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RESEARCH ARTICLE

Targets and trade-offs: Designing environmental water transactions to navigate compounding competition on the San Saba River in Texas

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Abstract

In river basins experiencing water scarcity, water demands for freshwater ecosystems and water users increasingly compete with one another. Environmental water transactions (EWT) offer a mechanism for resolving this competition via a voluntary agreement in which existing water users are paid to modify the time, place and/or volume of their water right to provide an environmental benefit. However, the disconnect between surface water and groundwater management creates barriers to implementation and scaling of EWTs. We study EWTs addressing water scarcity in Texas's San Saba River, focusing on targeting the location and timing to fulfill conservation objectives. We integrate recent hydrological studies to identify trends in groundwater-surface water interaction, prioritizing stream reaches for intervention and considering both geologic and anthropogenic drivers of scarcity. We analyze water rights and well data to estimate consumptive water demands during the irrigation season. We quantify the volumetric contribution of different portfolios of water rights paired with different types of EWT to assess their contributions to flow targets, including costs and benefits associated with each portfolio. Results demonstrate that the effectiveness of EWTs relies on coordinated spatial and temporal targeting within the context of hydrogeological settings and water users. We provide cost estimates for implementing four types of EWTs ranging from one season to perpetuity ($32,040 and $404,722 respectively) that can provide 3 cubic feet per second (cfs) (0.085 cubic meters) to help meet subsistence flows in the height of irrigation season (June-Aug). These costs are contextualized within a broader water governance context that considers the benefits to producers and the environment and underscores the importance of future policy to integrate groundwater-surface water interaction.

Introduction

Water scarcity in Texas

In water-scarce regions, water demands of food producers, urban centers, and the environment often compete for access to a limited supply of freshwater. This competition carries both economic and environmental implications, often placing rural and urban water users in conflict and frequently overlooking the essential requirements of environmental water [1,2]. The state of Texas, in the southwestern United States faces the dueling challenge of increasingly variable water supplies and shifting demands which give rise to water scarcity [3]. Climate change in Texas alters water availability, threatens groundwater recharge, and will increase aridity and temperatures across the state [4–6]. Historically, and today, water demand for irrigation exceeded municipal demands in Texas. However, water demand for municipal uses is projected to exceed water demand for irrigation by 2060 (TWDB 2021) as Texas' population is projected to nearly double and reach 47.4 million by 2050 (Texas Demographic Center). This increase in population is predominantly concentrated in urban centers, which has important implications for water management including how urban water use efficiencies can help decouple water use from economic growth [7,8].

Against this backdrop, Texas invests hundreds of millions of dollars each year in infrastructure to cope with water scarcity. Since 1957, Texas Water Development Board (TWDB) has spent $27.6 billion in financial assistance for water projects [9]. In 2020, the state budgeted over $62 million dollars for the Water Infrastructure fund, compared to only 1 million dollars for the Agricultural Water Conservation Acct (Texas Water Development Board, 2019). Texas also relies heavily on groundwater production for irrigation and municipal use. In 2020, more than one-third of irrigation and livestock water supplies came from the Ogallala and Edwards-Trinity (High Plains) Aquifer (TWDB State Water Plan 2022). Future groundwater production zones include brackish aquifers which may provide an additional 182,000 acre-feet (224 million cubic meters) of water/year by 2070 (TWDB State Water Plan 2020). Desalination and treating wastewater currently contribute to approximately 4% of water supplies. However supply-side measures, including building reservoirs, are increasingly costly, produce negative environmental externalities, and often do not provide their intended water security benefits [10–12].

Despite significant investment to increase water supplies, Texas water users and the environment are still vulnerable to water shocks and droughts which impact all sectors of the economy, especially the energy sector, agricultural producers, and municipal users [13,14]. The 2011 drought, for example, accounted for an estimated $5.2 billion USD in agricultural losses and threatened freshwater species across the state directly by dewatering streams and indirectly e.g., via toxic algae blooms [15–18]. These shortcomings suggest the need to look towards water management strategies that focus on reducing water demand.

Challenges in conjunctive use: A mismatch between water governance and hydrogeology

The Organisation for Economic Co-operation and Development (OECD) has identified water scarcity as primarily a challenge of governance [19]. In Texas, this challenge is exacerbated by outdated water laws that were originally designed for a different climate and demographic [19]. Texas water law is especially complex due to its legacies of Spanish, Mexican, and English legal traditions, as well as its division of the water cycle into legal components which do not recognize hydrologic connectivity. For additional literature on Texas water law

see [20–22]. Texas water law technically recognizes four distinct classes of water, although in practice, there are two (1) surface water and (2) groundwater [23].

Texas recognizes both riparian and prior-appropriation doctrines for surface-water rights, despite their fundamental differences. The riparian doctrine, dating back over 200 years to Spanish settlement in San Antonio, grants water rights to landowners along water bodies. In the late 19th century, Texas adopted the appropriation doctrine. Land acquired from the state after 1895 no longer automatically carried riparian water rights. Instead, individuals had to follow statutory procedures to appropriate water rights from the state. However, existing riparian rights were consistently acknowledged by all appropriation statutes during this period. Between 1895 and 1913, a landowner could divert water from a stream by filing a sworn statement and map with their county clerk [24,25]. As a result, today most rivers in Texas are overallocated [26].

Groundwater law on the other hand is based on the rule of capture. This strict common-law rule, often referred to as the 'English' rule, or 'rule of capture' was set by the Texas Supreme Court in the case of Houston and T. C. Ry. v. East (1904). According to this rule, the owner of the overlying land has relatively unrestricted rights to pump and use the water, regardless of its impact on neighboring landowners or more distant water users. The rule of capture has been a target of reform in Texas water law for its implications with personal property rights as well as an Achilles heel of groundwater markets [27–29]. Due to the historical differentiation in legal treatment between surface water and groundwater under these two doctrines, the management of groundwater and surface water has traditionally been conducted as separate entities, despite the acknowledged hydrological interconnection between them.

It is well established in the field of hydrology that groundwater and surface water dynamically interact, influenced by hydrogeological factors, especially in certain areas of Texas [30–33]. In hydrology, the movement of surface water into the groundwater system is termed 'infiltration.' Infiltration encompasses the flow of water into the ground through rock or soil at the land surface, as well as the transfer of water from a surface stream into its streambed [34]. Conversely, the movement of water from groundwater to surface water comprises spring flow and the contribution of baseflow to surface streams and lakes. In this context, baseflow refers to the seepage of groundwater into a stream. When dealing with a stream situated above an aquifer, water can either flow from the stream into the groundwater system, known as a 'losing stream,' or from the groundwater system into the stream, referred to as a 'gaining stream. As is observed in many Texas rivers, it is common to encounter stretches where the stream gains water in one section and loses it in another. A 2016 report published by the Texas Water Development Board (TWDB) quantified several metrics specifically related to groundwater-surface water interaction. For example, in an average year, approximately 9.3 million acre-feet (11.47 billion cubic meters) of groundwater flow from major and minor aquifers to surface water, constituting around 30% of Texas' average surface water flow. Regional and aquifer-specific variations in aquifer-surface water interactions exist, ranging from 14% to 72% of streamflow over aquifer outcrop areas originating from groundwater discharge. The most significant groundwater contributions to surface water are observed in East Texas, the Hill Country, and around major springs in West Texas. The Gulf Coast Aquifer leads in groundwater discharge to surface water, with an estimated annual contribution of 3.8 million acre-feet (4.69 billion cubic meters) [35]. This variation in terms of contribution depends on the specific interactions between the stream and the groundwater system. Understanding surface water-groundwater interaction is crucial for water management because changes in one resource often impact the other. Human activities can significantly influence this interaction [36,37]. For instance, aquifer pumping from wells can lead to reduced spring

flows and baseflows, affecting surface streamflow. In extreme cases, aquifer pumping can even reverse the natural flow, shifting water from the stream into the aquifer. Additionally, diverting streamflow before it infiltrates into an aquifer alters water levels and flow within the aquifer [38].

