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Surface water-groundwater interactions in the upper Brazos River basin of Texas and quantitative relationship to Smalleye and Sharpnose Shiner reproductive success

Prepared by:

Brad D. Wolaver, Ph.D.

TEXAS PARKS & WILDLIFE

Carter Smith

Executive Director

Craig Bonds

Director, Inland Fisheries

August 31, 2019

Personnel

Principal Investigator(s):
Brad D. Wolaver[1]

Consulting TPWD Project Coordinator:
Kevin B. Mayes

Other Project Personnel:
Lindsay V. Reynolds[2], Todd G. Caldwell[3]; Tara Bongiovanni[1]; Jon Paul Pierre[1]; Azadeh Gholoubi[1]. (1) Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX (UT-BEG). (2) Consulting Research Hydrologist at Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX. As of Fall 2019: Lead Riparian Ecologist, Bureau of Land Management, National Operations Center, Lakewood, CO.
(3) UT-BEG; Currently: U.S. Geological Service, Nevada Water Science Center, 2730 N Deer Run Rd, Carson City, NV

Location(s):

Upper Brazos River Basin, Texas

Objective(s):

This study (1) calculates flow metrics to understand how the flow regime has been altered by reservoir construction, groundwater development, or climate variability (such as droughts), (2) evaluates groundwater-surface water interactions and long-term groundwater inflows to streams, and (3) uses mixed-effects regression models and Poisson regression to assesses the relative importance of surface water utilization, groundwater development, and environmental factors in affecting streamflow regimes. Specifically, this study met these objectives by accomplishing this work:

1. Evaluation of groundwater-surface water interactions (Task 1)

Task 1 activities included data collection of continuous stream physical parameters using loggers deployed at the start of the project. Conductivity-temperature and stream stage loggers were downloaded for inclusion in this final report during field activities of

May 28, 2019. We calculated baseflow index (BFI) and assessed BFI trends using standard statistics (e.g., Kendall line, least trimmed squares regression, and related approaches; e.g., Fenelon and Moreo, 2002). We examined wells in the Texas Water Development Board (TWDB) groundwater database (TWDB, 2019a) with long-term groundwater level records and identified groundwater trends using standard statistical methods.

2. Assessment of how reservoirs alter natural flow regime and flows (Task 2)

We calculated streamflow metrics and correlated changes in the flow regime to environmental variables within the context of flows needed for aquatic ecosystem health (e.g., Durham and Wilde, 2009a). Streamflow metrics (e.g., changes in mean annual streamflow, mean summer spawning season streamflow, annual 7-day and 30-day minimum streamflow, annual zero-flow days, annual peak discharge, etc.) were calculated following the general approach of Reynolds et al. (2015). We related streamflow metrics to a suite of environmental variables (e.g., precipitation, groundwater development, reservoir construction) using mixed-effects regression models and Poisson regression to assess the relative importance of surface water utilization, groundwater development, and environmental factors in affecting streamflow regimes (e.g., Reynolds et al., 2015).

3. Recommendations for Recovery and management actions (Task 3)

We synthesized study results and related how groundwater use, surface water use, and climate to assess the streamflow regime at Seymour needed for reproduction identified by population dynamics models. We identified what stream reaches are particularly threatened by water use and droughts. We made inferences as to how forecasted climate change (e.g., IPCC, 2014) may increase stream intermittency (Reynolds et al., 2015). Finally, we provided recommendations for Recovery Plan research and management actions to restore spawning flows and maintain the species' long-term viability.

Significant Deviation(s):

The results of this study meet the objectives outlined above. Due to site-specific conditions, some particular methods were not employed. For example, we originally proposed a third approach to assess groundwater-surface water interactions in river reaches between established USGS stream gauges (Task 1c of proposal). This would have been a streamflow gain-loss study measuring instantaneous discharge using a FlowTracker acoustic Doppler velocimeter (ADV, SonTek, 2014). However, during completion of field activities, we realized that the geomorphology of the upper Brazos River was not suitable for reliable measurement of stream discharge using this technique (i.e., wide, shallow, and braided channel with mobile substrate and intermittent flows). We also proposed the use of a conductivity-based hydrograph separation approach to estimate baseflow (e.g., similar to the approach of Cox et al., 2007; Matsubayashi et al., 1993; Stewart et al., 2007). Thus, we estimated surface-water groundwater interactions using another complementary method (e.g., baseflow index calculation using USGS stream gauge data). Because of sensor limitations due to elevated stream salinity, the loggers (Onset U24) were not able to collect stream conductivity data on all reaches, particularly the Salt Fork Brazos River, making this technique not appropriate to estimate baseflow and assess the relative salt load from each tributary (Task 1d of original proposal). Instead, we used a simpler hydrograph separation using long-term streamflow (Sloto and Crouse, 1996) was employed because of its accepted, standard approach with readily available data. Similarly, we did not identify what streamflow conditions cause stream temperature and conductivity to exceed the shiners' maximum tolerable values (i.e., LC50s in Ostrand and Wilde, 2001) because of the aforementioned issues with conductivity data collection. We did, however, identify when long-term changes in streamflow conditions needed for aquatic ecosystem health (Task 2). Finally, the proposal included analyzing landscape variables (i.e., land use) as predictors of high and low flows (Task 2b of original proposal; e.g., Reynolds et al., 2015). However, as we progressed with the research, we realized that the actual differences in land use between catchments in the basin were insufficient to apply this method. Instead, we evaluated how reservoir construction, groundwater development, precipitation, temperature, and associated environmental variables affected streamflow metrics. Despite these limitations, we were able to satisfy the project objectives of assessing the factors influencing observed changes in flow regime, evaluating groundwater-surface water interactions, and understanding relative importance of reservoir construction, groundwater development, and climate variability on upper Brazos flow regime.

Reviewed by:

__________________________________ Date: _______________________

Kevin B. Mayes, Project Coordinator

Approved by:

__________________________________ Date: _______________________

Chelsea Acres, Rare and Listed Species Coordinator

Contents

1 Executive Summary

Two endangered cyprinids, Sharpnose Shiner *Notropis oxyrhynchus* and Smalleye Shiner *N. buccula*, were historically found throughout the Brazos River basin. However, their range has been greatly reduced by alteration of natural streamflow regimes by reservoirs, river fragmentation by physical barriers, and drying of groundwater inflows from aquifer pumping. The wide, shallow stream habitats the shiners utilize are now limited to the upper Brazos River (UB) basin above Possum Kingdom Reservoir. Increasing stream fragmentation and alteration of the natural flow regime, including reduced peak flows, decreased mean discharge, and increased baseflow has adversely impacted aquatic habitats of resident fish throughout the Great Plains, which reproduce by broadcast spawning. Successful recruitment requires flowing, unobstructed reaches of sufficient velocity to maintain fertilized eggs buoyant. This study (1) calculates flow metrics to understand how the flow regime has been altered by reservoir construction, groundwater development, and climate variability (such as droughts), (2) evaluates groundwater-surface water interactions and long-term groundwater inflows to streams, and (3) uses mixed-effects regression models and Poisson regression to assess the relative importance of surface water utilization, groundwater development, and environmental factors in affecting streamflow regimes. The key findings of this study include: (1) groundwater development resulted in reduced mean daily flows, peak flows, and zero-flow days (2) upstream impoundments increased zero-flow days and reduced mean daily flows, and (3) lower mean daily flows and peak flows occur during droughts—particularly after 1970, suggesting water resource development has exacerbated drought effects. We illustrate this approach using the UB basin of Texas; however, the results of this study can inform management actions to maintain spawning flows for streams in similar semi-arid settings.

2 Introduction

2.1 Reservoir construction

Reservoir construction and other human modifications have strongly altered natural flow regimes of streams across the U.S. (e.g., Poff and Zimmerman, 2010). Decreasing trends in peak streamflow have also been observed in basins of the southwest quarter of the

U.S. (Hodgkins et al., 2019). Groundwater development in the western U.S. has dried or substantially reduced streamflows in groundwater-dependent streams (Brune, 2002; Hoagstrom et al., 2011; Unmack and Minckley, 2008). Throughout the central Great Plains, where streams are closely connected to groundwater, both impoundments and groundwater pumping have adversely affected flows needed for recruitment of resident fish (Brikowski, 2008; Perkin et al., 2015; Perkin et al., 2017). While the impacts of groundwater abstraction on streamflow has been recognized from a water supply perspective since mid-1900s (Hantush, 1956; Theis, 1940), only more recently has the impact of groundwater development on inflows to streams and other groundwater-dependent ecosystems become more widely accepted (Currell, 2016; Gleeson and Richter, 2017; Harrington et al., 2017; Leake et al., 2008; Rohde et al., 2017).

2.2 Groundwater development

Further south, groundwater pumping in the Texas portion of the High Plains Aquifer System has lowered the potentiometric surface more than 45 m in some places (Konikow, 2013; McGuire, 2017), dried springs that feed streams (Brune, 2002), and caused streams flowing across depleted aquifers to lose water (Parsons, 1999). In particular, 10 large dams are located in the Upper Brazos River basin and several more have been proposed (FWS, 2014c; TWDB, 2012). As a result, Sharpnose Shiner (*Notropis oxyrhynchus)* and Smalleye Shiner *(N. buccula),* which were historically found throughout the Brazos River basin, are now in decline (Moss and Mayes, 1993). Brazos basin shiner and other prairie fishes reproduce by broadcast spawning (Perkin and Gido, 2011) and successful recruitment requires flowing, unobstructed reaches up to 270 river km (170 miles; Wilde and Urbanczyk, 2013). However, the range of these two endangered cyprinids has been greatly reduced due to alteration of natural streamflow regimes by reservoirs, physical barriers, groundwater withdrawals, and resulting river fragmentation (FWS, 2014c). The shiners are now limited to the UB basin (Upper Brazos) upstream of Possum Kingdom Reservoir in the High Plains of West Texas (Fig.1; FWS, 2014a). Compounding these threats is climate variability—including droughts (Fernando et al., 2016)—which further threatens to reduce availability of wide, shallow stream habitat utilized by the shiners.

2.3 Streamflow needs for Smalleye and Sharpnose Shiner

Population dynamics modeling suggests a May–September mean daily summer discharge of 6.43 m^3/s (227 cfs) at the Seymour gaging station is needed to maintain Smalleye Shiner populations (Fig.1; Durham and Wilde, 2009a; Durham and Wilde, 2009b). However, mean daily summer discharge decreased approximately 14% at Seymour during spawning between 1993, when the last major UB basin dam was completed, and 2006 (Durham and Wilde, 2009b). Also, flows at Seymour and other parts of the Upper Brazos watershed ceased during the 2011 drought, the strongest one-year drought on record (Fernando et al., 2016). Because shiners usually live only 1–2 years, spawning flow in summers must be restored immediately following any one-year dry period to prevent population collapse (Mayes et al., 2019).

