading for saved water under a Dry Cooling Scenario for Power Plants 5, some users benefits from improved resilience and some users experience reduced resilience. One user experiences a large reduction in resilience (over 15% compared to the baseline).

Vulnerability is measured as the average magnitude of deficits over the entire analysis period. The figures show a change in average deficit for individual users in the basin. Some of the cases shown have minimal effects on vulnerability (for example, Figure C.31). Some cases affect many users, but most effects are beneficial (for example, Figure C.29). Conversely, some cases affect one or more users negatively (for example, C.33). It is important to determine individual changes in average deficit in response to a reallocation of water in a trade to be able to mitigate them at the watermaster level, if possible.

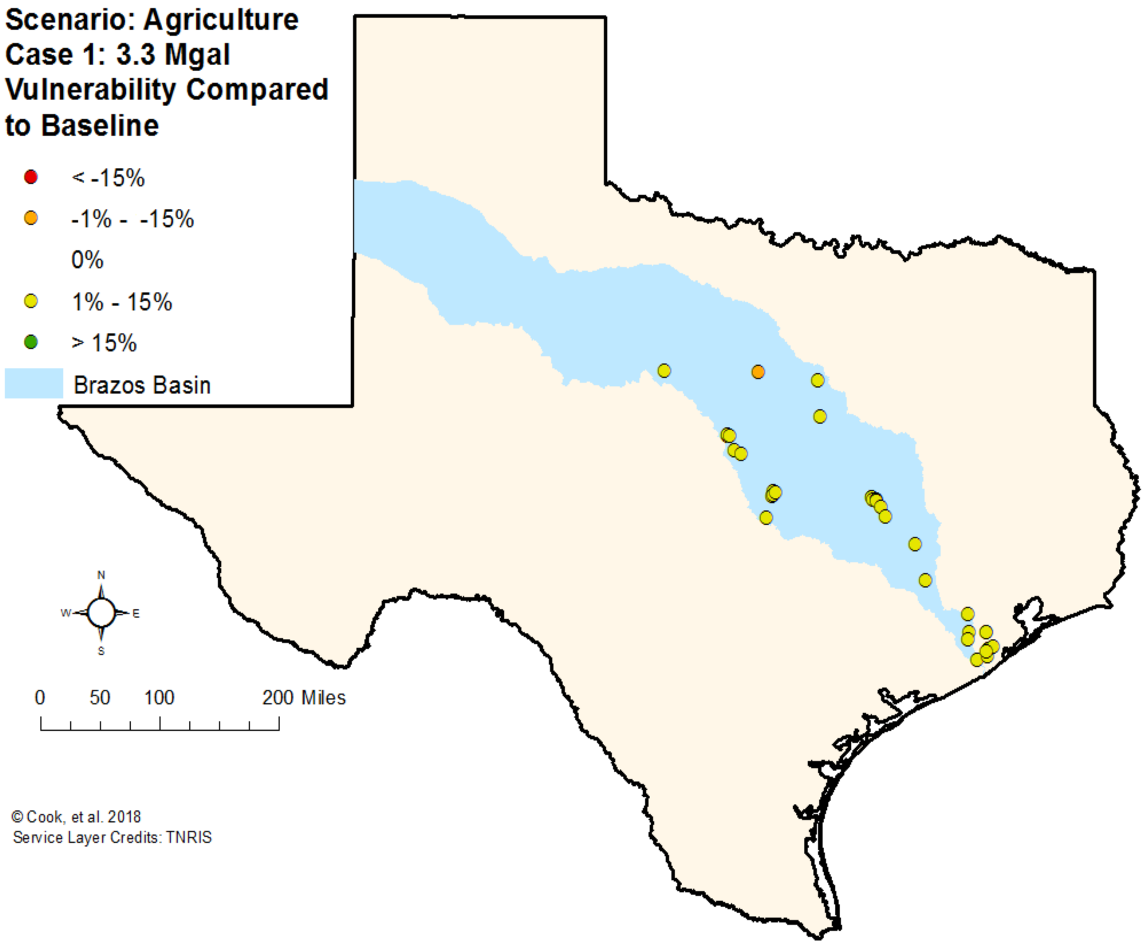

Figure C.29: After trading for saved water under Agriculture Case 1, many users experience a small increase in vulnerability (less than 15% compared to baseline). One experiences a small decrease in vulnerability.

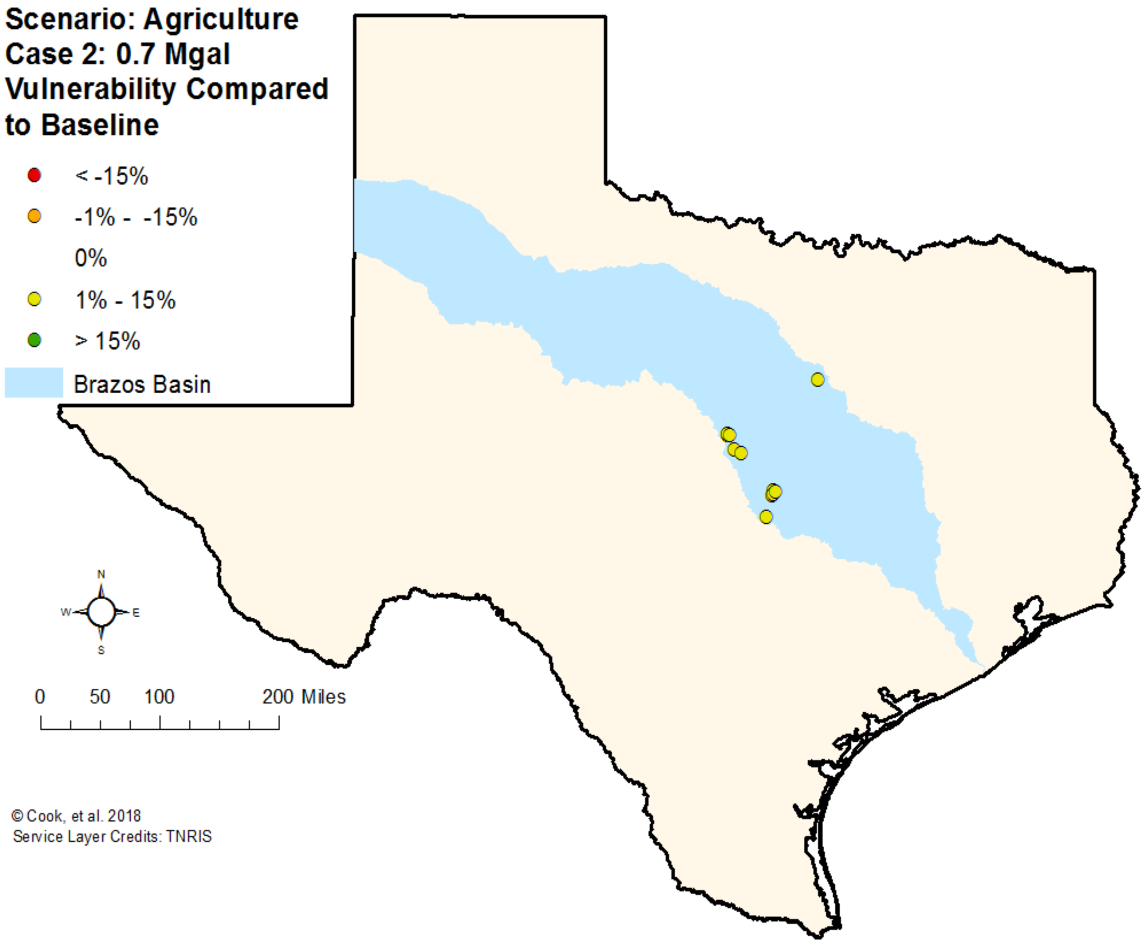

Figure C.30: After trading for saved water under Agriculture Case 2, many users experience a small increase in vulnerability (less than 15% compared to baseline).