Amidst the backdrop of hydrological interaction between groundwater and surface water, and legal doctrines rooted in traditional water compartmentalization, the concept of conjunctive use has been a topic of interest within policy, academia, and conservation circles for many years. Conjunctive water use is a water management strategy that involves the coordinated and integrated use of both surface water (such as rivers, lakes, and reservoirs) and groundwater (water stored underground in aquifers) to optimize water supplies and meet various demands. The literature on conjunctive water use points to various potential benefits of its implantation, including for irrigated agriculture, aquifer storage, and the environment [39–41]. Unlocking this potential largely depends on effective governance. Given the distinct legal treatment of surface water and groundwater, this presents a significant hurdle in many regions of Texas, especially as it relates to providing water for the environment.

Providing water for the environment – A balancing act of science and strategy

There is demonstrable evidence that allocating water to the environment provides multiple benefits, including indirect benefits to people by maintaining the ecosystem services on which they depend [42,43]. Although early efforts in environmental water legislation can be traced back to the UK Water Resources Act of 1963, and the Clean Water Act in the US in 1972, current sustainable development goals (SDGs) are more explicit in their calls for sustainable water withdrawals, as well as the protection and restoration of ecosystems (SDG 6) [44–46]. Environmental water targets are typically set either by (1) legislation, which specifies objectives for a river or (2) stakeholders and water users who define expectations for a river ecosystem and water uses [42,47]. Setting environmental water targets underpinned by a strong conceptual understanding of the ecological effects and flow regime is critical for evaluating how environmental water can enhance ecological outcomes [48].

One type of institutional arrangement for securing environmental water is through water markets, specifically through the use of environmental water transactions (EWTs) [49,50]. EWTs are voluntary agreements in which existing water users are paid to modify the time, place, and/or volume of the water they use to provide an environmental benefit. Like water transactions between water users, EWTs can be short-term leases or permanent sales. However, empirical evidence in the Western US and Texas demonstrates that leases are far more common than sales, highlighting the impact of transaction costs and associated legal, cultural, and economic barriers on different types of EWTs [51,52]. EWTs today build on decades of experimentation that originated in Oregon in the early 1990s (Neuman, 2004). What began as simple transactions involving water banks to purchase water rights from farmers and dedicate them instream has evolved into a sophisticated toolkit of transactions designed to provide multiple benefits to multiple users [53–56]. While Texas builds on a model tried across the Western US, including the development of a state water bank in 1993 and the water trust in 1997, several legal barriers challenge the implementation and efficacy of EWTs:

1. **Rule of Capture:** The adage 'whoever puts the biggest straw in the ground gets the most water' creates frictions between private property (e.g., groundwater in Texas), a common pool resource (CPR) like an aquifer, and how water could be traded in a market without a "cap."

2. **Non-Conjunctive Management:** The implicit assumption in the rule of capture contributes to poorly defined property rights and increased transaction costs associated with multiple agencies being responsible for different types of water (e.g., surface water vs. groundwater).
3. **No Specific Allocations for Environmental Water:** Texas does not consider the environment as a water user group in the context of water supply planning, which precludes water allocation from the state.

EWTs can occur within water markets lacking specific environmental water protections, such as Texas, or within dedicated environmental water markets with legal enabling conditions tailored for EWTs (Womble et al., 2022). Empirical evidence from the Colorado River Basin (one of the principal rivers in the Southwestern United States and in northern Mexico) suggests that EWTs can decouple market activity from water law to temporarily transfer water rights to the environment [57].

The San Saba River – A natural laboratory for studying compounding competition

The San Saba River, a major tributary of the Colorado River in Texas, faces multifaceted water scarcity challenges, making it an ideal natural laboratory for the study of Environmental Water Transactions (EWTs). Situated at the transition zone between the Hill Country and the Rolling Plains, the San Saba exemplifies many of the challenges confronting rivers in the western United States and abroad. These challenges include competition among water users, conflicts between water users and environmental considerations, increasingly unpredictable precipitation patterns, and land fragmentation. The San Saba River serves as a refugium for various freshwater species, including four freshwater mussels listed under the Endangered Species Act in June 2024. These mussels are highly sensitive to habitat alterations, particularly changes in flow and temperature. Due to this sensitivity, freshwater mussels serve as an important indicator species for overall river health [58]. Their presence and condition provide valuable insights into the ecosystem's status, making them an ideal focus for prioritization in water management and conservation strategies. From a governance perspective, the failure to recognize the environment as a water user adds complexity to the design of EWTs in the San Saba region. However, if EWTs can be designed and implemented in the San Saba despite these challenges, there is potential to scale their use in other basins facing similar types of scarcity, existing incentives, and governance challenges.

Fig 1 below illustrates the complexities of water use within the basin. In terms of surface water (lower map), water rights tend to cluster in both the upper and lower basins, fostering a local dialogue of competition between upstream and downstream users [59,60]. The adjudication of water rights in the San Saba occurred in the 1970s. The limited number of claims downstream of Menard County and upstream of the Brady Creek confluence suggests a historical absence of consistent surface water flows in this river stretch. Adjudication records from the 1800s indicate a historical lack of demand for irrigation water in the river stretch downstream of Menard County and upstream of the Brady Creek confluence. We interpret this as suggesting the limited development potential due to unreliable surface water flows in this region. The upper map illustrates groundwater use, showing that wells are distributed throughout the basin, with a notable concentration in the middle reach. This concentration corresponds to an area where historical flow records indicate less surface water is available for diversions.