2.4 Impacts of water resource development and climate on streamflows

Reservoirs and impoundments may also change surface water-groundwater interactions. In semi-arid rivers like the Brazos, regular floods recharge bank storage, which may maintain baseflow for years (Simpson et al., 2013). Thus, this study investigates:

(1) How has annual and seasonal streamflow in the Upper Brazos River Basin changed over the last century?

(2) How has annual and seasonal streamflow in the Upper Brazos River Basin been affected by twentieth century reservoir installations, groundwater well installations, and climate, especially drought, over the last century?

As a result of dam construction, ongoing groundwater withdrawals, and droughts threaten to dry or fragment streams and adversely impact recruitment; thus, the U.S. Fish and Wildlife Service (FWS) listed the two Shiner species as endangered in August 2014 and designated 1003 river km (623 miles) as critical habitat (FWS, 2014a, b). Current and projected water use threatens to further reduce streamflows necessary for successful reproduction, potentially causing extirpation (FWS, 2014c). Thus, this study investigates how reservoir operation, groundwater development, and climate variability has affected streamflow in the UB basin over the last century by:

(1) assessing changes in the flow regime of the Upper Brazos by calculating flow metrics using long-term stream gauge records, identifying trends (increasing, decreasing, or

stable), and identifying change points which may be caused by reservoir construction, groundwater development, or abrupt climate shifts (e.g., drought);

(2) evaluating groundwater-surface water interactions and groundwater inflows to streams by using baseflow indices (i.e., percent streamflow comprised of groundwater), estimating total groundwater inputs by comparing upstream and downstream streamflow and baseflow, and assessing long-term trends in groundwater levels; and

(3) assess relative importance of surface water utilization, groundwater development, and environmental variables (e.g., precipitation, land use, drainage area) on flow regime using conditional inference trees, random forests, or similar regression approaches (e.g., Reynolds et al., 2015).

The results of this study can be used by natural resource managers to inform recovery actions by (1) increasing the understanding of how groundwater and surface water resource development has quantitatively affected streamflows needed for reproductive success, (2) evaluating current and future threats to shiner habitat, and (3) identifying threats that could be reduced or managed for the conservation of the species. We illustrate this approach using the UB basin of Texas; however, the method can be applied to improve aquatic species conservation outcomes similar prairie stream systems and other semi-arid headwater streams by identifying linked aquifers.

3 Material and methods

3.1 Study area and land use

We evaluated streamflow regime, groundwater-surface water interactions, and factors affecting hydrology of the UB basin in the current range of *N. oxyrhynchus* and *N. buccula* (FWS, 2014c; Mayes et al., 2019) [Figure 1]. The study area includes 61,300 km^2 in west Texas at the intersection of the High Plains and the Rolling Plains ecoregions (Omernik and Griffith, 2014). The study area includes the cities of Abilene and Lubbock, with estimated 2018 populations of 122,000 and 255,000, respectively (Census, 2018). Primary land covers included cultivated crops (38%), shrub/scrub (36%), herbaceous (20%), developed (4%), and forest (2%) (Homer et al., 2015) [Table SI 1]. Agricultural activities, oil and gas production, and associated industries drive much of the region's economic activity (Comptroller, 2019).

Precipitation exhibits a bimodal distribution, with pulses in May–June and September–October [Figure 2]. Mean annual precipitation is 584 mm with a standard deviation of 133 mm and a maximum of 944 mm in 1941 (NOAA, 2019b). The most intense one-year drought in Texas history occurred during 2011 (Fernando et al., 2016), when a minimum recorded precipitation of 169 mm occurred. Using annual temperature data, mean annual temperature is 17.1ºC with a standard deviation of 0.7ºC while minimum and maximum average temperatures were 15.5ºC (1973) and 18.8ºC (2011; NOAA, 2019b). Evaluating monthly temperature data, minimum average monthly temperature was 4.4ºC and maximum average monthly temperatures were 28.8ºC (NOAA, 2019b). During the 2011 drought, water in the Upper Brazos was limited to drying pools and during a September rescue effort, Texas Parks and Wildlife (TPWD) biologists collected specimens of the focal species for transport to refugia at fish hatcheries (Mayes et al., 2019). Understanding climatic factors—particularly drought—which may affect streamflows during summer spawning (May–September) is of particular interest to conservation of the focal species. Wetter than average periods in the study area typically occur during El Niño-Southern Oscillation (Fernando et al., 2016). Most summer droughts were preceded by an anomalously dry winter and spring associated with La Niña, as occurred in 1951, 1954, 1955, 1956, 1967, and 2006 (Fernando et al., 2016). La Niña also occurred in 2000, however, the summer drought was different in that a wet spring followed a dry winter.

3.2 Hydrology and hydrogeology: Streams, springs, and aquifers

3.2.1 Upper Brazos River

The Upper Brazos watershed (approximately 61,300 km^2) stretches from the High Plains of eastern New Mexico (1,445 m above sea level, ASL) into the Rolling Plains of Texas (304 m ASL at present-day Possum Kingdom Reservoir). Upper Brazos streams historically flowed across and interacted with groundwater of shallow aquifers, particularly the Ogallala Aquifer of the High Plains Aquifer System (Konikow, 2013; McGuire, 2017) [Figure 3; Table 1]. As the Double Mountain Forks Brazos River (DMF) and Salt Fork Brazos River (SF) flowed over the ~100 m elevation break of the Caprock Escarpment, numerous springs from the Ogallala, Dockum, and Edwards-Trinity (High Plains) aquifers augmented streamflow (Brune, 2002) [Figure 3; Figure 4]. Salinity increased as the SF received inflows from saline seeps along outcrops of Permian Whitehorse Sandstone, Cloud Chief Gypsum, and Quartermaster Formation (Baker et al., 1964). Both streams cross the outcrop zone of the Blaine Aquifer and stream direction changes from east-west to north-south direction to skirt the ~40 m outrcop of northern pod of the Seymour Aquifer, from which numerous springs emanated. The Seymour Aquifer was further dissected on the east by Millers Creek (MCk). To the south, tributaries of the Clear Fork Brazos River incised into the Edwards-Trinity (Plateau) Aquifer and to a lesser extent from the Dockum, Seymour, and Trinity aquifers.

3.2.2 Construction of reservoirs and other impoundments

Modern hydrology of the the Upper Brazos has been profoundly altered by 10 large dams (USACE, 2019) [Table 2]. Fort Phantom Hill Reservoir began impoundment of the Clear Fork Brazos River (CF) in 1938, prior to long-term stream gauge records; thus, the effects of this dam on streamflow cannot be empirically assessed. Possum Kingdom Reservoir, the first and largest reservoir on the Brazos River mainstem, was constructed in 1941 and divided the stream into the Upper Brazos and Middle Brazos, shifting species from fluvial specialists to generalists (Mayes et al., 2019). A period of major dam construction continued following the drought of the 1950s through the 1960s. Lake Allan Henry was the last major reservoir, completed in 1994. Several additional reservoirs are proposed for the UB basin. The DMF has a water right already permitted for a possible dam, while another reservoir has been proposed further downstream. The third reservoir on the CF north of Abilene is in advanced design and permitting (FWS, 2014c; TWDB, 2012). Dams constructed in the 1900s in the Lower Brazos resulted in extirpation of the focal species (FWS, 2014c; Mayes et al., 2019).

3.2.3 Groundwater resources

Several aquifers are present in the Upper Brazos; however, only the Ogalla and Seymour aquifers are regionally important water sources [Fig. 3]. Pumping of Ogallala Aquifer groundwater for irrigated agriculture expanded rapidly in the headwaters of the Upper Brazos during the drought of 1950s, catylized by technical innovations in well drilling and high-capacity pumps (Colaizzi et al., 2009). High energy costs and low commodity prices caused a decilne in pumping and acreage from 1974 to 1989 (Musick et al., 1990). Activity renewed in the 1990s and 2000s, in part to supply feed demands for confined animal feeding operations (CAFOs; Almas et al., 2004) and as a result of Low Energy Precise Application (LEPA) center pivot irrigation, which allowed economic irrigation of a wider range of crops in a larger area (Colaizzi et al., 2009). Such extensive groundwater development of the Ogallala Aquifer caused widespread groundwater level declines (Chaudhuri and Ale, 2014; Konikow, 2013; McGuire, 2017) in addition to drying of most of the major springs of the Caprock Escarpment (Brune, 2002). Compared to the highly-developed Ogallala Aquifer, Seymour Aquifer groundwater abstraction is less intense and prior to 1950 was limited to relatively low-volume livestock, municipal, and domestic use (Jones et al., 2012). By the mid-1950s, irrigation had become—and still is—the largest groundwater user in the Seymour Aquifer; however, increased recharge caused by conversion of non-native forage to crops and relatively shallow groundwater levels (Hudak, 2000) resulted in nominal groundwater level changes compared to widespread Ogallala Aquifer depletion during the same time period (Chaudhuri and Ale, 2014). Compared to the Ogallala Aquifer, where spring discharge to headwater streams was readily apparent, the role of Seymour Aquifer groundwater inflows to the Brazos River is less well understood. Regional-scale groundwater modeling of the Seymour Aquifer (Jigmond et al., 2014; Jones et al., 2012) and groundwater level mapping (Harden and Associates, 1978) suggest on the order of ~0.0197 km^3/year (~16,000 acre-feet) of groundwater flows annually to the Upper Brazos. A synoptic 2010 gain-loss survey suggested DMF water losses while crossing the depleted Ogallala Aquifer and then generally gaining conditions of the DMF and SF (Baldys and Schalla, 2011).

3.3 Assessing climate

3.3.1 Climate Metrics

We obtained monthly climate data from the National Climate Data Center (NCDC) for Division 2 of Texas, “low rolling plains”, which captures the majority of the UB basin and well-represents the hydroclimatology of the Upper Brazos (NOAA, 2019b). Divisional climate data is computed by the NCDC for each month 1895–current, using daily station data within each division, to derive mean monthly temperature, mean total precipitation, and mean drought indices across stations. We used the NCDC monthly data to calculate water year and seasonal mean temperature, total precipitation, and Palmer Drought Severity Index (PDSI) for the UB basin [Table 4]. PDSI is a composite index of regional dryness calculated from measured temperature and rainfall data on a monthly time step (NOAA, 2019a).