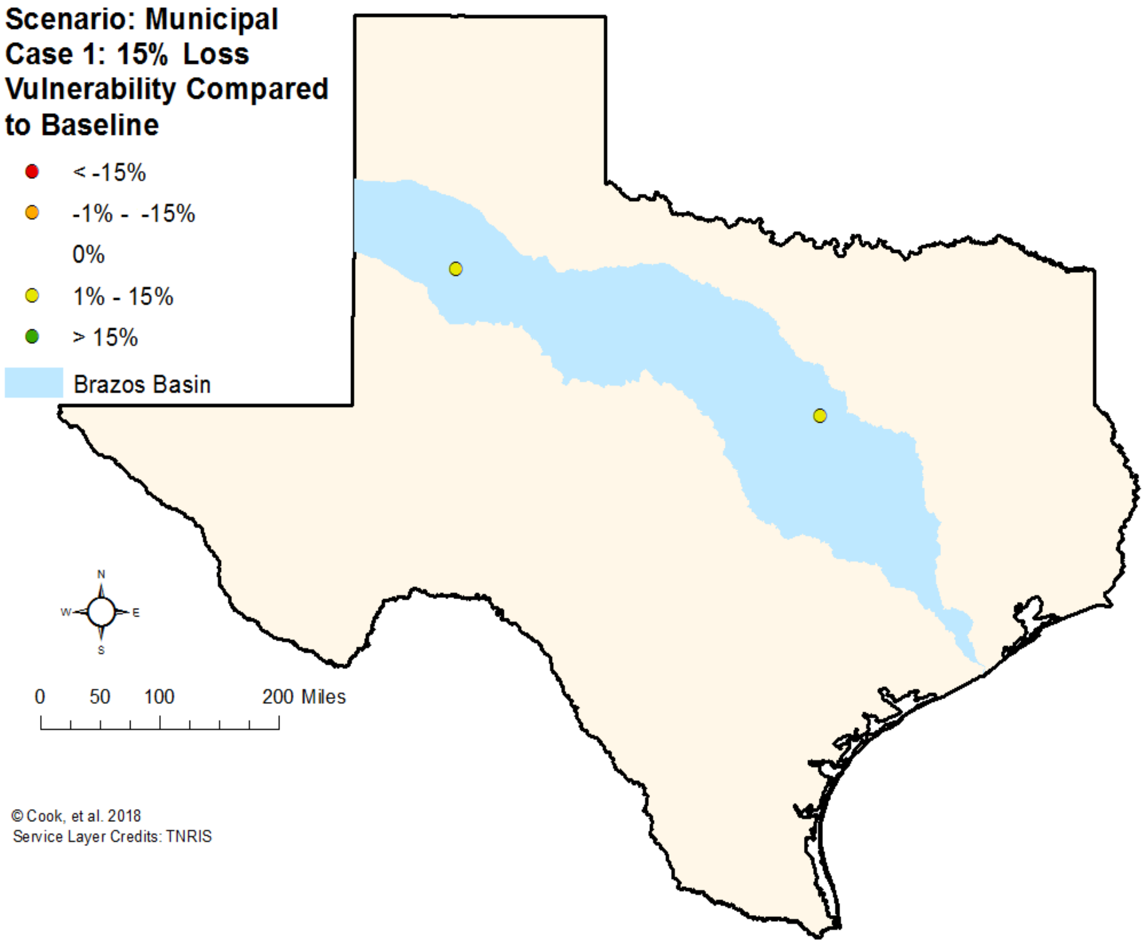

Figure C.31: After trading for saved water under Municipal Case 1, two users experience a small increase in vulnerability (less than 15% compared to baseline).

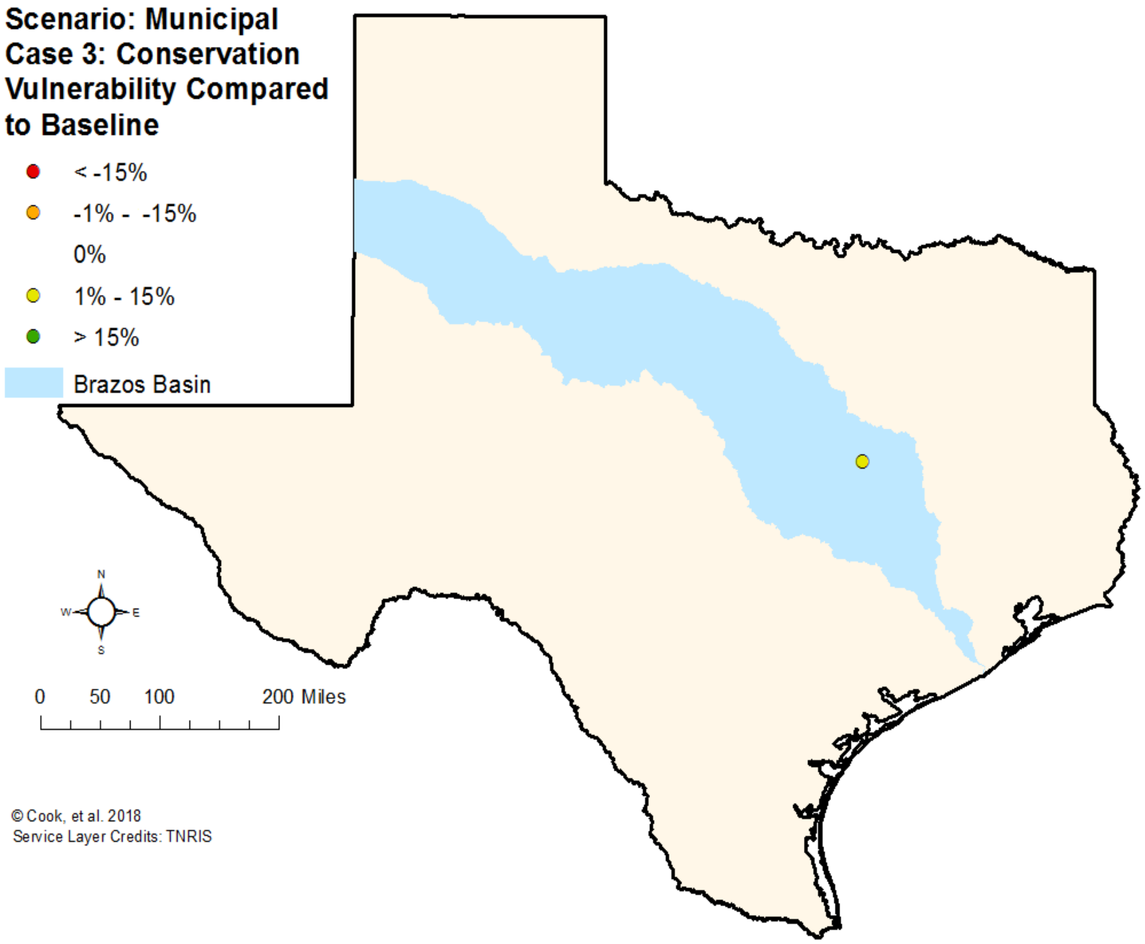

Figure C.32: After trading for saved water under Municipal Case 3, one user experiences a small increase in vulnerability (less than 15% compared to baseline).