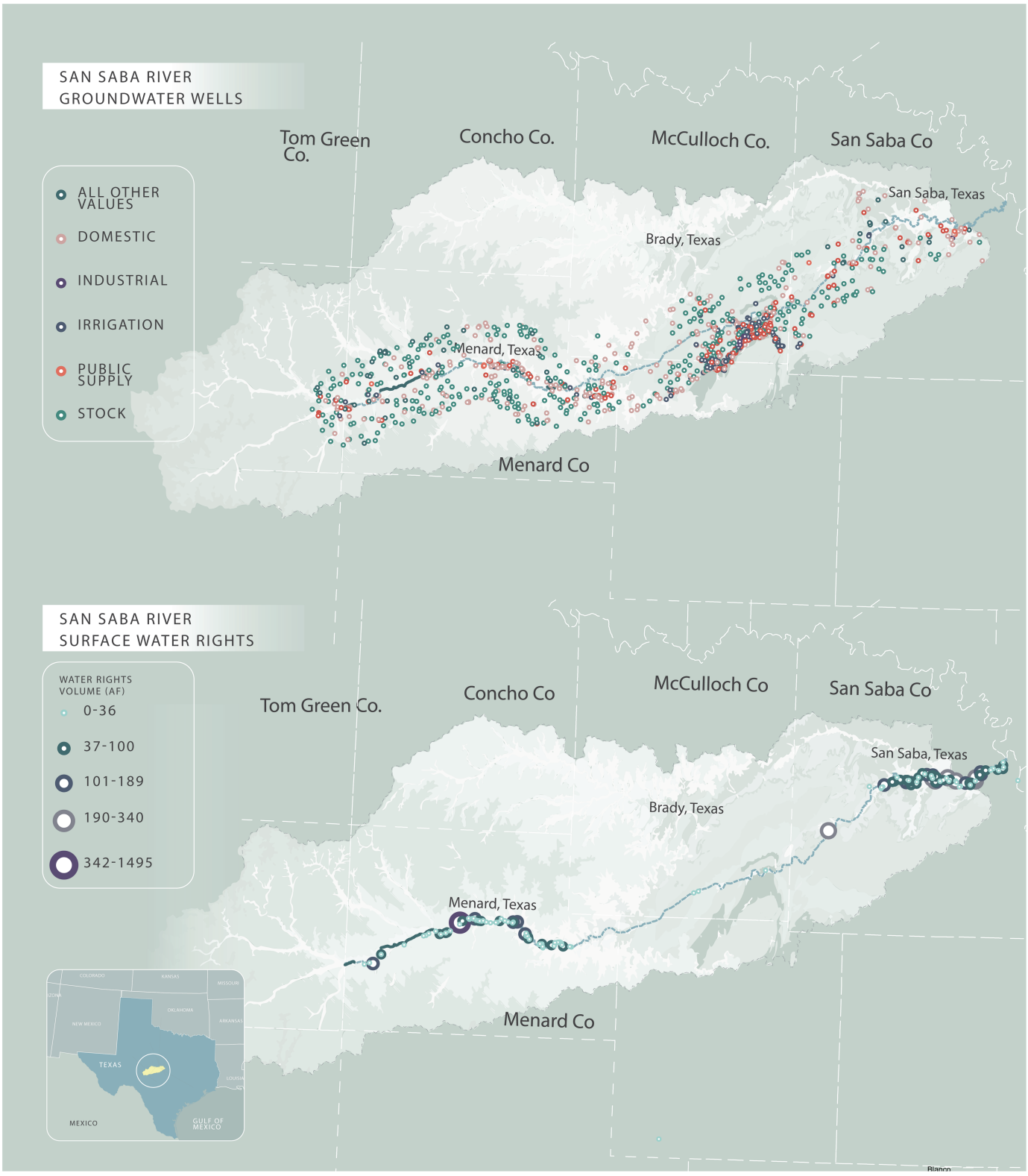


Fig 1. Two maps showing water-use on the San Saba via groundwater wells throughout the basins (above) differentiated by sector and surface water rights (symbolized by volume) which demonstrate the sharp divide in lower and upper basin water users.

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From a hydrogeological standpoint, surface water and groundwater are intricately connected, although we lacked a comprehensive map quantifying this interaction at the basin scale. Therefore, Fig 2 below was created to elucidate how the San Saba River both contributes to and draws from groundwater in different reaches. In Fig 2, as the river flows from Menard County (left-hand side), the water level (indicated by the blue line) remains close to the surface (alluvium) for the initial 40 miles, suggesting that groundwater contributes to the river's flow. Further downstream, the river intersects the Hickory Uplift, a series of faults (between miles 60–100), where the water level indicates a losing reach—where the river recharges aquifers. This losing reach subsequently transitions to a gaining reach around mile 90, near the Penn Marble Falls formation.

In this context, our article focuses on a hierarchical set of questions designed to disentangle the mismatch between the governance and hydrology of the San Saba, and use that information to spatially target EWT portfolios:

1. Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)
2. In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?
3. What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

Insights from our work on the San Saba can offer valuable contributions at multiple scales: at the basin scale, mapping the hydrogeology can provide a foundational understanding for local residents; at the state level, analyzing how to design EWTs to align with existing (non-environmental) water markets can unlock opportunities for EWTs in additional river basins; and as a case study from Texas, insights can contribute to the broader scholarship on EWTs, particularly in a state where such examples are relatively scarce. Additionally, our work offers a methodological contribution through the prioritization framework we have developed.

Methods

Gain-loss studies identify spatial and temporal dynamics of groundwater-surface water interaction

To identify priority reaches, we relied on a gain-loss study that took place between 2018-2021 in the section of the San Saba in Menard County. Gain-loss studies are an example of a physically based hydrologic model and are used to quantify interactions between groundwater and surface water within a system [61,62]. Measurements of streamflow are taken at various locations in the main channel. The channel gain or channel loss is computed for each sub-reach between measurements by comparing the inflows and outflows plus flow gain or flow loss in the sub-reach. We employed a gain-loss study because (a) we needed to identify reaches in the river that were losing and gaining to ensure we could meet the conservation objective; (b) the results allow us to contextualize the anthropogenic and hydrogeological influences on the system; and (c) there is a growing interest in the state of Texas to understand groundwater/surface water interaction considering the legal and governance implications [63,64]. For the San Saba, a gain-loss study was performed in June 2018 where streamflow was measured at 14 locations in Menard and McCulloch Counties to identify (a) where groundwater contributes to streamflow and (b) where water use may be reducing streamflow. The locations of the study were based on a previous study in July 1933 (found in [62]) and focused on the