3.3.2 Climate Breakpoint Analysis

Time series of climate variables (1940 to present; Texas Division 2, Low Rolling Plains: NOAA, 2019b) were evaluated for characteristic breakpoints using the Pettitt, Buishand Range, and Standard Normal Homogeneity (SNH) tests using the "trend" package in R (Pohlert, 2016). These tests are used to detect a single change point in the median/mean value of the observed series (Pohlert, 2018). The Buishand range and the Pettitt test are sensitive to discontinuities in the middle of a time series, while the SNH test is better suited to detect breakpoints near the beginning and end of a series. Also, the SNH and the Buishand range tests assume that the series are normally distributed while the Pettitt test does not. Furthermore, the Pettitt test is less sensitive to outliers due to the ranking approach used (Wijngaard et al., 2003). Additionally, the "findchangepts" function in MATLAB (Killick et al., 2012) is another method used to analyze breakpoints. This method detects breakpoints by minimizing the sum of the residual error over all possible locations using linear regression assuming a set number of breakpoints, which was set to one breakpoint for this case. The Chow test was used to determine if the coefficients before and after the breakpoints chosen are statistically different.

3.4 Assessing changes in groundwater/human alteration regime

3.4.1 Surface water and groundwater alteration metrics

The United States Army Corps of Engineers (USACE) National Inventory of Dams (NID; USACE, 2019), Texas Commission on Environmental Quality Dam Safety Division database (TCEQ, 2019), and the National Anthropogenic Barrier Database (NABD; Ostroff et al., 2013) were used to generate series of the annual cumulative number of dams, storage, and drainage area for each catchment corresponding to the USGS gauges of interest. We then adjusted the annual upstream dam storage area by dividing storage area (hectare-meters) by upstream stream channel length (km), thus deriving a stream-length corrected upstream storage variable (hectare-meters/kilometers), comparable across stream gages.

Information for publicly available wells in the Texas portion of the UB basin were collected from the Texas Water Development Board (TWDB) Groundwater Database. Wells in New Mexico were acquired from the Office of the State Engineer (OSE, 2019). The wells were accumulated by catchment and unique aquifers. We then corrected the number of wells by upstream stream channel length (km), thus deriving a stream-length corrected upstream groundwater well variable (wells/km) for each stream gage. The number of wells was also normalized by the catchment area.

3.4.2 Groundwater breakpoint analyses

Given the obvious sigmoid curve for the well development data (Texas and NM wells: OSE, 2019; TWDB, 2012), we implemented the “findchangepts” mean method assuming two breakpoints to find the peak well development in the area.

3.4.3 Groundwater level trends in Ogallala and Seymour Aquifers

Trends in long-term groundwater level were assessed for the Ogallala and Seymour aquifers to identify stream reaches potentially in connection with adjacent aquifers and identified where near-stream groundwater levels have experienced declines. Wells in the Upper Brazos and adjacent Red and Colorado river basins (within a 0.1° buffer around the study area) with publishable quality measurements were downloaded from Texas (TWDB, 2019a) and New Mexico (OSE, 2019) database. Data were reduced to November–April measurements to limit pumping effects during the summer growing season. If more than one data point occurred during November–April of the water year, it was averaged to create yearly data. For the wells in the study basin with long term records, three timeframes were examined for trends using the Mann-Kendall test: prior to 1950, 1960, and 1970 and all ending after 2010. Gridded potentiometric surface data of a resolution of 0.01° was created for the Ogallala and two pods in the Seymour aquifer. The first step was to fill gaps of two years or less using linear interpolation. This was done for both the Ogallala and two pods in the Seymour. All of the wells within the 0.1° of the specified aquifer were used in an extrapolation algorithm to create yearly maps. Mann-Kendall analysis was done at each grid cell to find trends.

We also investigated using the approach of Perkin et al. (2017); however, we did not complete this analysis, as data and site limitations precluded its successful implementation. In particular, the number of wells with long-term groundwater level data were insufficient for the Seymour Aquifer. In the Ogallala Aquifer, streams are disconnected with the aquifer due to long-term extensive groundwater drawdown.

3.5 Assessing changes in streamflow regime

We divided long-term USGS stream gauge data in the study area into three groups for subsequent analyses based upon data availability [Table 1, Table SI 1]. We consider Priority 1 gauges to be six USGS gauges which were also used in Texas environmental flow assessments (Gooch et al., 2012; Spurgin, 2012) with the longest continuous streamflow records (post-1940; USGS, 2019). Priority 2 are four gauges with shorter continuous records (~1966) [Figure SI 1] used for limited analyses. Priority 3 gauges are five with short, discontinuous records of limited value for analyses [Figure SI 2].

3.5.1 Streamflow Metrics

We selected ten streamflow gages (Priority 1 and 2) in the UB basin that have long term records (more than 50 years) and which represent locations across the basin to capture the impact of groundwater well installation and reservoir installation over the twentieth century in North-central Texas [Table 1]. We compiled daily flow data and annual peak flow data from long term streamflow records from the U.S. Geological Survey (USGS) National Water Information System for Surface Water Data (USGS, 2019). Using long-term stream gage records, we calculated a suite of annual low, mean, and high flow statistics for each water year (October 1–September 30) and focal fish spawning season (April–September)[Table 3].

3.5.2 Flow duration curves

Generalized changes in streamflow regime were evaluated for the six Priority 1 gauges using flow duration curves (FDC). The FDCs show the association between the magnitude and frequency of streamflow by providing the percentage of time the streamflow was equal to or exceeded over the time period. The FDC were calculated using the average daily streamflow values broken up into specified time periods separated to capture periods of major well drilling (1940–1949; 1950–2018) and intensive dam construction (1940–1969; 1970–2018) following the drought of the 1950s.

3.5.3 *Streamflow, baseflow, and trends in streamflow and baseflow for selected gauges*

Baseflow index (BFI), which is the percent of streamflow resulting from groundwater discharge, was calculated using long-term stream discharge records through 2018 (USGS, 2019). Using average daily streamflow, baseflow was calculated using "f_hysep" function in Matlab which provides the same outputs as the USGS Hydrograph Separation and Analysis(HYSEP) local minimum method (Sloto and Crouse, 1996). For this method, BFI was calculated using this equation:

$$BFI = \frac{\bar{b}}{\bar{Q}}$$

where $\bar{b}$ is the average daily baseflow and $\bar{Q}$ is the average daily discharge.

Long-term trends in annual average baseflow, storm flow, total streamflow, and BFI were calculated in Matlab using the Mann-Kendall trend test (Burkey, 2006). Mann-Kendall coefficient (τ) indicates whether there is a positive or negative trend. A larger magnitude indicates a stronger trend. Sen's slope was used to capture the magnitude of the trend (Sen, 1968).

3.6 Evaluating groundwater-surface water interactions

3.6.1 *Groundwater inflows using streamflow*

Groundwater inflows from the Seymour Aquifer to the Upper Brazos were estimated using BFI analysis. Annual baseflow volumes were calculated using data from gauges 08082000 (Salt Fk Brazos Rv nr Aspermont, TX) and 08080500 (DMF Brazos Rv nr Aspermont, TX), which were summed and subtracted from the baseflow at 08082500 (Brazos Rv at Seymour, TX). The residual is considered to be an estimate of Seymour Aquifer inflows to the stream, assuming that non-storm inflows from tributary streams (e.g., Croton Creek) are insignificant.

3.6.2 *Assessing climatic and human influences on streamflow regime*

To test the influence of climate and human impacts on streamflow in the UB basin, we used mixed-effects regression models to test the significance of climate and human influences on annual and seasonal streamflow metrics. Our mixed-effects regression models treated “year” nested within “gage” as a random effect, which considers each gage drawn from a larger population, but data within each gage (flow in each year) as non-independent, which corrects for potential within-gage autocorrelation across years of a time series.

A subset of our Priority 2 gages (N=3: DMF Brazos River near Justiceburg, TX; Clear Fork Brazos River near Roby, TX; Millers Creek near Munday, TX) have lesser degrees of twentieth century groundwater development or on-channel dam installations and associated reservoirs (Figure 1 and 2). We extracted these gages and analyzed them separately from the rest of the gages, since they represent relatively un-impacted rivers in the UB basin.

Using the other impacted gages (N=7), we modeled several select streamflow metrics including “zero-flow days/year,” “zero-flow days per spawning season (April–Sept),” “Water year mean daily flow,’ “spawning season (April–September) mean daily flow,” and “Annual instantaneous peak flow.” For the selected flow metrics, we used the predictor variables: water year precipitation, mean annual temperature, water year PDSI, previous falls’ PDSI, previous winters’ PDSI, spring PDSI, summer PDSI, and the human impact variables upstream water storage per kilometer and number of groundwater wells per river kilometer (Table 3). To model zero-flow day metrics, we used Poisson regression with a penalized quasi-likelihood for over-dispersed count data. For the other flow metrics, we tested normality of the flow metric data and transformed the data with a logarithmic transformation, where necessary. Log-transformed data were modeled using a Gaussian distribution link function.

To analyze our subset of three un-impacted rivers, we used mixed-effects models to analyze the influence of climate alone on annual stream flow in the UB basin. Similar to our mixed-effects models for impacted gages, we treated “year” nested within “gage” as a random effect, which considers each gage drawn from a larger population, but data within each gage (flow in each year) as non-independent, which corrects for potential autocorrelation across years of a time series. For our un-impacted gauges, we modeled several select streamflow metrics including: “zero-flow days/year,” “zero-flow days per spawning season (April–Sept),” “water year mean daily flow,’ “spawning season (April–

September) mean daily flow," and "annual instantaneous peak flow." Because we only had three gages for this modeling analysis [i.e., gauges with limited development in Table 1], we were careful not to over-parameterize our models, and thus used iterative small subsets of the climate variables to determine the best model for each flow metric time series. Again, to model zero-flow day metrics, we used Poisson regression with a penalized quasi-likelihood for over-dispersed count data. For the other flow metrics, we tested normality of the flow metric data and transformed the data with a logarithmic transformation, where necessary. Log-transformed data were modeled using a Gaussian distribution link function.

To compare our flow models to population dynamics modeling of the focal fish species, we extracted streamflow data for the Brazos River at Seymour, TX (08082500 Brazos River at Seymour, TX; Durham and Wilde, 2009a; Durham and Wilde, 2009b; USGS, 2019). We again used mixed-effects regression models to test the importance of climate and human influences on Seymour spawning season streamflow. For Seymour flow, our mixed-effects regression models treated only "year" as a random effect, which considers each year as non-independent and corrects for potential within-gage autocorrelation across years of a time series. We modeled both April–September and May–September mean daily streamflow during the summer spawning season with these predictor variables: water year precipitation, mean annual temperature, water year PDSI, previous falls' PDSI, previous winters' PDSI, spring PDSI, summer PDSI, and the human impact variables upstream water storage per kilometer and number of groundwater wells per river kilometer [Table 4].