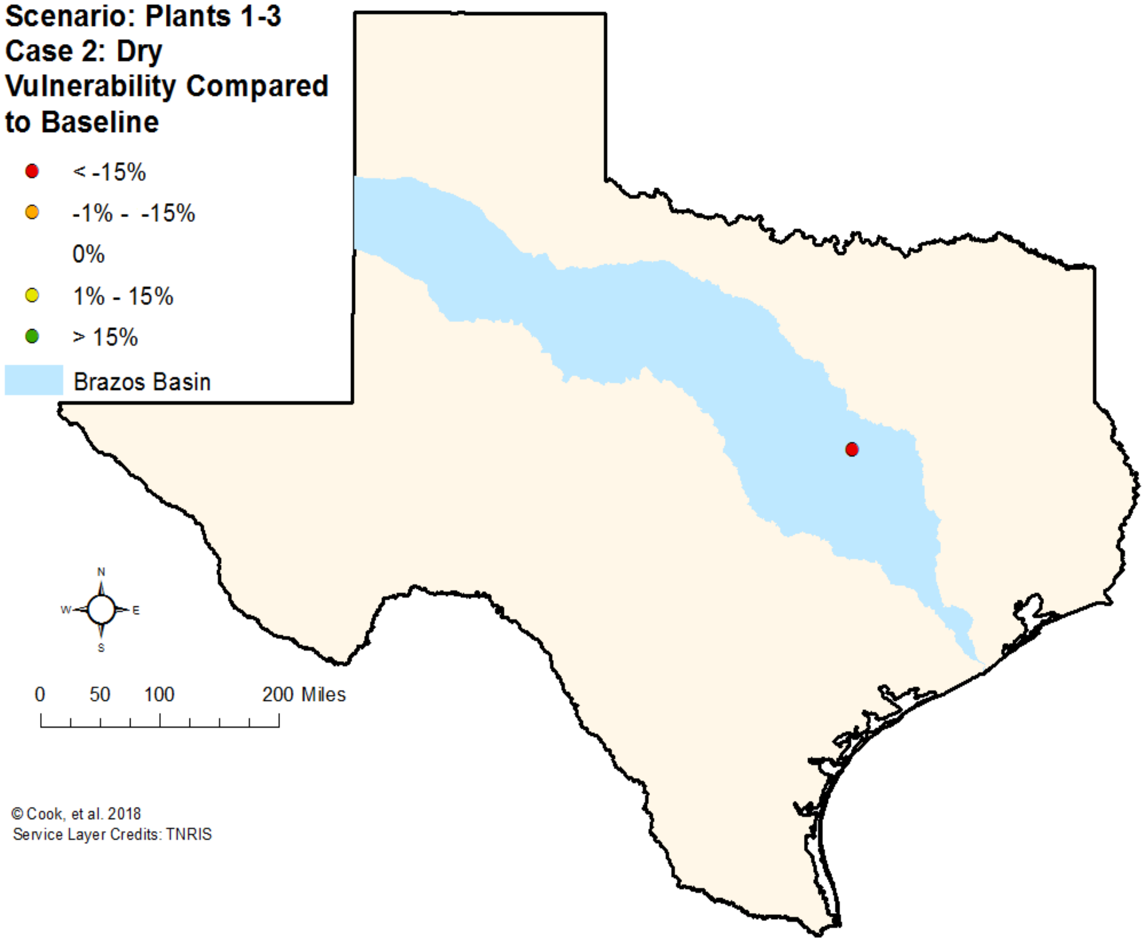

Figure C.33: After trading for saved water in a Dry Cooling Scenario for Power Plants 1–3, one user experiences a large decrease in vulnerability (more than 15% compared to baseline).

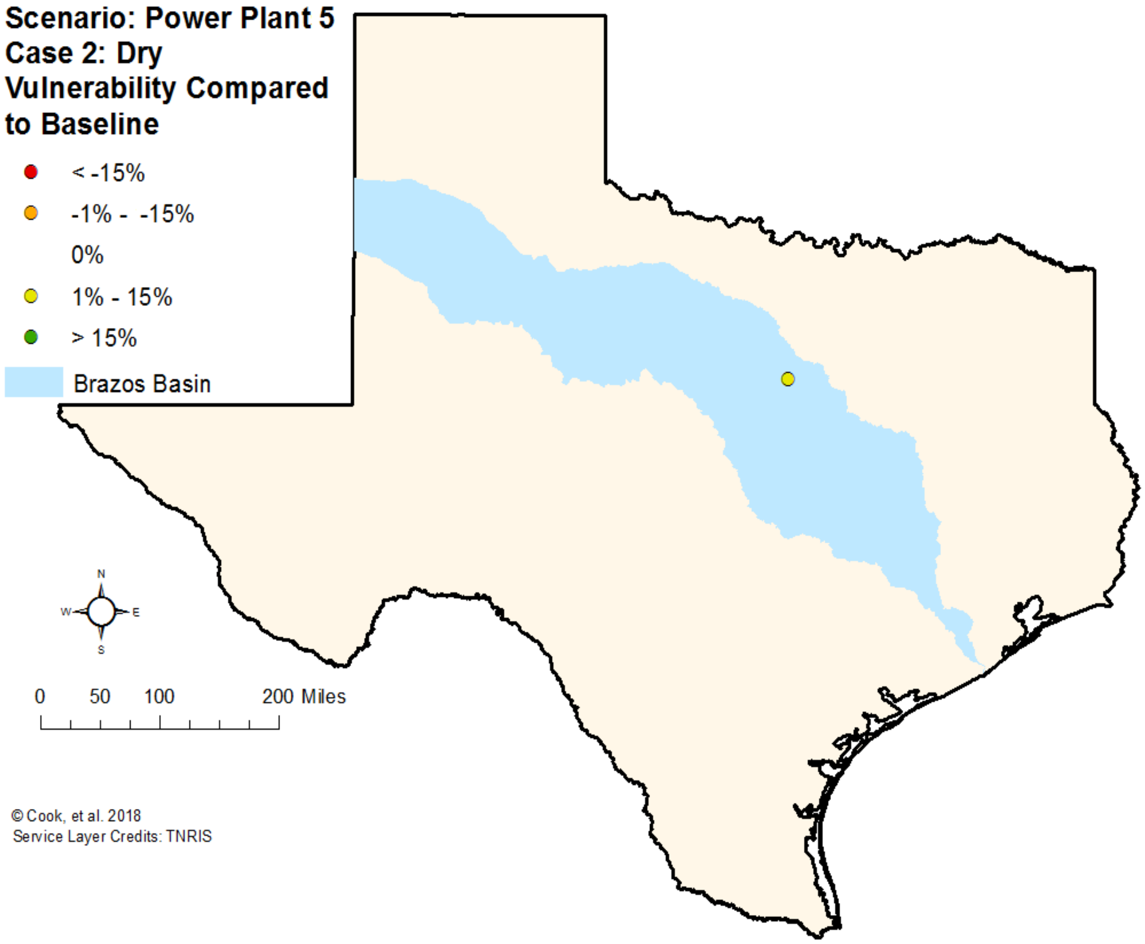

Figure C.34: After trading for saved water in a Dry Cooling Scenario for Power Plant 5, one user experiences a small increase in vulnerability (less than 15% compared to baseline).