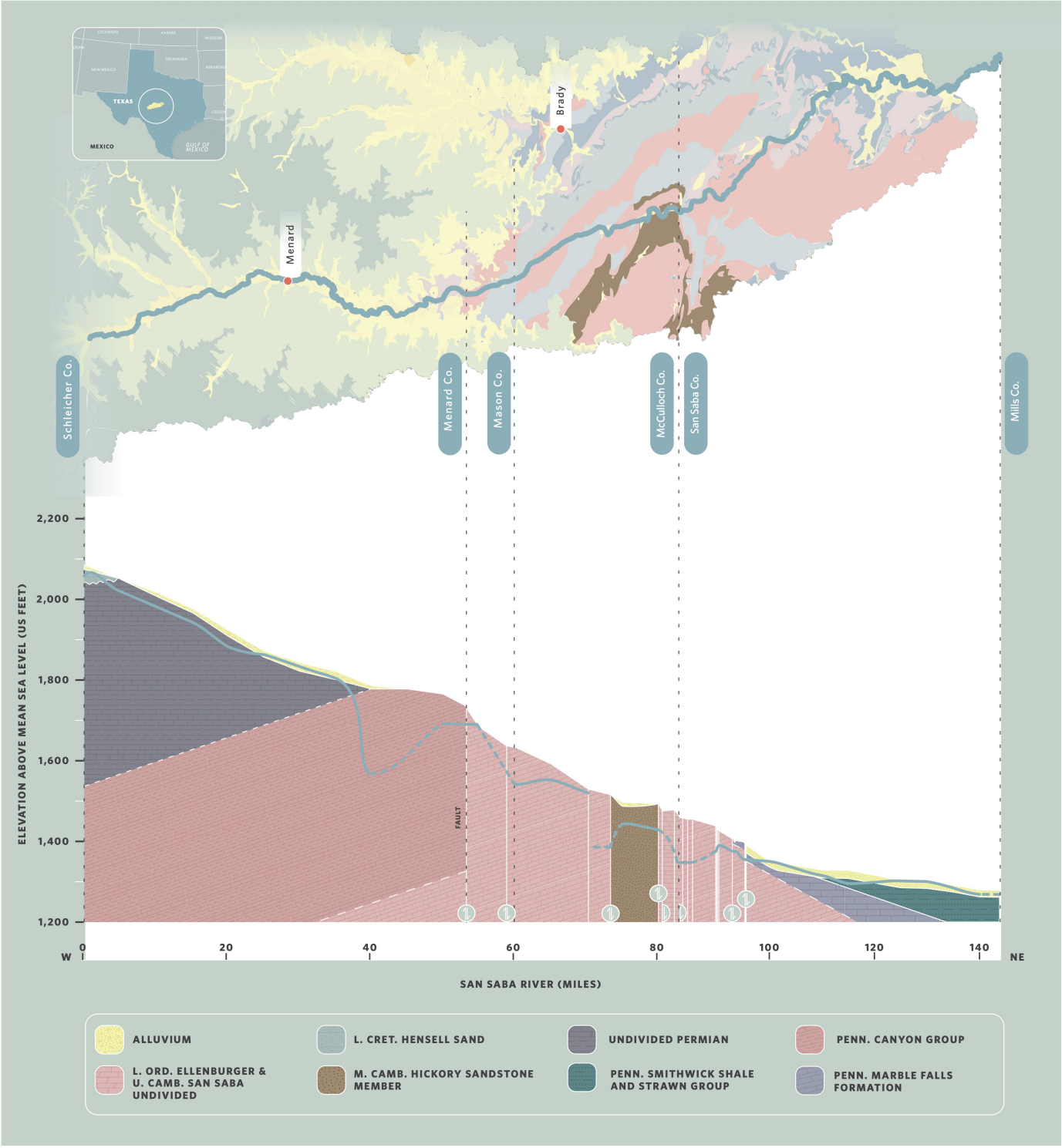


Fig 2. Two maps showing the hydrogeologic context of the San Saba. We aligned a geological map of the San Saba River Basin superimposed on a cross section of the San Saba River from its headwaters to the confluence of the Colorado showing the influence of geology on water levels (in blue in the cross section).

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reach between the head water springs and Paleozoic outcrop. This reach is where most irrigation takes place and is composed of complex interactions with underlying aquifers. The flow measurements were collected by The Nature Conservancy (TNC), Texas Parks and Wildlife Department, and WSP USA, an environmental consulting firm. All measurements were made with a Sontek FlowTracker following United States Geological Survey (USGS) protocols and measured twice at each location. June 2018 corresponded with very dry conditions immediately before a period of heavy rainfall in fall of 2018. Low flow periods provide an advantage for gain-loss studies because interactions between the river and the bedrock geology are more observable. Permits were not required for this research because researcher used public Right of Way as well as access agreements with private landowners for the collection of groundwater well data and streamflow measurements.

Monitoring wells uncover interactions between groundwater and surface water based on sources of water and geographic location

To understand the interactions between streamflow, precipitation, and groundwater levels, we relied on gauges from well data. Six In-Situ Model 400 Level-TROLL transducers were installed in local alluvium and Edwards-Trinity groundwater wells on June 28th and July 27th, 2018. These transducers record semi-hourly water level changes. On July 20th, 2018, two Model 100 Rugged-Troll transducers were installed at Fort McKavett Springs and Clear Creek, two locations previously measured by the USGS. The long-term goal with monitoring both surface water and groundwater levels are to identify gains and losses in both irrigation, and non-irrigation seasons to (a) understand how the system responds to pumping and (b) identify specific EWTs strategies that respond to the system and protect habitat.

Developing an estimate of mass water balance for the area of interest helps quantify consumptive water demand

Quantifying water use across different users and sources for the entire watershed presents significant challenges due to data limitations and resource restraints. Existing sources have notable drawbacks: Water Availability Models (WAM) only account for surface water and historic data, while Texas Water Development Board (TWDB) water use data is constrained by county boundaries rather than hydrological ones. Given these constraints, we opted to focus our analysis on the Menard County portion of the basin, which aligns with our prioritization area, rather than attempting to develop a comprehensive water use model for the entire watershed. To estimate the consumptive use of water in Menard County, we developed a model to estimate the volume of consumptive groundwater and surface water used during the irrigation season.

For surface water demand, we used a water availability model (WAM) run 8 scenario and selected water rights in Menard County (n=83) [65]. Run 8 of the model is current conditions and simulates recent demands. Therefore, we assume that volumes from users were consumptively used during this time period. We took the sum of the volumes from the WAM model for the months of March to October to represent the irrigation season. The volume of water, which we call the surface water demand irrigation season, is equal to 7,484 AF of water, which is 31.18 AF/day or 15.72 cubic feet per second (cfs) for 8 months.

For the groundwater demand of the model, we filtered groundwater wells inside Menard County. We then used data from the Texas Water Development Board (TWDB) which calculated the consumptive water demand of groundwater wells. We mapped the demand curve of the surface water demand irrigation season to the groundwater wells to provide an estimate of consumptive demand during the irrigation season. The volume of water, which we

call groundwater demand irrigation season, is equal to 440 AF of water, which is 1.83 AF/day or 1 cubic feet per second (cfs) for 8 months.

Future research could improve upon this methodology by focusing on field-level water demand calculations to provide a high-resolution picture of consumptive use, infiltration, and return flows across the basin. Integrating ground-truthing, well production volumes, and crop type data could significantly improve these estimations. Furthermore, differentiating between groundwater sources (alluvial, Edwards, and Hickory aquifers) is crucial for management, as their interactions with surface water vary. The deep Hickory aquifer, being largely disconnected from the river, offers potential for strategic groundwater source switching during scarcity. This approach could enhance river conservation efforts through more flexible and sustainable water management practices.

Results

Which sections of river require intervention during times of scarcity to maintain flow targets? (i.e., priority reaches)

Through a combination of previous fieldwork, stream gauge analysis, and our gain-loss study, we identified an area extending from a few miles upstream of the town of Menard to the Menard-McCulloch county line where (a) baseflows can drop below a subsistence flow of 4cfs, (b) there are existing habitat for freshwater mussels (Mitchell et al., 2021), (Randklev et al., 2018), and (c) there are numerous water rights which could be used for EWTs. Choosing this area as a priority reach means that our conservation objective is to maintain freshwater habitat in this reach, as well as extend areas of refugia in times of drought. Environmental flows were quantified using freshwater mussels as indicator species, with their flow requirements serving as benchmarks for overall ecosystem health and for assessing the potential effectiveness of EWTs in maintaining critical flow regimes [66]. Baseflows and subsistence flows for various sections of the San Saba River have been assessed in both academic literature (e.g. [67] and unpublished government reports (e.g., Senate Bill 3) using the Hydrology-Based Environmental Flow Regime (HEFR) and the Indicators of Hydrologic Alteration (IHA). We are aware of the 40-mile stretch of the San Saba River downstream of this priority reach which landowners have noted have run dry for 10 of the last 16 years (Friends of the San Saba 2015). However, there are economic and volumetric limits to employing EWTs to rewater this reach. Dewatering the priority reach not only impacts riparian habitat negatively but also brings economic hardship to landowners who rely on the river for domestic and livestock purposes. The timing of these dewatering events is also critical. The times of most scarcity coincide with the height of the irrigation season (late July and August) which overlap with the highest temperatures and highest crop stress. The graphic below (Fig 3) shows the geographic location of the priority reach and a hydrograph showing monthly discharge for 30 years at Menard.