4 Results

4.1 Breakpoint analysis for climate

A breakpoint analysis was conducted for a suite of climate variables [Table 5; Table 6]. Only temperature variables had statistically significant breakpoints. For example, mean water year temperature (meant_wy) had a significant breakpoint for the Pettitt, Buishand Range, and the SNH test in 1997. The mean prior to the breakpoint was 16.9^{0}C with a mean after the breakpoint of 17.6^{0}C. While all three breakpoint tests found mean previous winter temperature (meant_PrevWin) had a statistically significant breakpoint, the Pettitt and Buishand Range test found the breakpoint to be in 1989 compared 1991 for the SNHT. Mean spring temperature (meant_Spring) also had statistically significant breakpoints in the late 90s for the Pettitt and SNH test. Mean previous fall temperature (meant_PrevFall) was also important in 1998 for the Buishand Range and the SNH test. For the linear breakpoint test, various PDSI and temperature metrics were important during the drought of the 1950s except for meant_PrevFall which occurred in 1968 and pdsi_wy_sub1 which occurred in 2012.

4.2 What is the role of groundwater-surface water interactions in supporting streamflow?

4.2.1 Surface water and groundwater alteration metrics

Over 250 impoundments for water supply and flood control have been constructed in the Upper Brazos since the early 1900s, with total storage >2.5 km^3 [Figure 7; Figure 8; Table 2]. The majority of reservoir construction occurred during 1960–1980 following the drought of the 1950s [Figure 7]. The largest catchment in the study area is that of gauge 08088000 Brazos Rv nr South Bend, TX with a contributing area of 33,947 km^2 immediately upstream of Possum Kingdom Reservoir. Impoundments in this catchment—which includes all Priority 1 and 2 gauges—increased to ~100 around 1960 and double to ~200 by around 1970, reflecting a burst in reservoir construction following the drought of the 1950s [Figure 9]. By 1980, the number of additional impoundments is minimal; however, cumulative storage increase is not linear, reflecting the important contribution of a few dams, such as Hubbard Creek Reservoir in 1962 (CF), White River Reservoir in 1962 (Salt Fork), and Lake Alan Henry in 1994 (DMF). Fort Phantom Hill Reservoir on the upper CF is also a significant impoundment; however, no long-term, pre-development streamflow records exist prior to its 1938 construction date.

Substantial groundwater development occurred in the Upper Brazos, particularly in the Ogallala and Seymour aquifers [Figure 11]. A time series of well drilling reveals a spike during the 1950s which continued through ~1980s and surged again ~1990–2010—particularly for catchments 08088000 (Brazos Rv nr South Bend, TX), 08082500 (Brazos Rv at Seymour, TX), and 08080500 (DMF Brazos Rv nr Aspermont, TX) which include both the Ogallala and Seymour aquifers [Figure 12, Figure 13]. Conversely, the CF drainage has no Ogallala Aquifer and less Seymour Aquifer present. In terms of well development by aquifer, Ogallala, Seymour, Dockum, and Trinity took off as the drought of the 1950s set in. The Ogallala Aquifer is the most important in the Upper Brazos and drilling there has continued relatively steadily for ~70 years to >9,000 wells in publicly available databases. In the Seymour Aquifer, development was less extensive and plateaued by around 1975 at slightly less than 2,000 wells. The Dockum, Trinity, and Cross Timbers aquifers are much less important and show similar development patterns of 250–300 wells each; however, drilling (likely for stock and domestic use) started around 1900 in the Cross Timbers Aquifer.

4.2.2 Breakpoint Analyses for Ground Water

We completed a breakpoint analysis for groundwater to determine peak development [Figure 14; Table 7]. According to the breakpoint analysis on the number of wells, the beginning of the developmental period was the early 1950s (1951±3). This increased the mean of the installed wells by ~10 times that of pre development. This coincides with the introduction of high-capacity submersible pumps after WWII and also rapid response to the drought of the 1950s. Well construction was a faster response then resource-intensive and slower-paced reservoir construction. The year at which periods of major well drilling ends varies depending on the basin (1966±7 for mean method). Following the second break point, well development became 1/3–1/2 of that of the peak for basins 08080500 (DMF Brazos Rv nr Aspermont, TX), 08082500 (Brazos Rv at Seymour), and 08088000 (Brazos Rv nr South Bend) and relatively nonexistent for the other basins. In particular, for 08080500 (DMF Brazos Rv nr Aspermont, TX) the peak development is 1950–1967, which is earlier than the 1994 completion date of Lake Alan Henry. For 08082000 (Salt Fk Brazos Rv nr Aspermont, TX) peak development was 1951–1967, which includes the time White River Reservoir filled. In the CF drainage, 08085500 had a mean break point of 1949–1969, but has less wells completed than the Seymour basin (<100 wells/year compared to over 500 wells/year)

4.2.3 Groundwater level trends in Ogallala and Seymour Aquifers

Our evaluation of long-term changes in groundwater level revealed persistent declines for much of the Ogallala Aquifer [Figure SI 16]. Despite the thousands of wells drilled in the Ogallala Aquifer, relatively few have continuous groundwater level records. In order to evaluate more wells, we changed the start year from the 1950 to the 1970, but the overall declining trend did not change. The northern Ogallala has major downward trends when looking at both the individual wells with long-term data and the trends of the gridded surface [Figure 15]. However, three portions of the Ogallala Aquifer in our study area exhibited increases in groundwater level: the west-central portion, the south east at the Caprock Escarpment, and in and around Lubbock. Our analysis of groundwater levels in the Seymour Aquifer was hampered by lack of wells with long-term records. For the northern Seymour Aquifer pod, there is one well with a major increasing trend and one well with a major decreasing trend while the other wells have a slightly increasing/decreasing trend [Figure 15]. For the southern Seymour pod, there are three wells with a major decreasing trend and three wells with a slightly decreasing trend. Overall, there are too few wells in the Seymour Aquifer to map gridded groundwater level with any confidence [Figure 15]. However, the pattern of overall groundwater level decline in the Ogallala Aquifer is clear.

4.3 How have flow regimes changed?

We evaluated changes in the flow regime of the Upper Brazos and assessed possible surface water and groundwater management factors potentially contributing to these changes. All subsequent analyses are focused on Priority 1 gauges because ~1940 start data includes periods of intensive reservoir construction 1960–1980 and rapid well development during and after the drought of the 1950s. An assessment of three representative Priority 1 gauges shows that the Upper Brazos flow regime has a bimodal distribution with early summer and fall peak streamflow [Figure 6].

4.3.1 Flow duration curves

Our generation of annual [Figure 16], April–September [Figure SI 18], and May–September [Figure SI 19] flow duration curves reveal interesting patterns in the flow regime, looking at potential effects of surface water development (pre- and post-1970 period of heightened dam construction) and groundwater development (pre- and post-1950 start of intensive well drilling). For all gages [Figure 16], peak flows become less frequent. At 08080500 (DMF Brazos Rv nr Aspermont, TX), 08082500 (Brazos at Seymour, TX), 08088000 (Brazos at Seymour, TX) and 08085500 (CF, Ft. Griffin), the lowest flows also decrease, indicating flows become more consistent over time—particularly at DMF Brazos Rv nr Aspermont, TX. Interestingly, the decrease in peak flows at 08082000 (Salt Fk Brazos Rv nr Aspermont, TX) is less pronounced than in the DMF or Brazos River main stem. The 08084000 (CF, Nugent, TX) gauge exhibits a shift to more low flow days.

4.3.2 Streamflow, baseflow, and trends in streamflow and baseflow for selected gauges

Our evaluation of long-term streamflow data reveal interesting patterns in BFI (percentage of streamflow comprised of groundwater inflows), base flow (BF, groundwater discharge in a stream), storm flow (SF, discharge in stream related to runoff processes following precipitation), and total flow (Q, total stream discharge). Maximum BFI occurred in 2011 (during the most intense one-year drought on record; Fernando et al., 2016) for all Priority 1 gages except for 08084000 (CF at Nugent), which occurred in 1998 and was more than 0.60 for all of the gages [Figure 18; Table 9]. The minimum BFI occurred prior to 1955—when higher overall storm flows occurred—and the median BFI ranged from 0.101 to 0.169. All the Priority 1 sites had a significant increase in BFI according to the Mann Kendall test [Table 10]. This is primarily due to the decreasing trend in storm flow leading to a decreasing trend in overall flow. Maximum streamflow and maximum storm flow occurred prior to 1958 for all gauges. Minimum streamflow and storm flow occurred in 2011, 2012, or 2014 for most cases, with one minimum storm flow year in 1998.

Trends in BFI, BF, SF, and Q were analyzed using Mann Kendall and Sen's Slope tests. All six Priority 1 gages has decreasing slopes for storm flow (SF) and overall flow (Q) and increasing base flow index (BFI). Baseflow trends were less pronounced with statistically significant increases (per Mann Kendall τ) at Aspermont and Ft. Griffin. The steepest decreasing slopes for storm flow and overall flow (-0.179 $m^3/s/year$ and -0.196 $m^3/s/year$, respectively) were at South Bend, due to this site having the highest flow, while the Seymour site had the second steepest decrease in overall flow (-0.083 $m^3/s/year$). The Mann Kendall τ value for Q, which is a better way to make comparisons between sites, showed the greatest decrease for SF at Aspermont. The only site not to have a significant trend in total flow is CF at Ft. Giffin, which had a significant increasing trend in baseflow. The only other site with a statistically significant increasing trend in baseflow was DMF-Aspermont. When running the same statistics starting at 1964 rather than 1940, the only statically significant increasing trends in BFI were DMF Aspermont and Seymour

[Table SI 4]. The decreasing trend in total flow was still significant at all sites except CF at Ft. Giffin. The slope of the trend line for overall flow was not as steep for South Bend (Sen's slope was -0.164 $m^3/s/year$). At both Giffin and South Bend, the decreasing trend in stormflow was no longer significant. Nugent was the only site with a statically significant decrease in baseflow.

4.3.3 Breakpoint Analysis for flows

In addition to annual flows, we evaluated mean flows during summer spawning season (April–September) [Figure 17; Table 8]. For all gauges, the mean before the break point (mean 1) for years earlier in the record, is greater than the mean after the break point (mean 2), demonstrating consistent declines in summer spawning season flow [Table 8]. According to the Pettitt test, which is less sensitive to outliers, 08082000(SF Aspermont) and 08088000 (Brazos River at South Bend) had break points in 1972 and mean spawning season (April–Sept) flows were reduced by ~40% and 55%, respectively. For 08080500 (DMF BR Aspermont) and 08082500 (BR Seymour), breakpoints occurred in 1992 with 42% and 50% reduced flows. The last gage with a statistically significant breakpoint for the Pettitt test was 08084000 which occurred in 1997. The Buishand Range and Standard Normal Homogeneity test had statistically significant break points at different times than the Pettitt test. They both had break points in 1972 and 1961 for 08080500 (DMF BR Aspermont) and 08082000(SF Aspermont). The Standard Normal Homogeneity test also showed a statistically significant breakpoint in 1941 for 08082500(BR Seymour) and 08088000(Brazos River at South Bend). The only gage without statistically significant breakpoint in all tests was 08085500 (CF BR Ft Griffin).