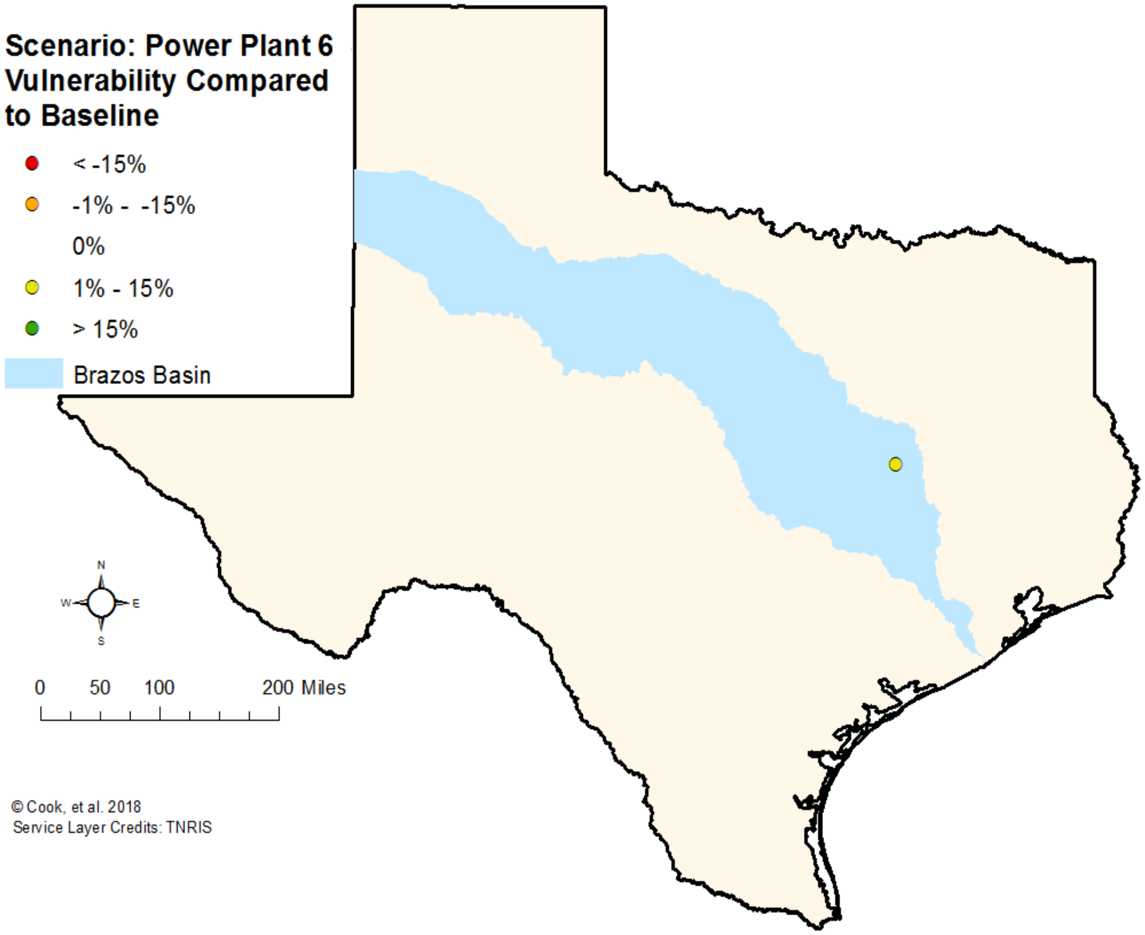

Figure C.35: After trading for saved water in a Dry Cooling Scenario for Power Plant 6, one user experiences a small increase in vulnerability (less than 15% compared to baseline).

Bibliography

[1] “Amarillo City Council Minutes.” http://www.amarillo.gov/departments/citymgr/2013/minutes/minutes_12_03_2013.pdf, 2013.

[2] Canadian River Municipal Water Authority, “Comprehensive Annual Financial Report,’ http://crmwa.com/wp-content/uploads/2013/02/FY-11-12-Audited-Financial-Statements-CAFR.pdf, 2012.

[3] A. Caputo, “Exelon Still Holding Onto Guadalupe Water,” *San Antonio ExpressNews*, http://thearansasproject.org/basin-management/exelon-still-holding-onto-guadalupe-water/, 2009.

[4] Z. Donohew and G. Libecap, “California Water Transfer Records.” http://www.bren.ucsb.edu/news/Water_Transfer_Data_Feb_10.xls, 2009.

[5] Edwards Aquifer Authority, “Comprehensive Annual Financial Report.” http://data.edwardsaquifer.org/files/FY2010%20Comprehensive%20Annual%20Financial%20Report.pdf, 2010.

[6] Edwards Aquifer Authority, “Comprehensive Annual Financial Report.” http://www.edwardsaquifer.org/files/download/3fdf1888cb38bda, 2011.

[7] Edwards Aquifer Authority, “Comprehensive Annual Financial Report.” http://www.edwardsaquifer.org/files/download/3fdf1888cb38bda, 2012.

[8] Edwards Aquifer Authority, “Comprehensive Annual Financial Report.” http://www.eaadevelopment.com/operating-budget/financial-overview, 2013.

[9] Edwards Aquifer Authority, "Comprehensive Annual Financial Report." http://data.edwardsaquifer.org/display_permit_portal_m.php?pg=permit_faqs/, 2014.

[10] Guadalupe-Blanco River Authority, "Minutes of the Board of Directors." http://www.gbra.org/documents/board/minutes/110518.pdf, 2011.

[11] M. Lee, "Parched Texans Impose Water-Use Limits for Fracking Gas Wells," *Businessweek*, http://www.businessweek.com/news/2011-10-06/parched-texans-impose-water-use-limits-for-fracking-gas-wells.html, 2011.

[12] N. Miller, "Organization looking to sell water to oil companies," *Odessa American*, http://www.oaoa.com/news/business/article_b00c22ce-99dd-11e3-8f85-001a4bcf6878.html, 2014.

[13] M. Muniz. Personal communication, 2012.

[14] M. Muniz. Personal communication, 2014.

[15] J. Patoski, "Boone Pickens Wants to Sell You His Water," *Texas Monthly*, http://www.texasmonthly.com/story/boone-pickens-wants-sell-you-his-water, 2001.

[16] "San Antonio River Authority Public Services Regional Planning." http://www.sara-tx.org/public_services/water_planning/, 2014.

[17] Texas Commission on Environmental Quality, "Public Information Request number (PIR number) 14-14509," 2013.

[18] Tarrant Regional Water District, "About Us." http://www.trwd.com/AboutUs, 2014.

[19] K. Welch, “City Might Sell Last of Hartley County Water Rights,” *Amarillo GlobeNews*, http://amarillo.com/news/local-news/2013-12-02/city-might-sell-holdings, 2013.

[20] K. Welch, “Water Authority May Sell Lipscomb County Rights,” *Amarillo GlobeNews*, http://amarillo.com/news/local-news/2013-07-10/water-authority-may-sell-lipscomb-county-rights, 2013.

[21] B. Bruun et al., “Water for Texas 2017 State Water Plan.” https://www.twdb.texas.gov/waterplanning/swp/2017/doc/SWP17-Water-for-Texas.pdf, 2017.

[22] Texas Water Development Board, “Interest Rates.” http://www.twdb.texas.gov/financial/interest.asp, 2017.

[23] Texas Water Development Board Water Conservation Division, “BMP Guide,” 2004.

[24] FracFocus, “Data Download Form.” http://fracfocus.org/data-download-form, 2016.

[25] U.S. Energy Information Administration, “Maps: Exploration, Resources, Reserves, and Production.” ftp://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm, 2012.

[26] TxDOT, “TxDOT Roadways.” http://gis-txdot.opendata.arcgis.com/datasets/d4f7206d27af4358acb70cb1cc819d10_0, 2018.

[27] Texas Water Development Board, “Groundwater Database.” http://www.twdb.texas.gov/groundwater/data/GWDBDownload.zip, 2018.

[28] Digital H2O, “Data Download.” https://app.digitalh2o.com/, 2017.

[29] Texas Water Development Board, "GMA4 MAG 2016a." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA4_MAG_2016a.pdf, 2016.

[30] Texas Water Development Board, "GMA4 MAG 2016b." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA4_MAG_2016b.pdf, 2016.

[31] Texas Water Development Board, "GMA3 MAG 2016a." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA3_MAG_2016a.pdf, 2016.

[32] Texas Water Development Board, "GMA3 MAG 2016b." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA3_MAG_2016b.pdf, 2016.

[33] Texas Water Development Board, "GMA2 MAG 2016a." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA2_MAG_2016a.pdf, 2016.

[34] Texas Water Development Board, "GMA2 MAG 2016b." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA2_MAG_2016b.pdf, 2016.

[35] Texas Water Development Board, "GGMA 7 MAG." http://www.twdb.texas.gov/groundwater/dfc/docs/summary/GMA_7_MAG.pdf, 2016.

[36] C.J. Vorosmarty et al., "Global threats to human water security and river biodiversity," *Nature*, vol. 467, pp. 555–561, 2010.