In these priority reaches, what are the spatial and temporal influences of natural (geologic) and anthropogenic (water use) drivers of scarcity?

Results from the gain loss studies (Fig 4 below) identify reaches where surface water contributes to aquifers, and where groundwater contributes to river discharge. WSP USA, a licensed professional geoscientist firm in Texas (License No. 50561), conducted a hydrogeologic assessment of the San Saba River for TNC in November 2020. This assessment summarized historical studies and compared them with the 2018 gain-loss study. It included an analysis by LBG-Guyton Associates (2002) that reviewed existing gain-loss data from studies conducted in 1918, 1933, 1940, and 1994. Analyzing the results of the 2018 gain-loss study

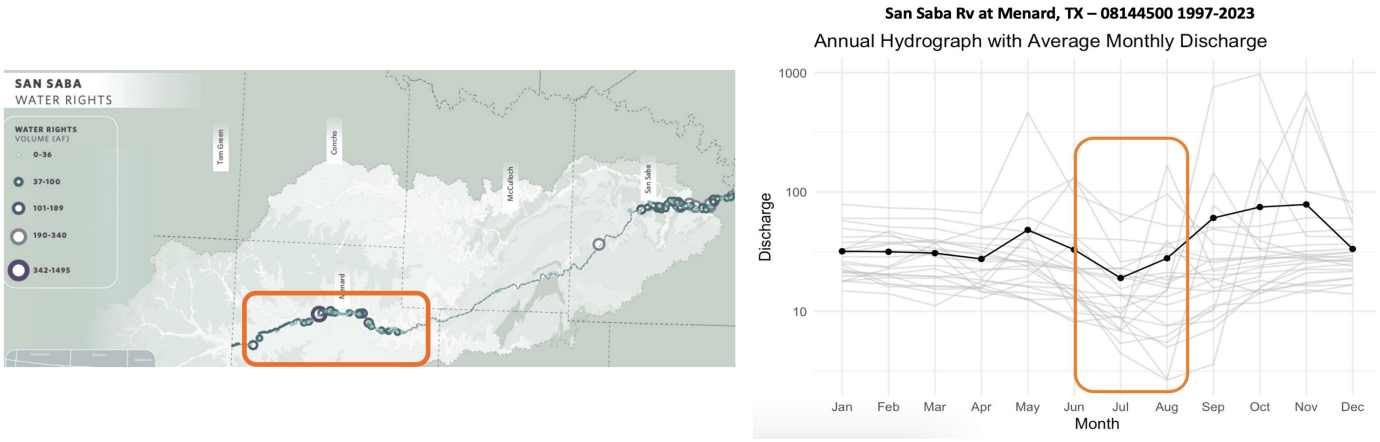


Fig 3. A graphical display of the priority reach surrounded by numerous water rights, and the hydrograph showing the timing of the lowest flows historically, July and August (right hand side).

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and those of the 1933 study allow us to interpret the results in the context of pre-development conditions (with no significant groundwater pumping) and assume that loses in the reach in 1933 are primarily attributed to recharge [62]. Streamflow during the 1933 study was generally twice as much as the 2018 study. Flow at Menard in 1933 was 19 cfs, compared to 9.5 cfs in 2018. Likewise, flows at Fort McKavett were 21.1 cfs in 1918 and 5.4 cfs in 2019. Rainfall totals were similar for both time periods suggesting that reduced flow at the Schleicher-Menard County line can be partially attributed to increased groundwater pumping in the headwater since 1933. Agreement between the 1933 and 2018 study shows a 10 cfs loss in eastern Menard County which occurs below the downstream confluence of the Menard irrigation canal and river at Ten Mile Crossing. Measured channel loss between Menard irrigation canal inflow and outflow varied between the 1933 and 2018 studies. There is loss in the system due to the hydrogeologic circumstances, but the difference between the loss in 1933 vs. 2018 (holding precipitation close to constant between the two studies) shows a loss of 0.05 cfs in 1933 and 4.2 cfs in 2018 between Menard and Fivemile crossing.

The graphic below (Fig 4) illustrates the spatial and temporal variability of gaining and losing reaches based on data from three different gain-loss studies conducted in 2018, 2019, and 2021. Future fieldwork should focus on collecting data from the same month across multiple years—such as March 2024, March 2025, and March 2026. This approach will help distinguish whether the observed monthly differences stem from climate variability or increased water usage in the basin. For instance, the notable variation between June 2018 and June 2021 is likely due to climate fluctuations.

Fig 4 below depicts changes in the San Saba River under varying climatic, groundwater levels, and irrigation conditions between March 2018 and June 2021. In March 2018, representing average pre-irrigation season conditions, no significant losing stretches were observed in the study area. However, by June 2018, during a typical dry condition for the watershed in the irrigation season, we observed losses in the upper headwaters and in a reach with irrigation just upstream of the highly faulted Ellenburger group.

In August 2019, after a recharge event, we noted significantly fewer losses, even during the irrigation season. Fast forward to June 2021, with higher groundwater levels, which represented normal irrigation season conditions, and we found that the gaining stretch in the headwaters was longer than in June 2018. Notably, the gaining stretch in the headwaters resembled