4.4 Groundwater-surface water interactions

4.4.1 Groundwater inflows using streamflow

Our estimate of daily stream inflows from groundwater (and any ungauged smaller catchments) between the SF and DMF Aspermont gauges and the downstream Seymour gauge are shown on Figure 19. Generally positive inflows reveal that the stream is typically gaining. However, the stream alternates fairly readily between gaining and losing over the period of record, particularly prior to ~1980. The highest losing stream conditions were during 23-Sep-1942, 15-May-1947, and 09-Jul-2010 and the analysis reveals that

25% of the time the stream was losing. The greatest gaining conditions, when groundwater inflows were maximum (or were unmeasured flows from smaller drainages), occurred during flows of 13-Jun-1941, 24-Jun-1982, 01-Jun-1992, 28-May-2015. Our analysis of daily baseflow conditions revealed that 10% of the time the stream gained 90% of its flow between the upstream and downstream gauges from groundwater inflows or small drainages. During 55% of the period of record between 1940 and 2019, the stream gained more than half of its flow from groundwater inflows or unaged smaller drainages. An analysis of annualized stream inflows reveals mean contributions from groundwater (and ungauged smaller catchments) of 0.0237 km^3/year (gaining), with a minimum of -0.0053 km^3/year (losing in 1974, 2010, and 2012), and a maximum of 0.1347 km^3/year (gaining, 1992).

4.4.2 Streamflow, Human and Climate Metrics: What factors influence streamflow most?

For gages impacted by water resource development, we found that the number of groundwater wells per river km was a significant predictor in all flow variable models: Zero-flow days per year, zero-flow days per spawning season, water year mean daily flow, spawning season mean daily flow, and annual peak flow (Table 11). An increase in the number of groundwater wells is associated with decreased mean daily flows (annual and spawning season) and lower peak flows, but fewer zero-flow days (annual and spawning season). Reservoir storage was a significant predictor in all except the spawning season zero-flow days (Table 11). Increasing reservoir storage is associated with increased annual zero-flow days, decreases in mean daily flows (annual and spawning season), and decreases in peak flows. Climate variables had mixed effects on human-impacted gages. For zero-flow days and spawning season zero-flow days, the previous years' winter and spring drought conditions are also significant (Table 11). However, for water year mean flow, spawning season mean daily streamflow, and annual peak flows, there is a negative drought signal for previous winter and spring, but a positive drought signal for the water year over-all (Table 11).

For the three un-impacted gages, we found that overall drought conditions as measured by PDSI for the water year, and PDSI for the previous fall and previous winter were significant for predicting the number of zero-flow days: more intense drought lead to more zero-flow days. Annual water year precipitation became important for water year and spawning season mean daily flow and annual peak flows, with more precipitation leading to higher mean daily flows and annual peaks. Drought conditions for the year was also a significant predictor for spawning season flows, with annual PDSI positively related to spawning mean daily flows.

At the Brazos River Seymour gauge, we found that the streamflow during the April–September and May–September spawning seasons was most highly correlated to annual water year precipitation. Thus, greater precipitation leads to higher mean daily flows. For flows during April–September and May–September, the number of wells installed per river kilometer was a marginally significant predictor variable with a negative relationship, indicating that as the number of wells have increased, spawning season mean daily flows have decreased.

5 Discussion

This study increases our understanding of how surface water development, groundwater use, and climate variability affects streamflow in the Upper Brazos. Specifically, the study (1) assesses how the basin's flow regime has changed, (2) evaluates groundwater-surface water interactions for the Ogallala and Seymour aquifers, and (3) investigates the relative contributions of surface water use, groundwater pumping, and climate on the flow regime. This work is important because it may be used to inform development of recovery actions for the two focal species, other prairie broadcast spawning (PBS) fish, and overall aquatic ecosystem heath in the UB basin.

5.1 Flow Regime Changes

Long-term streamflow records (1940–2018) at the six Priority 1 gauges reveal changes in the flow regime. Flow duration curves [Figure 16] and baseflow analyses [Figure 19] reveal that in general: (1) annual stream discharge volume is declining and (2) streams are becoming less flashy with a reduction in peak flows, increase in baseflow index, and an overall decrease in non-zero-flow days. These patterns are also supported in the streamflow metrics, which generally show decreases in mean annual flow (Figure SI 5), decreases in zero-flow days (Figure SI 11), and decreases in annual peak flows (Figure SI 12). In three of the six gauges (08080500 DMF Aspermont, 08082500 BR Seymour, and 08085500 CF Ft Griffin), these changes become more pronounced 1970–2018 compared to 1950–2018, suggesting that surface water impoundments (or the drought of the 1950s) may exert more effect on the flow regime than groundwater development. Similarly, in terms of summer spawning flows (April–September), gauges 08080500 (DMF Aspermont) and 08082500 (BR Seymour) [Figure 17; Table 8] have a breakpoint (Pettitt test) of 1992, suggesting the impoundment of Lake Alan Henry may be responsible (1994); however, 08084000 (CF, Nugent) also had a 1997 breakpoint, suggesting perhaps climate variability was an important influence. The breakpoint analysis for well drilling [Figure 14; Table 7] reveals that the potential effects of groundwater development on the flow regime span longer periods of time than impoundment construction; however, the onset of well drilling for the ten Priority 1 and 2 gauges is from 1944–1962.

Our breakpoint analysis of climate variables revealed that temperature has the clearest changes through the study period. Mean water year temperatures and temperatures in the previous winter and spring all have clear breakpoints from 1989–1999, suggesting the importance the 1995–1996 drought (Hayes et al., 1999) as a climatic change point in the basin. Alternatively, the linear breakpoint analysis revealed that eight of the ten years with significant break points occurred in the 1950s, revealing the potential importance of this multi-year drought on Upper Brazos hydrology.

Thus, the flow regime of the Upper Brazos is clearly affected by the construction of impoundments. Superimposed upon the anthropogenic effect of dams are the hydrologic impacts of drought, with the 1950s, 1990s, and 2011 droughts (Winters, 2013) all showing up as important stressors. The potential effects of groundwater development on streamflows are harder to resolve. Clear are the effects of pumping in the Ogallala Aquifer, which have reduced spring flow along the Caprock Escarpment and made streams disconnecting and losing where they cross and interact with the Ogallala Aquifer. Less clear, are potential effects of Seymour Aquifer pumping on groundwater flows to the river, given the paucity of wells with long-term data. However, the increase in Seymour Aquifer recharge attributed to agricultural development in the mid-1990s (Jigmond et al., 2014; Jones et al., 2012) may have increased flows to the stream, which may have been reduced by groundwater pumping and evapotranspiration losses from crop irrigation.

5.2 Groundwater's Role in Maintaining Streamflow

Based on historical assessments of spring discharge along the Caprock Escarpment (Brune, 2002), it is clear that spring flow from the Ogallala Aquifer used to provide important contributions to streamflow in the headwater reaches. Decades of groundwater extraction has lowered groundwater levels in the Ogallala Aquifer and reduced or dried source springs. Groundwater management plans for the Ogallala Aquifer include planned depletion (TWDB, 2019b); thus, groundwater inflows to the UB basin can be expected to decrease further. Using the baseflow separation of daily long-term stream gauge data [Figure 19], we found that the Upper Brazos typically gains between the SF and DMF Aspermont gauges and Seymour, Texas an average 0.0237 km^3/year (~19,200 acre-ft/year) from the Seymour Aquifer, minor aquifers (e.g., Blaine Aquifer, alluvial aquifer), and any ungauged streams. Interestingly, numerical modeling estimated a very similar number for inflows to the stream from the Seymour Aquifer of ~0.0197 km^3/year (~16,000 acre-feet/year) (Jigmond et al., 2014; Jones et al., 2012).

Another interesting finding of our annual groundwater inflows analysis is that the Upper Brazos is a losing stream (i.e., the stream is losing water to its bed, alluvial aquifer, and other aquifers the stream crosses) during 1974, 2010, and 2012. Losing stream conditions in 2010 and 2012 almost certainly related to the intense one-year drought of 2011 and hydrologic conditions leading up to and following 2011. Oddly, 1974 is not characterized by Fernando et al. (2016) as a strong drought year. However, while monthly historic Palmer Drought Severity Index values reveal a normal to moderately moist fall 1973 and early winter 1974, moderate drought conditions start in March, 1974, turning to extreme drought in July, 1974, before returning to mid-range conditions in August, 1974 with flows at both the DMF (08080500) and SF (08082000) Aspermont gauges which did not make their way downstream to Seymour (08082500) (NOAA, 2019a, b; USGS, 2019). Of interest is that strong drought years of 1951, 1954–56, 1967, and 2006 did not have losing stream conditions. A possible explanation is that hydrologic alteration of the Upper Brazos from dam and well construction may not yet have had affects. Of importance for conservation of the focal species is that under the Upper Brazos' current flow regime, it can be expected that following a strong drought the stream will continue to lose water to the shallow local aquifers and that more normal streamflow may not return—given sufficient precipitation—for one or more years after the drought.

In addition to an evaluation of baseflow using long-term stream gauge data, we also attempted to apply to the Upper Brazos the approach of Perkin et al. (2017) to investigate the possible connection of streams with aquifers they interact with. However, we found that a lack of wells with long-term groundwater level data in close proximity to streams, particularly in the Seymour Aquifer, made applying this approach intractable in the Upper Brazos. In addition, groundwater level declines in the southern High Plains Aquifer System (i.e., Ogallala Aquifer) of the Upper Brazos are extraordinary, at >45 m in some places. However, aquifer drawdowns in the central High Plains Aquifer System of Colorado, Kansas, and Nebraska Perkin et al. (2017) studied are much less extensive, with maximum declines of 15–30 m. Thus, streams in the Upper Brazos are almost completely disconnected with the Ogallala Aquifer, whereas to the north, streams still have a greater degree of connection with groundwater.

Currently, groundwater recharge in the Southern High Plains is quite low (10 mm/year) and focused at ephemeral lakes and playas (Scanlon et al., 2012). Future recharge under climate change forecasts is expected to further reduce by 10% (Crosbie et al., 2013). The implication of current and future High Plains Aquifer System groundwater recharge and planned aquifer depletion from pumping is less groundwater flows from the Ogallala Aquifer. Future climate scenarios may also suggest a reduction in groundwater outflows from the Seymour Aquifer to the Upper Brazos because of reduced recharge rates.