[37] B.G. Rabe and R.L. Hampton, "Trusting in the future: the re-emergence of state trust funds in the shale era," *Energy research & social science*, vol. 20, pp. 117–127, 2016.

[38] M. Rodell et al., "Emerging trends in global freshwater availability," *Nature*, p. 1, 2018.

[39] H. Bjornlund et al., “An overview of water sharing and participation issues for irrigators and their communities in Alberta: Implications for water policy,” *Agricultural water management*, vol. 145, pp. 171–180, 2014.

[40] M. Rosegrant et al., “Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation,” *World development*, vol. 22, no. 11, pp. 1613–1625, 1994.

[41] S.B. Megdal et al., “Groundwater governance in the United States: Common priorities and challenges,“ *Groundwater*, vol. 53, no.(5), pp. 677-684, 2015.

[42] G. Libecap, “Transaction costs, property rights, and the tools of the New Institutional Economics: Water rights and water markets,” *New institutional economics: a guidebook*, pp. 272–291, 2008.

[43] D. Getches, *Water Law in a Nutshell.* West Publishing Company: St. Paul, MN, U.S.A., 2009.

[44] “Texas Water Code § 11.085,”

[45] K. Ali and K. Klein, “Implications of current and alternative water allocation policies in the Bow River Sub Basin of Southern Alberta,” *Agricultural water management*, vol. 133, pp. 1–11, 2014.

[46] Texas Commission on Environmental Quality, “Rio Grande Watermaster Program.” https://www.tceq.texas.gov/permitting/water_rights/wmaster/rgwr/riogrande.html, 2015.

[47] I.H. Potter, “History and Evolution of the Rule of Capture,” *Report 361, Proceedings of the 100 Years of Rule of Capture: From East to Groundwater Management Conference*, 2004.

[48] G. Hardin, “The tragedy of the commons,” *Science*, vol 13, no. 162, pp. 1243–1248, 1968.

[49] S. Holland and M. Moore, “Cadillac Desert revisited: property rights, public policy and water-resource depletion,” *Journal of Environmental Economics and Management*, vol. 46, pp. 131–155, 2003.

[50] J.J. Haydu,, “Economic impacts of the turfgrass and lawncare industry in the United States” *Publication of the University of Florida Extension, Report Number FE632.* IFAS, 2006.

[51] O. R. Burt, “Economic control of groundwater reserves,” *Journal of Farm Economics*, vol. 48, no. 3_Part_I, pp. 632–647, 1966.

[52] R. Lacewell and H.W. Grubb, “Economic Implications of Alternative Allocations of an Exhaustible Irrigation Water Supply,” *Journal of Agricultural and Applied Economics*, vol. 3, no. 1, pp. 149–154, 1971.

[53] D. Hardin and R.D. Lacewell, “Temporal implications of limitations on annual irrigation water pumped from an exhaustible aquifer,” *Western Journal of Agricultural Economics*, pp. 37–44, 1980.

[54] M. Qureshi et al., “Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia,” *Agricultural Water Management*, vol. 96, no. 11, pp. 1641–1651, 2009.

[55] T.R. Lee and A. Jouravlev, “Prices, property and markets in water allocation,” 1998.

[56] G. Halich and K. Stephenson, "Effectiveness of residential water-use restrictions under varying levels of municipal effort," *Land Economics*, vol. 85, no. 4, pp. 614–626, 2009.

[57] F. Ward et al., "Integrated economic, hydrologic, and institutional analysis of policy responses to mitigate drought impacts in Rio Grande Basin," *Journal of Water Resources Planning and Management*, vol. 132, no. 6, pp. 488–502, 2006.

[58] J. Freebairn, "Principles for the allocation of scarce water," *Australian Economic Review*, vol. 36, no. 2, pp. 203–212, 2003.

[59] J. Lund and M. Israel, "Optimization of transfers in urban water supply planning," *Journal of Water Resources Planning and Management*, vol. 121, no. 1, pp. 41–48, 1995.

[60] D. Zilberman and K. Schoengold, "The use of pricing and markets for water allocation," *Canadian Water Resources Journal*, vol. 30, no. 1, pp. 47–54, 2005.

[61] H. Bjornlund, "Farmer participation in markets for temporary and permanent water in southeastern Australia," *Agricultural Water Management*, vol. 63, no. 1, pp. 57–76, 2003.

[62] R. Coase et al., "The problem of social cost," *Journal of law and economics*, vol. 3, no. 1, pp. 1–44, 1960.

[63] K. Frederick, *Scarce water and institutional change*, vol. 3. Routledge, 2013.

[64] K. Madani and A. Dinar, "Non-cooperative institutions for sustainable common pool resource management: Application to groundwater," *Ecological Economics*, vol. 74, pp. 34–45, 2012.

[65] J. Calatrava and A. Garrido, "Spot water markets and risk in water supply," *Agricultural economics*, vol. 33, no. 2, pp. 131–143, 2005.

[66] S. Ahmad and D. Prashar, "Evaluating municipal water conservation policies using a dynamic simulation model," *Water Resources Management*, vol. 24, no. 13, pp. 3371–3395, 2010.

[67] D.D. Bauman et al., "The problem of defining water conservation, The Cornet Papers, University of Victoria, Victoria," *British Columbia*, pp. 125–134, 1980.

[68] P. Gleick et al., "Water-use efficiency and productivity: rethinking the basin approach," *Water International*, vol. 36, no. 7, pp. 784–798, 2011.

[69] F. Ward and M. Pulido-Velazquez, "Water conservation in irrigation can increase water use," *Proceedings of the National Academy of Sciences*, vol. 105, no. 47, pp. 18215–18220, 2008.

[70] G. Schaible and M. Aillery, "Water conservation in irrigated agriculture: Trends and challenges in the face of emerging demands," USDA-ERS Economic Information Bulletin No. 99, 2012.

[71] E. Fereres and M. Soriano, "Deficit irrigation for reducing agricultural water use," *Journal of experimental botany*, vol. 58, no. 2, pp. 147–159, 2006.

[72] A. Sarwar and C. Perry, "Increasing water productivity through deficit irrigation: Evidence from the Indus plains of Pakistan," *Irrigation and Drainage*, vol. 51, no. 1, pp. 87–92, 2002.

[73] K. Wagner, "Status and Trends of Irrigated Agriculture in Texas." http://twri.tamu.edu/docs/education/2012/em115.pdf, 2012.

[74] H. Bjornlund et al., “Challenges in implementing economic instruments to manage irrigation water on farms in southern Alberta,” *Agricultural Water Management*, vol. 92, pp. 131–141, 2007.

[75] S. Amosson et al., “Economic impacts of selected water conservation policies in the Ogallala Aquifer,” *Ogallala aquifer project*, p. 50, 2009.

[76] J. Rockström et al., “Assessing the water challenge of a new green revolution in developing countries,” *Proceedings of the National Academy of Sciences*, vol. 104, no. 15, pp. 6253–6260, 2007.

[77] I. Hussain et al., “Measuring and enhancing the value of agricultural water in irrigated river basins,” *Irrigation Science*, vol. 25, no. 3, pp. 263–282, 2007.

[78] D. Molden, *Water for food water for life: a comprehensive assessment of water management in agriculture.* Routledge, 2013.

[79] T.S. Arabiyat, *Agricultural sustainability in the Texas High Plains: the role of advanced irrigation systems and biotechnology.* PhD thesis, Texas Tech University, 1998.

[80] B. Terrell et al., “Ogallala aquifer depletion: economic impact on the Texas high plains,” *Water Policy*, vol. 4, no. 1, pp. 33–46, 2002.

[81] R.K. Skaggs, “Predicting drip irrigation use and adoption in a desert region,” *Agricultural Water Management*, pp. 125–142, 2001.

[82] F. Alcon et al., “Duration analysis of adoption of drip irrigation technology in southeastern Spain,” *Technological Forecasting and Social Change*, vol. 78, pp. 991–1001, 2011.