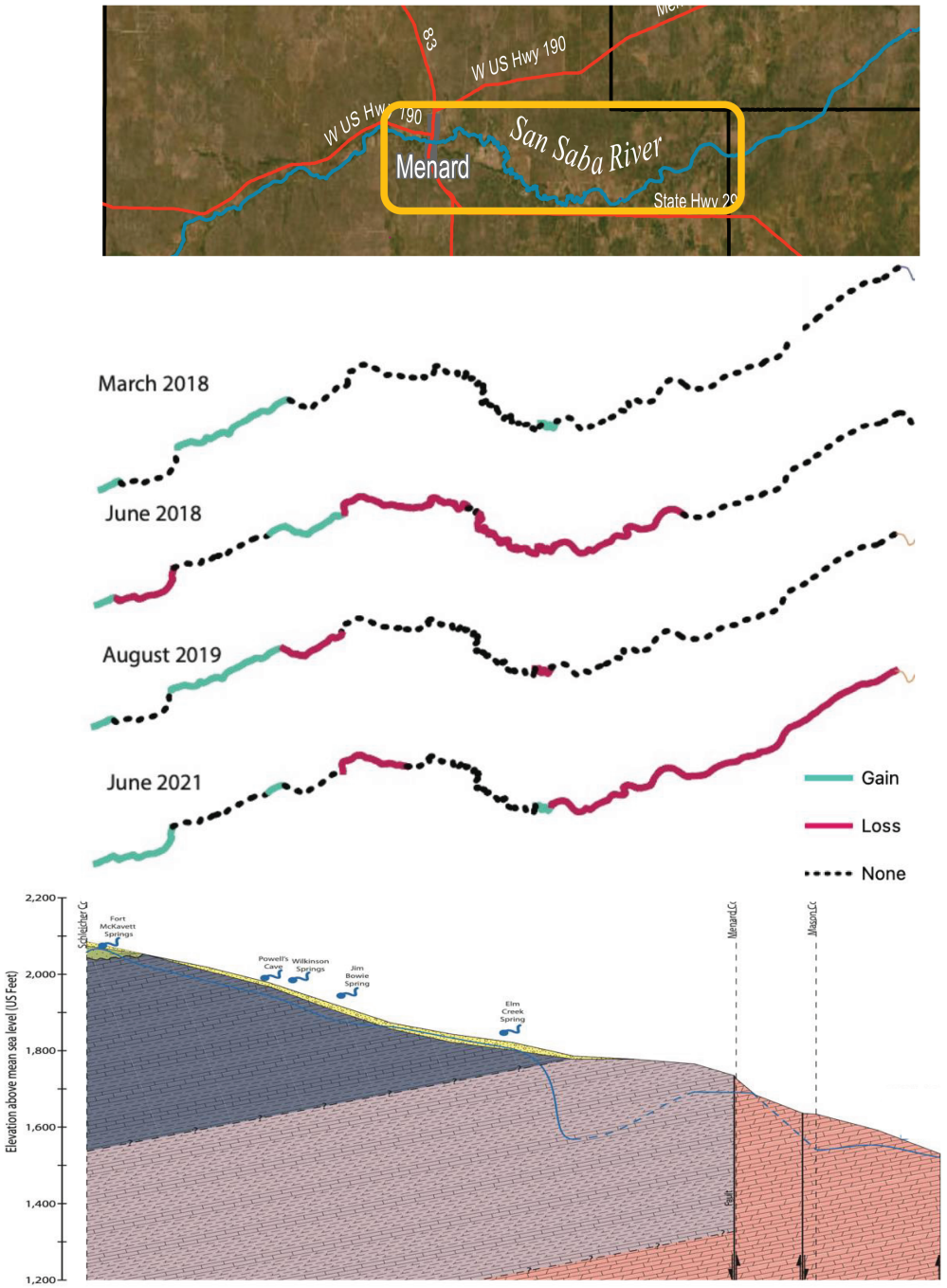


Fig 4. The top map shows the study area centered in the eastern portion of Menard County, Texas. The orange box in this map indicates the location of gain-loss studies, results of which are presented in the four maps below. These maps correspond to studies conducted under varying conditions:(March 2018) Normal conditions during non-irrigation season (top); (June 2018) Dry conditions during irrigation season (second); (August 2019) wetter conditions during irrigation season (third); (June 2021) normal conditions during irrigation season (bottom); The bottom graphic presents a longitudinal profile of the same reach where the gain-loss studies took place, illustrating the geologic formations, springs, and water levels along the study area.

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that of March 2018, but the area downstream of Menard, which was gaining in June 2021, had turned into a losing stretch, along with a small section upstream of Menard.

These four graphics collectively demonstrate how different stretches of the San Saba can shift between gaining and losing depending on climatic conditions and the presence or absence of irrigation. When comparing March 2018 and June 2021, we can discern an anthropogenic influence during the irrigation season, particularly in the extent and number of losing sections. Notably, the section most susceptible to low flows in various conditions, including dry years and dry-year irrigation, lies downstream of Menard toward the county line between Menard and McCulloch counties.

Upon overlaying these gain-loss maps with transects, we observe the influence of two key hydrological attributes: springs and geologic formations. For instance, the uppermost section of our graphics, associated with the Hensell Sand group near the alluvium and in proximity to Fort McKavett Springs, consistently exhibits gaining characteristics. Conversely, approximately 15 miles upstream of the Menard/Mason County line, water levels dip into the Penn Canyon Group before encountering a series of faults near the county line. This stretch coincides with losing conditions, especially during periods of high-water demand, such as in June 2018 and 2021.

To further illustrate the connectivity between groundwater and surface water, please refer to Fig 5 below. The figure shows wells located in relatively close proximity that draw water from hydrologically disconnected sources. The results of the well data were generated using the Ecohydrology package in R (Fuka et al., 2014). All the results are presented for the same time period, indicated on the lower x-axis, with the San Saba streamflow (in cubic feet per second, cfs) displayed on the y-axis. The upper x-axis represents rainfall in inches. Well levels, depicted in blue, are presented in feet, corresponding to the depth of the wells below the ground surface.

These graphics serve as valuable tools for visualizing distinct hydrogeological characteristics and how various wells along the same river respond differently to precipitation events. For instance, we observe that both alluvial wells, represented as K and M, exhibit fluctuations in response to changes in streamflow discharge and precipitation. The signature of well K is so closely aligned with streamflow that we interpret it as actively pumping river water. Conversely, the signature of well M, while also drawing water from the alluvial layer, suggests a more pronounced storage component within the alluvium.

In contrast, well E appears to draw water from the Edwards-Trinity aquifer, making it less dependent on both precipitation and streamflow. Precipitation in the region closely correlates with spring discharge, as supported by all three wells in Fig 5. Although the response times of springs may vary, it's worth noting that spring discharge in the basin has exhibited a decreasing trend over the past 30 years (refer to the spring discharge trendline in supplementary materials), indicating changes in overall water supply, likely influenced by precipitation patterns.

What volumetric contribution can different portfolios of water rights paired with different types of EWT contribute to flow targets? And what are the costs and benefits associated with each portfolio?

Based on the conservation objectives and scope of this study, our interventions focus on dry-year conditions during the irrigation season in the priority reach. There is opportunity for future research to quantify the costs and benefits of employing nature-based solutions (NbS), crop optimization, and other market-based incentives during non-irrigation season. However, for the purposes of prioritization, the scope for this study focused on the time of most need,