5.3 Importance of Water Resource Development and Climatic Variability on Streamflow

In our streamflow metric models, we tested the human development variables of upstream storage and groundwater wells, as well as climate variables as predictors for variation in streamflow metrics across the Upper Brazos basin. The number of groundwater wells per river kilometer was an important, negative predictor in all of the models, meaning that the more ground water wells being installed over time has led to declines in mean daily flows and peak flows (Table 11). Increases in upstream reservoir storage caused increases in zero-flow days and decreased mean daily discharge. Thus, catchments with the most intensive groundwater well installation and reservoir construction have water resource development as a strong signal for streamflow metrics. Climate also influences selected streamflow variables, showing that drier years with elevated PDSI and low annual precipitation result in lower mean discharge and more zero-flow days.

For un-impacted streams with minimal well installation and reservoir construction, overall drought conditions were most important for zero-flow days (water year and spawning season). Precipitation became important for annual and spawning season mean daily flows and annual peak flows.

Interestingly, the number of zero-flow days both annually and during the spawning season, was negatively related to the number of groundwater wells installed per year; meaning increases in groundwater pumping resulted in fewer zero-flow days (probably higher baseflows). This could be due to increased return flows from agricultural lands to streams—at least along the Seymour Aquifer, where groundwater levels have changed much less than precipitous Ogallala Aquifer declines. However, if return flows are increasing baseflows and decreasing the number of times that a stream dries (zero-flow days), they are also at the same time bringing down mean flows and peak flows [Table 11].

The rivers in the Upper Brazos Basin are closely connected to their alluvial aquifers and regional climate conditions, and our results support and emphasize this hydrology. In basins where groundwater development and reservoir construction has occurred steadily over the second half of the twentieth century, climate still influences annual stream flows. However, both reservoir construction and groundwater pumping have altered streamflow hydrology with decreases in mean flows and decreases in peak flows.

In the three catchments without major impoundments and with less intense well development, California Creek near Stamford, TX (08084800) and Clear Fork Brazos River near Roby, TX (08083100) both show an increase in zero-flow days after ~2000 [Figure SI 11]. During this time, major droughts occurred in 2000, 2006, and 2011 (Fernando et al., 2016); thus, this prolonged period of lower precipitation and elevated PDSI could have resulted in less flows to streams via storm runoff or groundwater baseflow. Increased zero-flow days could have also been caused by greater agricultural reliance on groundwater pumping for irrigated agriculture, instead of rainfall-dependent crops [Table SI 1]. Increased zero-flow days at more downstream locations at the Clear Fk Brazos at Nugent (08084000) and Clear Fk Brazos at Ft Griffin (08085500) could potentially reflect reduced outflows from Fort Phantom Hill Reservoir [Table 2] as more surface water is retained for use by Abilene (HDR, 2011). The overall trend in a decrease in zero-flow days at DMF Brazos nr Aspermont (08080500) and Brazos at Seymour (08082500) is a bit perplexing, as our modeling shows that upstream dams, including Lake Alan Henry and White River Reservoir caused more zero-flow days [Table 2], which does make sense, as these reservoirs lack the necessary infrastructure to releases water for environmental flow during lower-precipitation periods. Furthermore, evaluating the role of steady treated effluent releases from Lubbock—which include an increasing share of imported Ogallala Aquifer groundwater and surface water from Lake Alan Henry that is piped to Lubbock (DBS&A, 2015)—on DMF Brazos near Aspermont (08080500) flows could be an important topic for further study. Also, groundwater in the Ogallala Aquifer around Lubbock has increased in recent decades (McGuire, 2017) [Figure 15], most probably as a result of leaky pipes, lawn irrigation return flows, and potential leakage of Lubbock-area dams now filled with treated effluent [Table SI 2]. Such rising groundwater conditions (a unique condition for the Ogallala Aquifer) may actually have increased groundwater discharge to farthest upstream portions of the DMF catchment. These ideas are somewhat supported by visual inspection of the Salt Fk Brazos nr Aspermont (08082000) gauge streamflow metrics. The SF does not receive treated wastewater and by visual inspection over the entire period of record does not have a clear trend in zero-flow days. Alternatively, as previously mentioned, return flows from irrigated agriculture may also play a role in decreasing zero-flow days.

A key finding based on visual inspection of all four Priority 1 Brazos River gauges (i.e., 08080500, 08082000, 08082500, 08088000) [Table 1], construction of dams and drilling of wells strongly impacted flows necessary for aquatic ecosystem health by:

(1) reducing annual streamflow volume [Figure SI 5],

(2) decreasing mean annual spawning flows (particularly the three most upstream gauges) [Figure SI 6], and

(3) diminishing peak annual discharge [Figure SI 12].

Natural climatic variability (i.e., droughts) exacerbates impacts to the streams caused by surface water and groundwater resource development.

5.4 Implication for Conservation and Recovery of Streamflow in the Upper Brazos

Conservation of the focal species requires preservation of summer spawning flows as well as flows for instream habitat for the remainder of the year following reproduction. While forecasting future stream conditions is challenging, the trend of decreased annual discharge at 08082000 (SF, Aspermont), 08080500 (DMF, Aspermont), and 08082500 (Seymour) suggests a continued decline in streamflows. Furthermore, regional water planning groups have established Desired Future Conditions for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers that include drawdowns of nearly 10 m from 2012 to 2070 (Groundwater Management Area 2; TWDB, 2019b) and 5.5 m declines in the Seymour Aquifer 2020 to 2070 (Groundwater Management Area 6; TWDB, 2019b). Conversely, downward trends in annual discharge and overall groundwater development are somewhat less in the CF drainage, so at least upstream of the proposed Cedar Breaks Reservoir, long-term preservation of streamflows may be better than in the SF and DMF. However, the CF tributary near Roby and California Creek may be particularly susceptible to drying from droughts. Compounding planned aquifer drawdown are forecasts of reduced groundwater recharge, higher streamflow evaporation from elevated temperatures, and potentially lower streamflow (Bertrand and McPherson, 2018; Crosbie et al., 2013).

Thus, what can be done to recover flows and instream habitats needed for long-term viability of the focal species? Surface water impoundments in the Upper Brazos appear to markedly affect pulse flows needed for recruitment. To this end, it would be good if the Post Reservoir—which has already been granted a water right—not be constructed in the upper reaches of the DMF and that the proposed mid-basin reservoir and Cedar Breaks Reservoir on CF not be constructed (DBS&A, 2015; HDR, 2011). If possible, it would be useful to retrofit Lake Alan Henry and White River Reservoir with infrastructure so that some flood flows may be released downstream. As part of a modification of Lake Alan Henry operations could include a reduction of surface water diversions to Lubbock to liberate water for instream flows. To make up this volume, perhaps Lubbock could increase water conservation, treated water reuse, or brackish groundwater desalination. Additionally, leasing of surface water rights during droughts, if available, may also represent an opportunity to augment streamflows. In terms of groundwater management, the historical importance of springs in the Ogallala Aquifer along the Caprock Escarpment in supporting streamflows is well documented (Brune, 2002). Furthermore, this study and previous numerical modeling suggest ~0.02 km^3/year of groundwater discharge from the Seymour Aquifer supports UB basin streamflow. Hence, preservation of streamflow may be supported by selecting Desired Future Conditions that minimize aquifer drawdowns (e.g., TWDB, 2019b). Fallowing fields or leasing groundwater rights near streams may also be an opportunity to increase streamflows.

For near-term conservation of the focal species, ongoing monitoring of weather conditions, specifically drought conditions, in the UB basin will be required to determine when collection individuals and transport to refugia at fish hatcheries may be required. We know that strong droughts in Texas often immediately follow onset of La Niña (Fernando et al., 2016). Thus, early indicates of La Niña conditions setting up in the fall and winter would be an early warning that drought conditions and reduced UB basin streamflows may soon follow. Additionally, if warmer or drier than normal winter or springs occur, these climatic conditions may also precede reduced summer flows. Our analysis also showed that—related to the 2011 drought—the Upper Brazos was a losing stream in 2010 and 2012. So, it would be important not to repatriate captured fish until a return of flows after a drought, as the first heavy rains may be lost to re-wet the bed, banks, and shallow alluvial aquifer.

5.5 Assumptions and limitations of this approach

The results of this study are only as good as the input data. Thus, we assume that streamflow measurements by the U.S. Geologic Survey are correct (USGS, 2019), groundwater levels in Texas and New Mexico are measured accurately (OSE, 2019; TWDB, 2019a), and that regional climate data accurately represent local conditions in the Upper Brazos (NOAA, 2019b). In addition, we intended to conduct a gain-loss study to estimate groundwater inflows, however, the wide, shallow, braided, mobile stream bed made this measurement difficult. We also investigated using conductivity-based hydrograph separation (e.g., Cox et al., 2007; Matsubayashi et al., 1993; Miller et al., 2014; Stewart et al., 2007) to estimate baseflow, but used the simpler hydrograph separation using long-term streamflow (Sloto and Crouse, 1996) because of its accepted, standard approach and because elevated salinity in SF made continuous conductivity measurements difficult. Similarly, we were unable to assess the relative salt load from each tributary because the elevated salinity of the SF was above the range of the loggers we used (Onset U24). Finally, the proposal included analyzing landscape variables (i.e., land use) as predictors of high and low flows (e.g., Reynolds et al., 2015); however, the differences in land use between catchments in the basin were insufficient to apply this method. Despite these limitations, we were able to meet project goals to assess factors influencing observed changes in flow regime, evaluating groundwater-surface water interactions, and understanding relative importance of reservoir construction, groundwater development, and climate variability on Upper Brazos flow regime.

6 Conclusions

The results of our study suggest that the flow regime needed for reproductive success focal species in the UB basin of Texas has been affected by a combination of water resource management and natural climatic variability.

- Mixed-effects regression models and Poisson regression suggest that (1) groundwater development caused reduced mean daily flows and peak flows but decreased zero-flow days, (2) upstream impoundments increased zero-flow days and reduced mean daily flows, and (3) droughts result in lower mean daily flows and peak flows.
- Construction of impoundments, and particularly large reservoirs, following the drought of the 1950s in an active period from 1960 to 1980 appears to have both reduced peak streamflows and annual stream discharge. Impoundments have also increased, in some cases, lower-end flows. Long-term trends in stream discharge are declining in the SF, DMF, and Brazos main stem above Seymour. Stream discharge declines are less in the CF drainage. Modification of existing dams to release storm flows to augment streamflows could be a conservation strategy. Stopping construction of future reservoirs would also increase conservation outcomes.

- Groundwater development responded more rapidly to the drought of the 1950s than impoundment construction, most likely because capital-intensive and shorter-duration to completion. Study results suggest that in some parts of the basin, peak well drilling activity started in most catchments around 1950 and lasted between ten to twenty years. Intensive pumping of the Ogallala Aquifer reduced flows and dried springs along the Caprock Escarpment which previously supported headwater streamflows. The Seymour Aquifer appears to provide approximately 0.02 km^3/year of groundwater inflows to the Brazos River.
- Droughts during the 1950s and also 1995–96, 2000, 2006, and 2011 influenced streamflows. Reduced summer flows follow increased winter and spring temperatures. Forecasts of future climate suggest reductions in groundwater recharge, increased evaporation, and reduced runoff are possible, which could adversely affect streamflows needed for long-term viability of the focal species. Droughts almost always follow establishment of La Niña.