[83] M.E. Qureshi et al., “Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia,” *Water Policy*, vol. 13:1, 2010.

[84] O.K. Uysal and E. Ats, “Assessing the performance of participatory irrigation management over time: A case study from Turkey,” *Agricultural Water Management*, vol. 97, pp. 1017–25, 2010.

[85] K. Senthilkumar et al., “Characterising rice-based farming systems to identify opportunities for adopting water efficient cultivation methods in Tamil Nadu, India.,” *Agricultural Water Management*, vol. 06, pp. 1851–60, 2009.

[86] T.A. Khalkheili and G.H. Zamani, “Farmer participation in irrigation management: the case of Doroodzan Dam Irrigation Network, Iran,” *Agricultural Water Management*, vol. 96, pp. 859–65, 2009.

[87] L. Friedlander et al., “Technical considerations aecting adoption of drip irrigation in sub-Saharan Africa,” *Agricultural Water Management*, vol. 126, pp. 125–132, 2013.

[88] C. Kirda, “Deficit irrigation scheduling based on plant growth stages showing water stress tolerance.” *Food and Agricultural Organization of the United Nations, Deficit Irrigation Practices, Water Reports*, vol. 22, no. 102, 2002.

[89] M. English and S.N. Raja “Perspectives on deficit irrigation,” *Agricultural Water Management*, vol. 32, no. 1, pp. 1–14, 1996.

[90] C.M. Feldhake et al., “Turfgrass Evapotranspiration, Responses to Deficit Irrigation,” *Agronomy Journal*, vol. 76, no. 1, pp. 85–89, 1984.

[91] D.J. Garrot and C.F. Mancino, “Consumptive water use of three intensively managed bermudagrasses growing under arid conditions,” *Crop Science*, vol. 34, no. 1, pp. 215–221, 1994.

[92] M. DaCosta and B. Huang, “Drought survival and recuperative ability of bentgrass species associated with changes in abscisic acid and cytokinin production”. *Journal of the American Society for Horticultural Science*, vol. 132, no. 1, pp. 60–66, 2007.

[93] R.E. Danielson et al., “Urban lawn irrigation and management practices for water saving with minimum effect on lawn quality,” Completion report (Colorado Water Resources Research Institute), no. 106, 1981.

[94] F.S. Zazueta et al., “Reduced irrigation of St,” *Augustinegrass turfgrass in the Tampa Bay area. University of Florida, IFAS, Coop. Exten. Pub. AE-264*, 2000.

[95] M.S. McCready et al., “Water conservation potential of smart irrigation controllers on St. Augustinegrass,” *Agricultural Water Management*, vol. 96, no. 11, pp. 1623–1632, 2009.

[96] Y. Tsai et al., “The impacts of water conservation strategies on water use: four case studies,” *JAWRA Journal of the American Water Resources Association*, vol. 47, no. 4, pp. 687–701, 2011.

[97] I. Biran et al., “Water Consumption and Growth Rate of 11 Turfgrasses as Affected by Mowing Height, Irrigation Frequency, and Soil Moisture,” *Agronomy Journal*, vol. 73, no. 1, pp. 85–90, 1981.

[98] R.N. Carrow, “Can we maintain turf to customers’ satisfaction with less water?” *Agricultural Water Management*, vol. 80, pp. 117–131, 2006.

[99] R.N. Carrow et al., “Two case studies: State BMPs for water conservation on golf courses,” *Golf Course Management*, vol. 73, no. 9, pp. 83–86, 2005.

[100] K. Sovocool et al., “An in-depth investigation of xeriscape as a water conservation measure,” *Journal (American Water Works Association)*, vol. 98, no. 2, pp. 82–93, 2006.

[101] S. Hermitte and R. Mace, “The Grass is Always Greener... Outdoor Residential Water Use in Texas,” *Texas Water Development Board Technical Note*, vol. 2012, pp. 12–01, 2012.

[102] L. McCormick and J. Walker, “Sprayed away: Seven ways to reduce Texas outdoor water use,” Texas Living Waters Project, http://wwwtexaswatermatters.org/pdfs/sprayed%20away_report.pdf, 2010.

[103] C.S. Throssell et al., “Golf course environmental profile measures water use, source, cost, quality, management and conservation strategies,” *Applied Turfgrass Science*, vol. 6, no. 1, pp. 0–0, 2009.

[104] R. Cabrera et al., “An evaluation of urban landscape water use in Texas,” *Texas Water Journal*, vol. 4, no. 2, pp. 14–27, 2013.

[105] S. Shmanske, “The economics of golf course condition and beauty,” *Atlantic Economic Journal*, vol. 27, no. 3, pp. 301–313, 1999.

[106] J.L. Schmidt, “Determinants of water conservation irrigation practices: A study of park and golf turfgrass management in Oklahoma,” Oklahoma State University. 2011.

[107] R.N. Carrow et al., "BMPs: critical for the golf industry," *Golf Course Management*, vol. 73, no. 6, pp. 81–84, 2005.

[108] G. Klein and R. Green, "A survey of professional turfgrass managers in Southern California concerning their use of turfgrass best management practices," *HortTechnology*, vol. 12, no. 3, pp. 498–504, 2002.

[109] D. Katz et al., "Evaluating the effectiveness of a water conservation campaign: Combining experimental and field methods," *Journal of environmental management*, vol. 180, no. September, pp. 335–343, 2016.

[110] S.M. Olmstead and R.N. Stavins, "Comparing price and nonprice approaches to urban water conservation," *Water Resources Research*, vol. 45, p. W04501, 2009.

[111] M. Espey et al., "Price elasticity of residential demand for water: a meta-analysis," *Water resources research*, vol. 33, no. 6, pp. 1369–1374, 1997.

[112] J.M. Dalhuisen et al., "Price and income elasticities of residential water demand: a meta-analysis," *Land economics*, vol. 79, no. 2, pp. 292–308, 2003.

[113] E.T. Mansur and S.M. Olmstead, "The value of scarce water: Measuring the inefficiency of municipal regulations," *Journal of Urban Economics*, vol. 71, no. 3, pp. 332–346, 2012.

[114] C.J. Wichman et al., "Conservation policies: Who responds to price and who responds to prescription?" *Journal of Environmental Economics and Management*, vol. 79, pp. 114–134, 2016.

[115] R. Hilaire et al., "Efficient water use in residential urban landscapes," *HortScience*, vol. 43, no. 7, pp. 2081–2092, 2008.

[116] D.S. Kenney et al., “Residential water demand management: lessons from Aurora, Colorado,” *JAWRA Journal of the American Water Resources Association*, vol. 44, no. 1, pp. 192–207, 2008.

[117] R. Kjelgren et al., “Water conservation in urban landscapes,” *HortScience*, vol. 35, no. 6, pp. 1037–1040, 2000.

[118] A. Liu et al., “Urban water conservation through customised water and end-use information,” *Journal of Cleaner Production*, vol. 112, pp. 3164–3175, 2016.

[119] A.C. Landon et al., “Predicting compliance with an information-based residential outdoor water conservation program,” *Journal of Hydrology*, vol. 536, pp. 26–36, 2016.

[120] P.J. Ferraro et al., “The persistence of treatment effects with norm-based policy instruments: evidence from a randomized environmental policy experiment,” *American Economic Review*, vol. 101, no. 3, pp. 318–22, 2011.

[121] P.J. Ferraro and M.K. Price, “Using nonpecuniary strategies to influence behavior: evidence from a large-scale field experiment,” *Review of Economics and Statistics*, vol. 95, no. 1, pp. 64–73, 2013.

[122] J. Thornton et al., *Water loss control*. McGraw Hill Professional, 2008.

[123] US Environmental Protection Agency, “Water Audits and Water Loss Control for Public Water Systems.” https://www.epa.gov/sites/production/files/2015-04/documents/epa816f13002.pdf.

[124] Natural Resources Defense Council, “Cutting Our Losses.” https://www.nrdc.org/resources/cutting-our-losses, 2017.