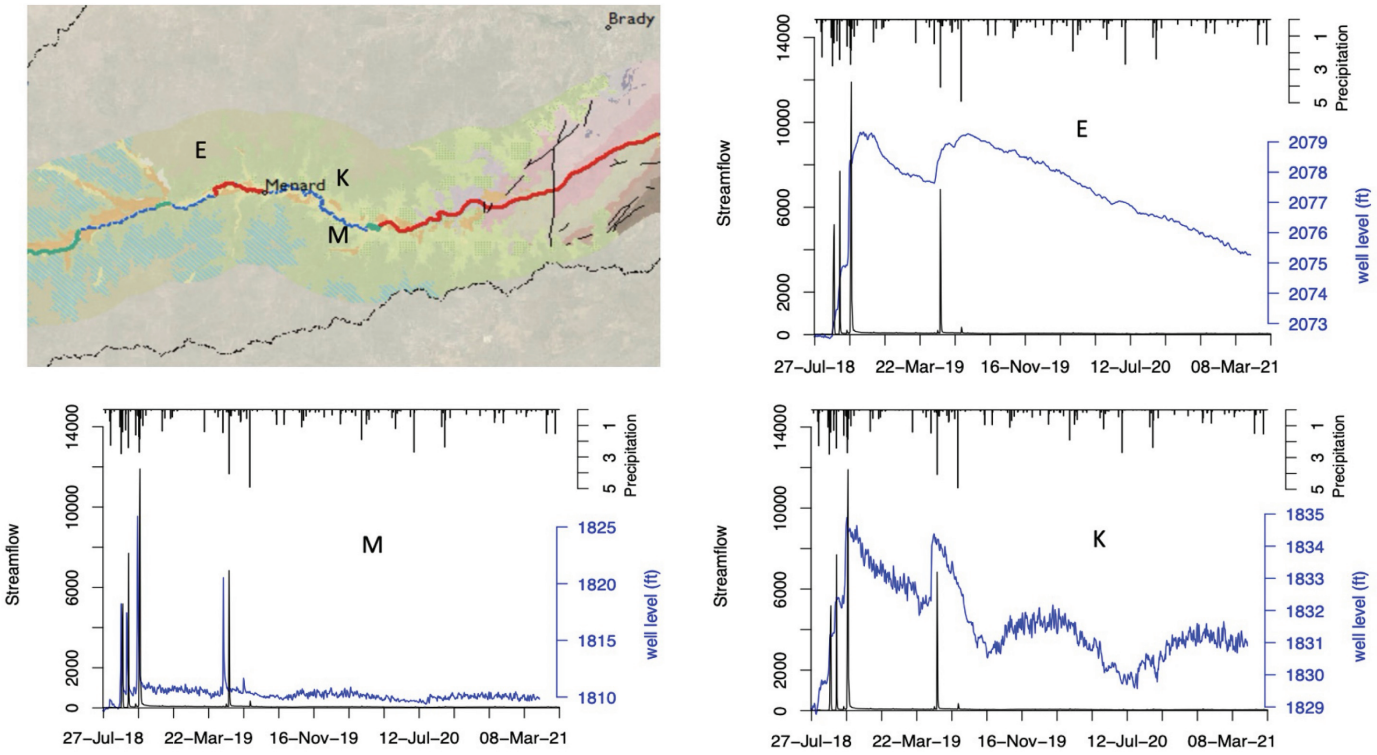


Fig 5. Hydrographs of three representative groundwater wells in the San Saba Basin, illustrating distinct aquifer signatures by displaying streamflow (black on bottom) precipitation (black on top) and well levels in blue. Well "M" exhibits a close correlation between streamflow and well level, characteristic of an alluvial aquifer. In contrast, Wells "K" and "E" display lags in well levels relative to streamflow, more characteristics of Edwards-Trinity aquifer wells.

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which is a dry-year irrigation season where the compounding factors of less than average precipitation and more than average water-use drive water scarcity in the river. We also note that in the San Saba, like many other rivers with groundwater-surface water interaction, we must consider EWTs which work to decrease water use on both surface and groundwater sources.

Based on target flow calculations from the Great Plains (GP) Environmental Flow Information Toolkit (EFIT) Hydrology Dashboard, which are based on Indicators of Hydrologic Alteration (IHA) and Hydrology-Based Environmental Flow Regime (HEFR), our target low baseflow in the summer (June-Aug) is 5.4 cfs. Therefore, we focused on designing three portfolios using EWTs which can each provide 356 AF to the priority reach in July. 356 AF provides 3 cfs for 2 months and assumes that the EWTs would be deployed when discharge reaches 3 cfs.

Of the 224 water rights on the San Saba, 178 have a reliability over 90% (WAM3) and of those with high reliability, 37 are downstream from Menard, which is where we prefer to focus intervention. Of the 37 water rights which meet our criteria, only one has a volume over 356 AF, the minimum value is 9AF with a median and mean value of 45 and 77 AF respectively.

We estimated the financial costs associated with leasing, and purchasing different water rights by using a database on water transactions with 59 transactions in the Colorado, Llano, and San Saba basins in the last 30 years [68]. We further calibrated our costs based on knowledge of five EWTs in the San Saba and neighboring Llano Basin. Based on the most recent EWTs the median price for leases for EWTs was $50/AF and the median price for sales was

$1,137/AF. However, we know these numbers vary significantly depending on supply and demand of water in addition to other factors associated with the water right, including seniority. We use the median price because water this transaction data is skewed and non-normally distributed. For the purposes of this model, we use a price of $70 USD per AF which represents a competitive market price for high seniority and high reliability water rights. Fig 6 below shows the tradeoff associated with different types of simplified EWTs to provide the same volumetric contribution 356 AF. Our study presents a simplified approach that captures the core contribution of this article. However, it's important to acknowledge that in practice, each water transaction is tailored to its specific target. A wide range of transaction scenarios and strategies can be employed to meet various objectives, including partial water right leases, aggregation of multiple rights, and coordinated storage releases. This diversity of approaches allows for flexible and targeted solutions in water management.

While Fig 6 provides a simplified overview of complex transactions, it is important to note that each transaction entails extensive trade-off and cost-benefit analyses by both parties involved. For instance, if a producer opts for a forbearance agreement during a multi-year crop rotation, additional costs for weed control must be considered. Similarly, a producer

Type of EWT	Costs	On farm considerations	
Dry-year options	3-year term agreement if no dry-year event costs = $10,680; if 1 dry-year event, costs = $32,040	Economic security in the event of a dry year. Reduced maintenance costs for fields out of production. Soil health advantages for resting field.	Risk associated with starting and potentially abandoning a crop
Forbearance agreement	3-year term agreement totaling **$74,760** for $70/AF per year	Economic security for a season. Reduced maintenance costs for fields out of production. Soil health advantages for resting fields.	Missed economic opportunity in the event of a wet year or high crop demand.
Water Rights purchase	A one-time cost of **$404,722** ($1,137/AF)	Immediate Capital: Selling water rights can provide an immediate infusion of capital, which can be valuable for funding the source switch to hickory/more reliable water sources, paying off debts, or making investments in other areas.	Permanent loss of water rights and potential long-term consequences for water availability
Water rights lease	A yearly cost of **$24,920** ($70/AF)	Flexibility: Leasing allows water rights holders to retain ownership while temporarily transferring usage rights to others.	Managing leases, ensuring compliance, and negotiating terms can be administratively burdensome, particularly for small water rights holders.

Fig 6. An example of financial tradeoffs and on farm consideration of different EWTs.

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contemplating source switching, such as tapping into the deep Hickory Aquifer with wells reaching depths of 2,000 ft., must factor in fixed costs of drilling and variable costs of powering the pump. These factors must be weighed against the economic gains from selling water rights, which may be less reliable and less readily available than water from a Hickory well, all while considering the associated trade-offs, particularly in terms of water quality.

Dry-year lease options pose intricate trade-off considerations for both producers and NGOs. In a three-year dry-year lease, the NGO initiates the agreement with an upfront payment, typically at a reserve price of $10 per acre-foot (AF) or $8 per 1,000 cubic meters. If river flows fall below a predetermined threshold, for example, 8 cubic feet per second (cfs) or 0.227 m^3/s the NGO pays $70/AF ($56/1,000m^3, which can incentivize producers by exceeding their irrigation opportunity costs during dry years. In any of the EWTs there are significant administrative challenges and transaction costs can impede environmental benefits. For instance, creating EWTs during dry years is impractical due to the need for contract completion well in advance of option activation. One reason forbearance agreements are appealing to NGOs is their lower administrative and transaction costs, even if the financial cost is higher in terms of $/AF. One significant incentive for the producer is that EWTs offer a level of resilience that is challenging to find a substitute for in the current market. Finally, there exist new frontiers for scholars in the field of EWTs to explore. These include developing structural strategies that offer long-term incentives, such as over a 20-year period. Such incentives should be substantial enough to not only cover irrigation opportunity costs but also address capital expenditures related to source switching, exemplified by the case of the San Saba with its deep Hickory well.

Discussion

Upstream and downstream water users in the San Saba River basin agree that water scarcity is a threat to their livelihoods, although they may not agree on who is to blame [59,69]. Amidst increasing competition, conservation organizations are grappling with how to commit water to the environment in times of scarcity. A multidisciplinary perspective reveals that solutions to water scarcity in the San Saba must navigate an irreconcilable rift between the hydrology and governance of the groundwater/surface water relationship. On one hand, the hydrogeology of the basin does not discriminate groundwater from surface water. Depending on climatic conditions and water use, gaining and losing stretches in the river work together to balance aquifer levels and streamflow. On the other hand, water users who rely on water to grow food lack the governance and institutional capacities to manage water use conjunctively. This disagreement between hydrologic communication and water governance limits options for managing water by challenging the typical common pool resource (CPR) or private property strategies for scarcity.