The results of this study can be used by U.S. Fish and Wildlife Service to inform development of the Recovery Plan for the Sharpnose Shiner *Notropis oxyrhynchus* and Smalleye Shiner *N. buccula*. To this end, the plan may incorporate surface water and groundwater management strategies listed above to increase the probability of the species' long-term viability. The results of this study may also be used to give forewarning as to when individuals may need to be captured and transported to refugia when climate conditions during the three to nine months before summer spawning flows (i.e., during late summer to late winter) suggest reduced summer flows are likely.

This study increased our understanding of how groundwater and surface water use—exacerbated by droughts and climate change—threaten current and future streamflows. While we illustrate this approach in the UB basin of Texas and New Mexico using the Sharpnose Shiner *Notropis oxyrhynchus* and Smalleye Shiner *N. buccula* as focal species, these methods can be used to understand threats to other species of conservation interest in other streams with extensive surface water and groundwater development in similar semi-arid and arid settings globally.

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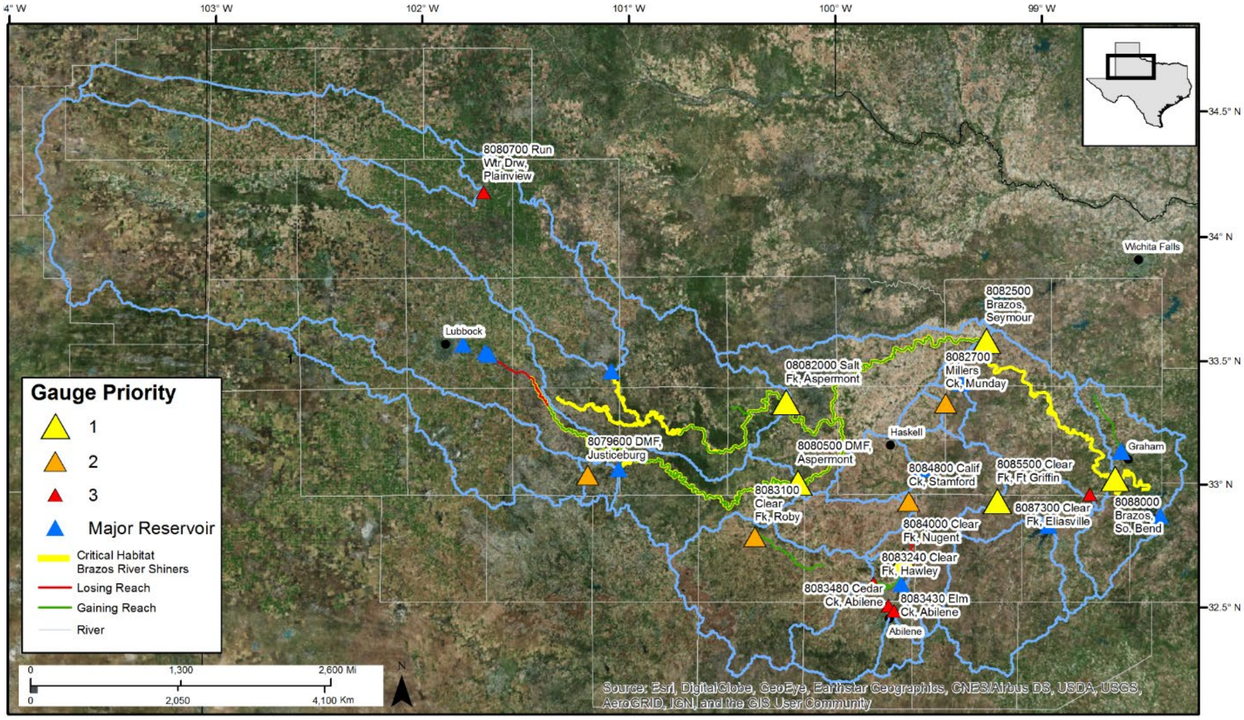
10 Figures



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. Study area

Smalleye and sharpnose shiner critical habitat (FWS, 2014a), streams, reservoirs, aquifers, historic springs, selected wells (including three TWDB wells with long-term data), and Seymour stream gage. Gauges and Priority groupings are shown in Table 1 and Table SI 2.

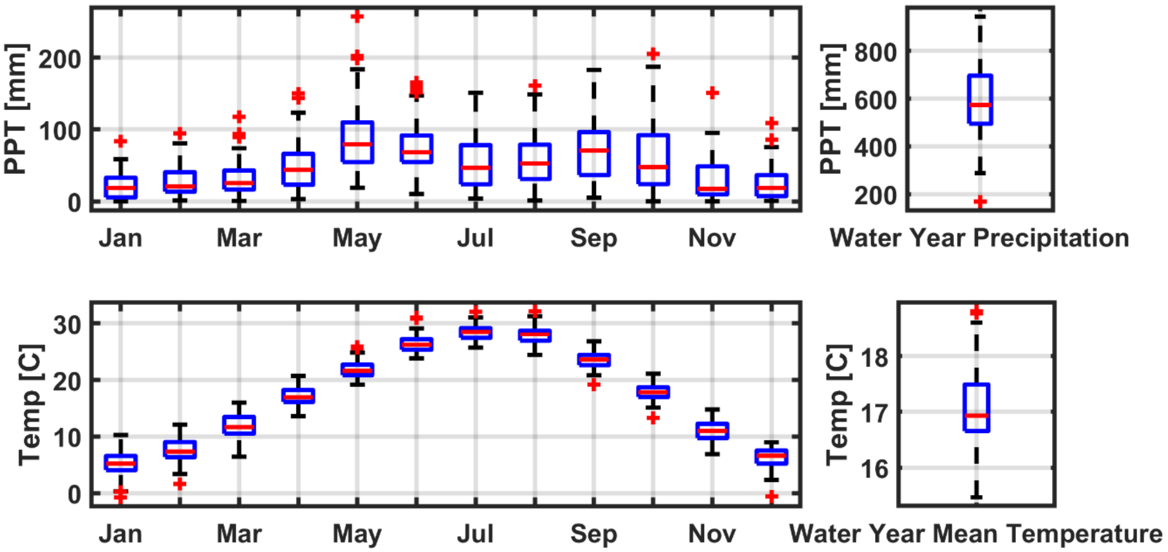
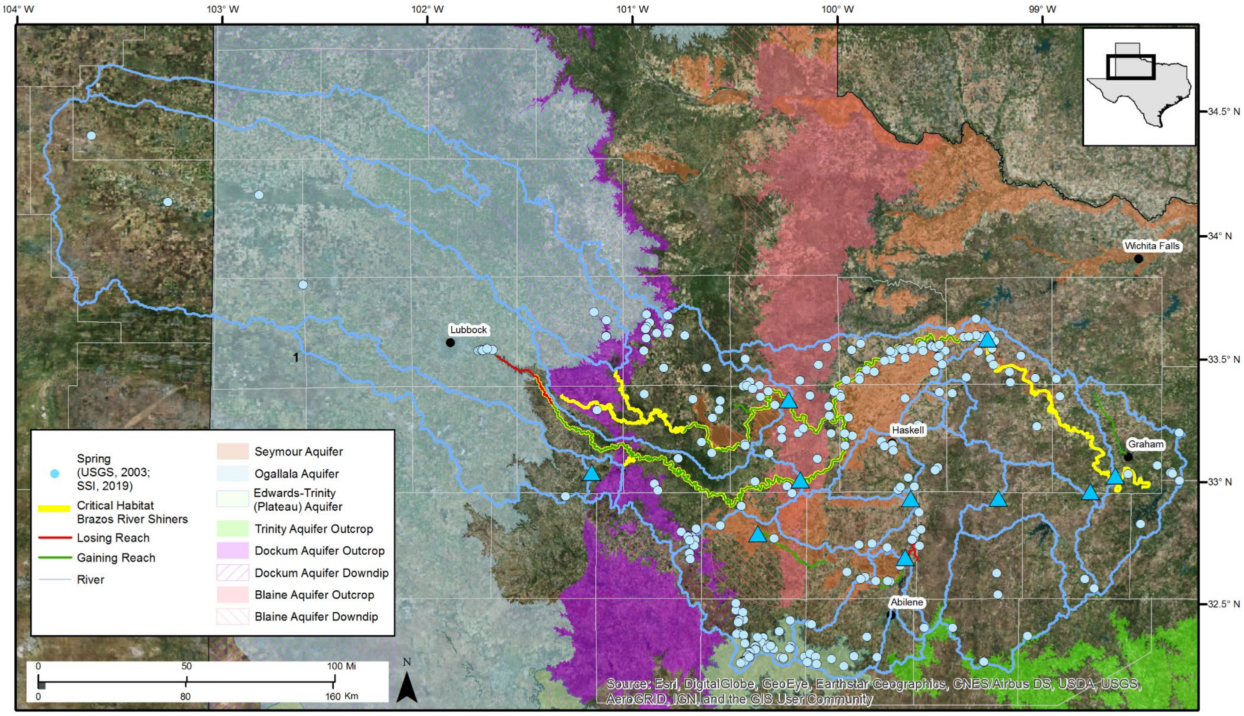


Figure 2. Annual and monthly precipitation and temperature

Notes: PPT=mean precipitation (upper panels) and Temp=mean temperature (lower panel). Source: (NOAA, 2019b)



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

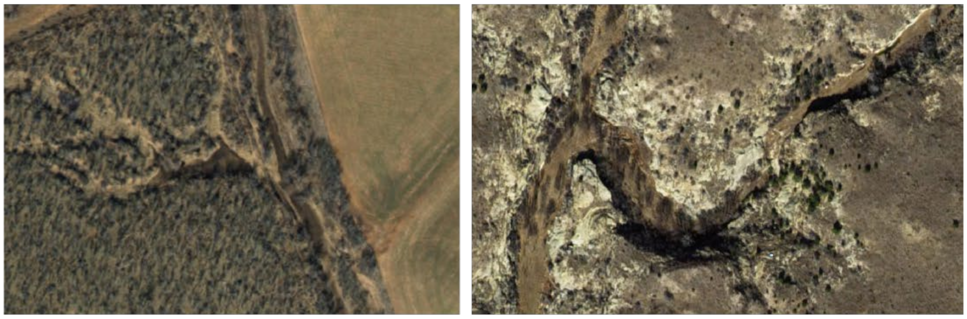
Figure 3. Aquifers and major springs

Source: (Brune, 2002; Heitmuller and Reece, 2003; SSI, 2019)

Seymour

Edwards-Trinity (Plateau)

Dockum



Ogallala and underlying Edwards-Trinity (High Plains)

Figure 4. Representative springs for selected aquifers

Essentially all Ogallala Aquifer springs along the Caprock Escarpment are dry (Brune, 2002) which is confirmed by visual inspection of 2016 aerial imagery in Google Earth, which also revels several Seymour Aquifer springs are still flowing and some springs and flowing streams are visible along Dockum Aquifer outcrop (particularly Dockum and McDonald creeks). Salt seeps in the headwaters of the SF are also present but not shown here (Baker et al., 1964). Not to scale.