[125] Natural Resources Defense Council, "Water Audits & Water Loss Control for Drinking Water Utilities: Costs and Benefits." https://www.nrdc.org/sites/default/files/wat_15040301a.pdf, 2015.

[126] US Environmental Protection Agency, "What is the Infrastructure Needs Survey and Assessment?" http://water.epa.gov/infrastructure/drinkingwater/dwns/factsheet.cfm, 2011.

[127] P. Fanner, *Evaluating water loss and planning loss reduction strategies.* 2007.

[128] "Water Audits in the United States: A Review of Water Losses and Data Validity." http://www.waterrf.org/PublicReportLibrary/4372b.pdf, 2015.

[129] Y. Glazer et al., "An Inventory and Engineering Assessment of Flared Gas and Liquid Waste Streams From Hydraulic Fracturing in the USA," *Current Sustainable/Renewable Energy Reports*, vol. 4, no. 4, pp. 219–231, 2017.

[130] K. Guerra et al. "Oil and gas produced water management and beneficial use in the Western United States," U.S. Geological Survey. 2011.

[131] S.A. Ikonnikova et al., "Projecting the Water Footprint Associated with Shale Resource Production: Eagle Ford Shale Case Study," *Environmental science & technology*, vol. 51, no. 24, pp. 14453–14461, 2017.

[132] E.L. Walker et al., "Water Use for Hydraulic Fracturing of Oil and Gas in the South Platte River Basin, Colorado," *JAWRA Journal of the American Water Resources Association*, vol. 53, no. 4, pp. 839–853, 2017.

[133] H. Chen and K.E. Carter, "Water usage for natural gas production through hydraulic fracturing in the United States from 2008 to 2014," *Journal of environmental management*, vol. 170, pp. 152–159, 2016.

[134] B.R. Scanlon et al. “Water Issues Related to Transitioning from Conventional to Unconventional Oil Production in the Permian Basin,” *Environmental science & technology*, vol. 51, no. 18, pp. 10903–10912, 2017.

[135] C.E. Clark et al. “Life cycle water consumption for shale gas and conventional natural gas,” *Environmental science & technology*, vol. 47, no. 20, pp. 11829–11836, 2013.

[136] T.J. Gallegos et al. “Hydraulic fracturing water use variability in the United States and potential environmental implications,” *Water Resources Research*, vol. 51, no. 7, pp. 5839–5845, 2015.

[137] T.J. Gallegos and B.A. Varela “Trends in hydraulic fracturing distributions and treatment fluids, additives, proppants, and water volumes applied to wells drilled in the United States from 1947 through 2010: Data analysis and comparison to the literatur,” *Scientific Investigations Report*, pp. 2014–5131, 2015.

[138] R.W. Harden et al. “Northern Trinity/Woodbine GAM Assessment of Groundwater Use in the Northern Trinity Aquifer Due To Urban Growth and Barnett Shale Development,” *Texas Water Development Board*, 2007.

[139] EOG Resources. “Water Management.” http://www.eogresources.com/responsibility/water_management.html, 2018.

[140] T. Staples, “Oil and Natural Gas Leads Water Technology Innovation.” http://riograndeguardian.com/staples-oil-and-natural-gas-leads-in-water-technology-innovation/, 2016.

[141] C. Cooper et al. Personal Communication, 2014.

[142] C. Eaton, "The oil bust forced more than 330 North American energy companies into bankruptcy, report says." https://www.houstonchronicle.com/business/energy/article/The-oil-bust-forced-more-than-330-North-American-12831308.php, 2018.

[143] "Anadarko expects Permian service costs to jump in 2018." https://www.reuters.com/article/us-anadarko-petrol-cost/anadarko-expects-permian-service-costs-to-jump-in-2018-idUSKBN1H31ZZ, 2018.

[144] J. Hiller, "Oil field wastewater finds a second life." https://www.expressnews.com/business/eagle-ford-energy/article/Oil-field-wastewater-finds-a-second-life-12893773.php#photo-15515702, 2018.

[145] Pioneer Natural Resources, "News Release." http://investors.pxd.com/news-releases/news-release-details/water-project-save-millions-gallons-freshwater-throughout, 2017.

[146] K. Geddes, "Midland City Council approves amendments to Pioneer Water agreement." http://www.ktre.com/story/38459171/midland-city-council-approves-amendments-to-pioneer-water-agreement, 2018.

[147] N. Miller, "Council Approves Re-assignment of Contract." http://www.gcwda.com/articles/Council-approves-re-assignment-of-contract.pdf, 2014.

[148] D.E. McNamara et al. "Reactivated faulting near Cushing, Oklahoma: Increased potential for a triggered earthquake in an area of United States strategic infrastructure," *Geophysical Research Letters*, vol. 42, no. 20, pp. 8328–8332, 2015.

[149] A. McGarr "Coping with earthquakes induced by fluid injection," *Science*, vol. 347, no. 6224, pp. 830–831, 2015.

[150] W.L. Ellsworth "Increasing seismicity in the US midcontinent: Implications for earthquake hazard." *The Leading Edge*, vol. 34, no. 6, pp. 618–626, 2015.

[151] B.K. Sovacool and K.E. Sovacool, "Identifying future electricity–water tradeoffs in the United States," *Energy Policy*, vol. 37, no. 7, pp. 2763–2773, 2009.

[152] A.S. Stillwell et al., "The energy-water nexus in Texas," *Ecology and Society*, vol. 16, no. 1, 2011.

[153] DoE, US, "Energy Demands on Water Resources: Report to Congress on the interdependency of energy and water," *Washington DC: US Department of Energy*, vol. 1, 2006.

[154] A. Smart and A. Aspinall "Water and the electricity generation industry," Waterlines report, National Water Commission, pp. 34, 2009.

[155] H. Zhai and E.S. Rubin, "Performance and cost of wet and dry cooling systems for pulverized coal power plants with and without carbon capture and storage," *Energy Policy*, vol. 38, no. 10, pp. 5653–5660, 2010.

[156] DoE, US, "Concentrating solar power commercial application study: reducing water consumption of concentrating solar power electricity generation," in *Report to Congress. Washington, DC: USDOE*, 2009.

[157] A. Stillwell et al., "Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges," *Environmental Research Letters*, vol. 6, p. 034015, 2011.

[158] J. Gerston et al., "Efficient Water Use for Texas: Policies, Tools, and Management Strategies," 2002.

[159] L. Wang et al., "Basin-wide cooperative water resources allocation," *European Journal of Operational Research*, vol. 190, no. 3, pp. 798–817, 2008.

[160] H.J. Vaux and R.E. Howitt, "Managing water scarcity: an evaluation of interregional transfers," *Water resources research*, vol. 20, no. 7, pp. 785–792, 1984.

[161] B.H. Hurd et al., "Climatic change and US water resources: from modeled watershed impacts to national estimates," *JAWRA Journal of the American Water Resources Association*, vol. 40, no. 1, pp. 129–148, 2004.

[162] B. Hurd et al., "Economic effects of climate change on US water resources," in *Water Resources and Climate Change*, 2002.

[163] J. Brewer et al., "Water markets in the West: prices, trading and contractual forms," vol. 46, pp. 91–112, 2008.

[164] T. Doherty and R. Smith, "Water Transfers in the West 2012: Projects, Trends, and Leading Practices in Voluntary Water Trading." http://www.westgov.org/component/docman/doc_download/1654-water-transfers-in-the-west?Itemid=, 2012.

[165] D. Garrick and B. Aylward, "Transaction Costs and Institutional Performance in Market-Based Environmental Water Allocation," *Land Economics*, vol. 88, pp. 536–560, 2012.

[166] L. McCann, "Transaction costs and environmental policy design," *Ecological Economics*, vol. 88, pp. 253–62, 2013.

[167] B.G. Colby, "Transactions costs and efficiency in Western water allocation," *American Journal of Agricultural Economics*, vol. 72, pp. 1184–92, 1990.