Studying the San Saba contributes to advancing EWT science and strategy. While future policy changes could enhance outcomes for both producers and the environment, there is an immediate need for effective tools that operate within current institutional conditions to address existing environmental water needs. The results of the hydrological studies (results Figs 4 and 5) inform a spatial targeting method which helps spatially target EWTs and compare the tradeoffs for addressing water scarcity. The following sections focus on the final considerations of applying spatially targeted EWTs by drawing on the literature of spatial action mapping [70].

Actions

Increasing attention is being placed on quantifying actions, analyzing relationships among actors, and measuring the impacts of conservation initiatives [71–73]. In the case of EWTs in the San Saba River of Texas, we limited our focus to a short list of EWTs which have a record of implementation. This decision was pragmatic as the objective of our study was to contribute to the science of spatial targeting of EWTs. However, given the evolving demographic landscape and potential shifts in political priorities in Texas, future studies should expand beyond this initial focus to explore a broader range of EWTs that could be relevant under changing state and local water policies [74]. For instance, emerging research could examine the impacts of revised groundwater policies, such as strengthening the capacity of groundwater conservation districts or adapting legal frameworks for conjunctive use [75,76]. Additionally, future work should consider comparing the outcomes of EWT interventions to counterfactuals or business-as-usual (BAU) scenarios, in order to more clearly illustrate the expected benefits of EWTs relative to no intervention [77,78]. Another potential area of investigation involves the development of sustainable funding strategies, potentially through Federal and State partnerships, to ensure the long-term renewal of contracts with producers, thus overcoming the challenges often posed by traditional philanthropic grant cycles.

Actors

In conservation strategy, community leaders, traditional knowledge holders, activists, and others play a crucial role in providing input for spatially targeting actions. These decision-makers are collectively referred to as actors. For this study, we implicitly focused on three types of actors which carried their own assumptions and limitations:

1. **Producers** who use water as an economic input for their business (farming)
2. **Water districts** who play role in organizing trades at the basin level, but who lack sufficient funding to provide adequate monitoring and conflict resolution
3. **NGOs** who fund different transactions with the aim to contribute to pre-defined conservation objectives without expectation of financial returns

Similar to the limitations of our focus on specific actions, our emphasis on these particular actor types comes with certain constraints. To enhance equity and conservation outcomes, a more comprehensive analysis of the actor landscape—including an examination of power dynamics—is strongly recommended [79,80]. From an economic perspective, further research could explore how transaction costs influence actors' willingness to engage with EWTs and affect the incentive structures themselves [51,81]. Additionally, there is a rich opportunity to quantify the unintended social and environmental consequences of EWTs at the basin level, contributing to more effective water resource management [55,82].

Impacts

Although EWTs have played a role in securing water for the environment in specific locations, under certain conditions they have struggled to scale [83–85]. EWT's future success could be improved by incentive design which can respond to seasonal fluctuations in supply and demand, while providing a minimum threshold of private and public benefits. For example, in years where minimum flow metrics are met (i.e., public benefit satisfied), "conserved" water which has already been allocated to the EWT but no longer needed, could be reallocated on a spot market for downstream users to increase private benefits. In this article, we

focused on spatially targeting EWTs during the irrigation season which represents the greatest threat to environmental flows. However, sustainable pathways for addressing water scarcity need to also focus on actions during times of decreased scarcity so that communities invest and maintain the institutional capacity necessary for facilitating transactions under shocks or conflict.

For example, designing a EWT for properties who source water from alluvial wells like well M (Fig 5), and are located on a reach that loses streamflow during the irrigation season, may benefit from focusing on reducing consumptive use, and on a permanent basis, e.g., water acquisition or direct intervention. Alternatively, properties located in the headwaters where the reach transitions from losing to gaining depending on the climate condition may be better served by a EWT that focuses on temporary agreements, e.g., dry-year lease, or forbearance. These results demonstrate how an EWT focused on changing water withdrawals should pay particular attention to the (a) location and (b) volume of their intervention relative to a losing reach. An EWT implemented upstream of a losing reach with insufficient volume (or seasonal baseflow) to pass through the reach may inadvertently be recharging an aquifer. An additional limitation of EWTs is that fulfilling system-level outcomes requires investments in coordination and group level interventions (e.g., environmental flow legislation or mitigation banks). Changes in water-use behavior (e.g., improved monitoring to irrigate more efficiently without increasing acreage) on farms near the river, should be considered with caution so as not to increase consumption [86,87]. Recent evidence suggests resources focused on researching and testing feasibility and performance of transition pathways for transformational institutional change have a better ROI for water savings than technology for water use efficiency [88]. In line with this recommendation, we also note that decisions on targeting specific reaches or properties should balance the short vs. long term trade-offs of on farm technologies vs. institutional transformations in the context of sustainable pathways.

Conclusion

In river basins experiencing water scarcity, competition for freshwater extends to include environmental needs. Environmental Water Transactions (EWTs) present a means to alleviate this competition through voluntary agreements, compensating existing water users for adjusting the timing, location, and volume of their water rights to benefit the environment. Despite sporadic success, scaling EWTs faces significant hurdles in design and implementation. A prominent challenge lies in designing EWTs for areas lacking conjunctive management of surface and groundwater interactions. The San Saba River offers a valuable opportunity to advance EWT science and strategy, given its complex scarcity drivers: geological and anthropogenic factors, coupled with a deficit in governance to ensure environmental flows. Our study makes two key contributions. Methodologically, we use a triangulation approach across multiple hydrological studies to quantify the spatial and temporal dynamics of surface-groundwater interaction. This includes constructing a longitudinal transect that integrates water levels and geological data, conducting gain-loss studies over different periods, and using well gauges to explore the intricate relationships between surface water and groundwater. Additionally, we estimate the consumptive demands of both surface and groundwater users during the irrigation season using a water availability model for surface water and well data for groundwater use. Building on this methodological foundation, we offer cost estimates for four EWT types, spanning from single-season lease transactions to perpetual water rights purchase, with costs ranging from $24,920 to $404,722, respectively. These EWTs have the potential to contribute 3 cubic feet per second (cfs) (0.0850 m^3/s) to support subsistence flows during the peak irrigation season (June-August). Our findings underscore that

EWTs, akin to other tools addressing water scarcity, come with inherent limitations, costs, and benefits. While our study does not include a formal optimization analysis, we emphasize that spatial targeting of EWTs can address several inherent limitations and costs, providing a strategic pathway to maximize benefits for both producers and environmental outcomes. In conclusion, this study advances our understanding of EWTs in complex hydrological settings like the San Saba River basin. By integrating detailed surface-groundwater interaction analysis with practical EWT cost estimates, we provide a framework for more effective water management strategies. This approach not only addresses immediate water scarcity issues but also paves the way for sustainable long-term solutions that balance human needs with environmental conservation.

Supporting information

S1 Materials.Contains data related to the study.
(ZIP)

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Formal analysis: Charles Wight.

Investigation: Charles Wight, Kyle Garmany.

Methodology: Charles Wight.

Visualization: Charles Wight.

Writing – original draft: Charles Wight.

Writing – review & editing: Charles Wight, Dustin Garrick, Brian Richter.

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