[168] D. Garrick et al., "Understanding the evolution and performance of water markets and allocation policy: A transaction costs analysis framework," *Ecological Economics*, vol. 88, pp. 195–205, 2013.

[169] R.R. Hearne and K.W. Easter, "Water Allocation and Water Markets: An Analysis of Gains-From-Trade in Chile. World Bank Technical Paper Number 315," 1995.

[170] R.E. Howitt, "Empirical analysis of water market institutions: the 1991 California water market," *Resource and Energy Economics*, vol. 16, pp. 357–371, 1994.

[171] M. Cook and M. Webber, "Food, Fracking, and Freshwater: The Potential for Markets and Cross-Sectoral Investments to Enable Water Conservation," *Water*, vol. 8, p. 45, 2016.

[172] R.L. Teasley, "Evaluating water resource management in transboundary river basins using cooperative game theory: the Rio Grande/Bravo basin," 2009.

[173] Texas Commission on Environmental Quality, "Water Availability Models." https://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html, 2017.

[174] R.A. Wurbs, "Modeling river/reservoir system management, water allocation, and supply reliability," *Journal of Hydrology*, vol. 300, pp. 100–113, 2005.

[175] A. Stillwell and M. Webber, "Evaluation of power generation operations in response to changes in surface water reservoir storage," *Environmental Research Letters*, vol. 8, p. 025014, 2013.

[176] "Texas Water Code § 36.001." http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.36.htm.

[177] R.E. Mace et al., "A streetcar named desired future conditions: The new groundwater availability for Texas (Revised)," 2008.

[178] N. E. Deeds et al., "Final Conceptual Model Report for the High Plains Aquifer System Groundwater Availability Model.." https://www.twdb.texas.gov/groundwater/models/gam/hpas/HPAS_GAM_Conceptual_Report.pdf, 2015.

[179] Environmental Systems Research Institute, "Algorithms used by the ArcGIS Network Analyst extension." http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/algorithms-used-by-network-analyst.htm#ESRI_SECTION1_6FFC9C48F24746E182082F5DEBDBAA92, 2018.

[180] P.J. Densham, Paul J and Rushton, Gerard, "Strategies for solving large location-allocation problems by heuristic methods," *Environment and Planning A*, vol. 24, no. 2, pp. 289–304, 1992.

[181] E.L. Hillsman, "The p-median structure as a unified linear model for location-allocation analysis," *Environment and Planning A*, vol. 16, no. 3, pp. 305–318, 1984.

[182] M.B. Teitz and P. Bart, "Heuristic methods for estimating the generalized vertex median of a weighted graph," *Operations research*, vol. 16, no. 5, pp. 955–

961, 1968.

[183] T. Hashimoto et al., “Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation,” *Water Resources Research*, vol. 18, pp. 14–20, 1982.

[184] S. Sandoval-Solis et al., “Sustainability index for water resources planning and management,” *Journal of Water Resources Planning and Management*, vol. 137, pp. 381–390, 2010.

[185] D. Loucks, “Quantifying trends in system sustainability,” *Hydrological Sciences Journal*, vol. 42, pp. 513–530, 1997.

[186] D. Loucks et al., “Water resources systems planning and management: an introduction to methods, models and applications,” 2005.

[187] S. Sandoval-Solis, “Water planning and management for large scale river basins case of study: the Rio Grande/Rio Bravo transboundary basin,” 2011.

[188] Southwestern Energy, “Water Use.” https://www.swn.com/responsibility/documents/water_fact_sheet.pdf, 2015.

[189] Texas Water Development Board and Texas State Soil and Water Conservation Board, “An Assessment of Water Conservation, Report to 82nd Legislature.” http://www.twdb.texas.gov/publications/reports/special_legislative_reports/doc/TWDB_TSSWCB_82nd.pdf, 2012.

[190] H. Cooley, “California agricultural water use: Key background information,” *Pacific Institute, Oakland, CA*, 2015.

[191] D.M. Yoskowitz, “Spot market for water along the Texas Rio Grande: opportunities for water management,” *Natural Resources Journal*, vol. 39, p. 345, 1999.

[192] Texas Commission on Environmental Quality, “Annual Financial Report.” http://www.tceq.state.tx.us/assets/public/comm_exec/pubs/sfr/045-14.pdf, 2014.

[193] S. Luther. personal communication, 2017.

[194] US Energy Information Administration, “Form EIA-860 detailed data.” https://www.eia.gov/electricity/data/eia860/, 2018.

[195] US Energy Information Administration, “Form EIA-923 detailed data.” https://www.eia.gov/electricity/data/eia923/, 2018.

[196] R. Sturm and J. Thornton, “Water loss control in North America: More cost effective than customer side conservation: Why wouldnt you do it?” in *AWWA Ca/NV Spring Conference*, pp. 17–20, 2007.

[197] “Water Landscape and Patio Coupons.” http://www.gardenstylesanantonio.com/coupons-and-rebates/, 2017.

[198] A.S. Stillwell and M.E. Webber, “Novel methodology for evaluating economic feasibility of low-water cooling technology retrofits at power plants,” *Water Policy*, vol. 15, no. 2, pp. 292–308, 2013.

[199] Texas Commission on Environmental Quality, “Brazos Watermaster.” https://www.tceq.texas.gov/permitting/water_rights/wmaster/brazos-river-watermaster/, 2015.

[200] R.Q. Grafton et al., “Comparative assessment of water markets: insights from the Murray-Darling Basin of Australia and the Western USA,” *Water Policy*, vol. 14, p. 175, 2011.

[201] “Water Data for Texas.” http://www.waterdatafortexas.org/reservoirs/statewide, 2015.

[202] M. Cook et al., “Who Regulates It? Water Policy and Hydraulic Fracturing in Texas,” *Texas Water Journal*, vol. 6, pp. 45–63, 2015.

[203] A. Mittal and M. Gaffigan, “Energy-Water Nexus: Improvements to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use.” http://www.gao.gov/new.items/d1023.pdf, 2009.

[204] L.F. Avioli, “A new phase in water resource allocation : the case for groundwater markets in Texas.” https://repositories.lib.utexas.edu/bitstream/handle/2152/22451/AVIOLI-MASTERSREPORT-2013.pdf?sequence=1, 2013.

[205] “Texas Water Code § 36.064.” http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.36.htm.

[206] “Texas Water Code § 36.122.” http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.36.htm.

[207] C.M. Barnes et al., “The new reality of hydraulic fracturing: treating produced water is cheaper than using fresh,” *In SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers. 2015.

[208] US Environmental Protection Agency, “Enforcement and Compliance History Online.” https://echo.epa.gov/, 2018.

[209] Texas Commission on Environmental Quality, "PWS Wells & SW Intakes SHP." https://www.tceq.texas.gov/assets/public/gis/exports/pws_wells_intakes.zip, 2018.

Vita

Margaret Cook is from the Texas Gulf Coast. She received her Bachelor of Science degree in Civil Engineering with a minor in Religious Studies in 2011 from the University of Texas at Austin. While a student in 2010, she received the Civil Engineering Undergraduate Student Leadership Award. Margaret earned dual master's degrees in Environmental and Water Resources and Public Affairs from the University of Texas at Austin in 2014. During her graduate studies, Margaret served as the President of the Longhorn Energy Club. She also interned with the Texas House of Representatives, the Department of Energy's Office of Policy and International Affairs, Apache Corporation, and Austin Energy. As an intern for the Department of Energy, she contributed to "The Water-Energy Nexus: Challenges and Opportunities." She served as a teaching assistant and student mentor for multiple classes at the University of Texas, has volunteered in classrooms in the Austin area, and served for a year as Scientist in Residence in a 6th grade Science classroom in Austin. In her spare time, she served as a youth minister at a church in South Austin and volunteered at other churches around Texas as a Young Adult Resource Person (YARP).

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