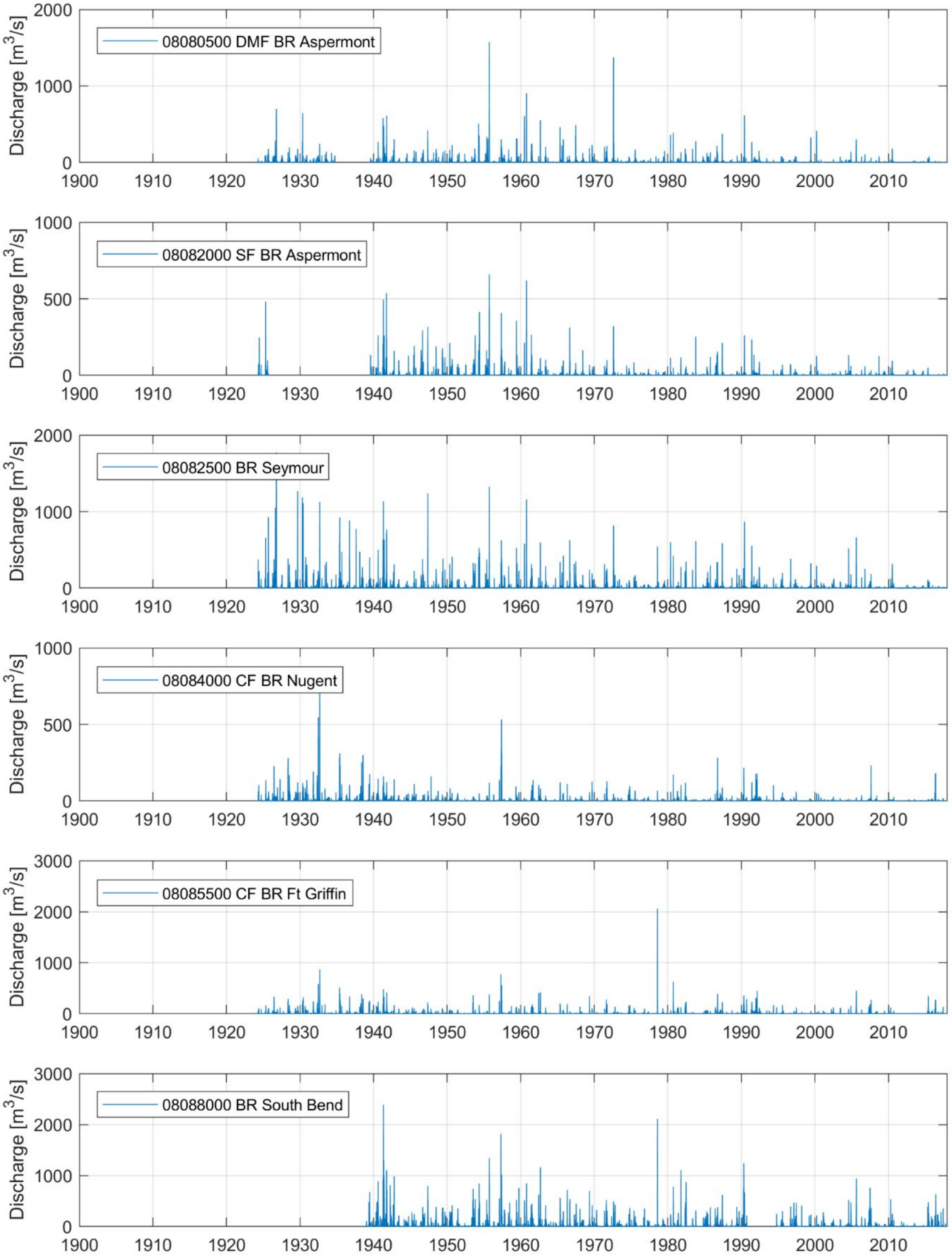


Figure 5. **Streamflow at Priority 1 study gauges**

Priority 1 gauges are six USGS gauges with the longest continuous streamflow records [Table 1] (USGS, 2019), which were also used in Texas environmental flow assessments (Gooch et al., 2012; Spurgin, 2012).

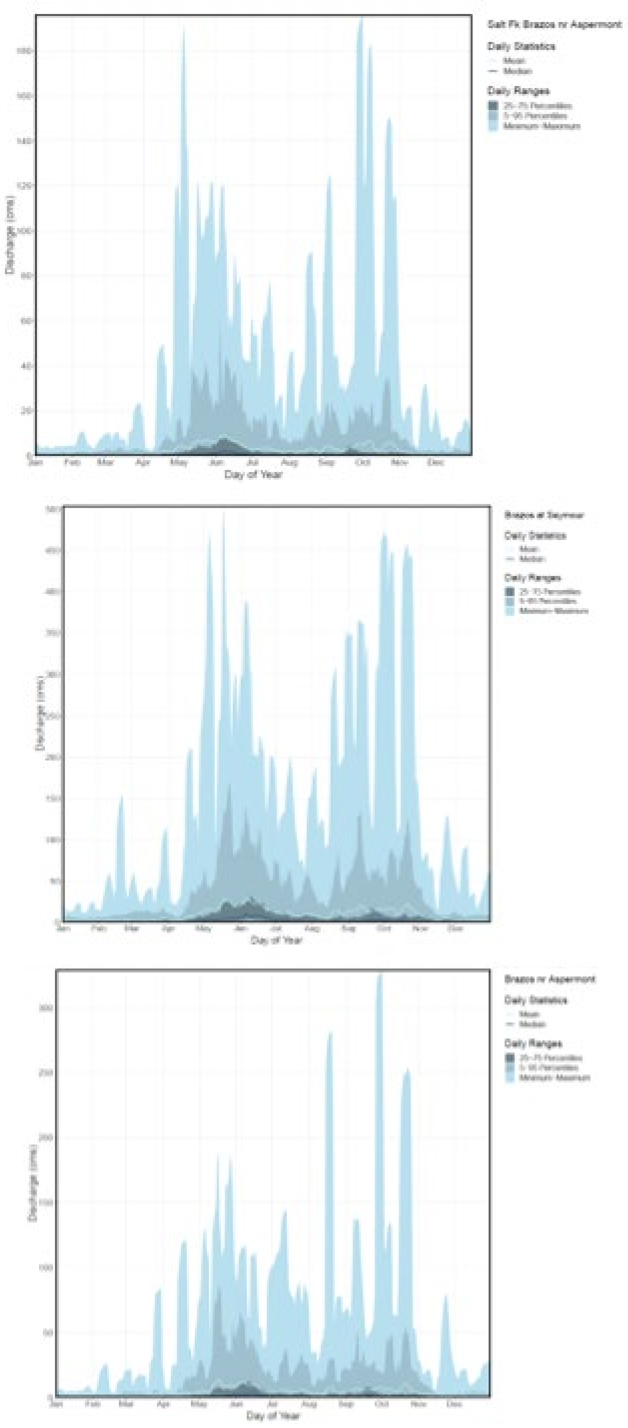


Figure 6. Streamflow summaries at selected gauges

Note: cfs=cubic feet per second. Source: (USGS, 2019)

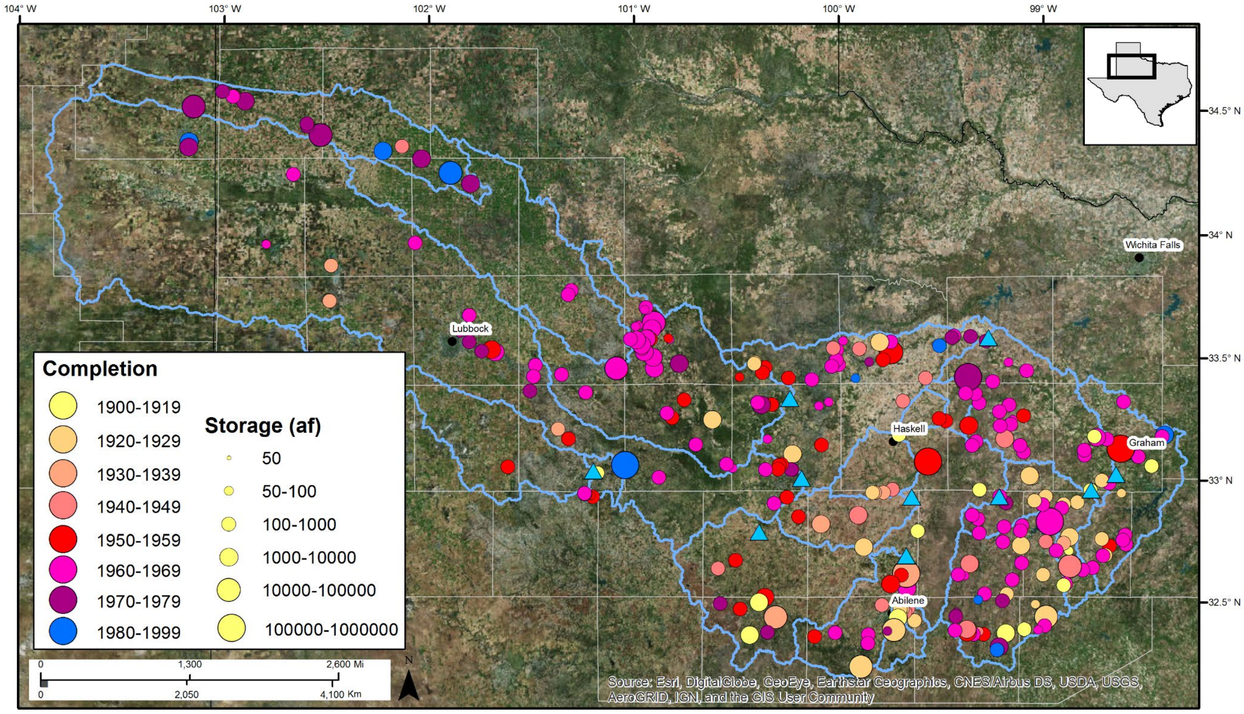


Figure 7. **Impoundment completion date and storage volume**

Source: (Ostroff et al., 2013; TCEQ, 2019; USACE, 2019)

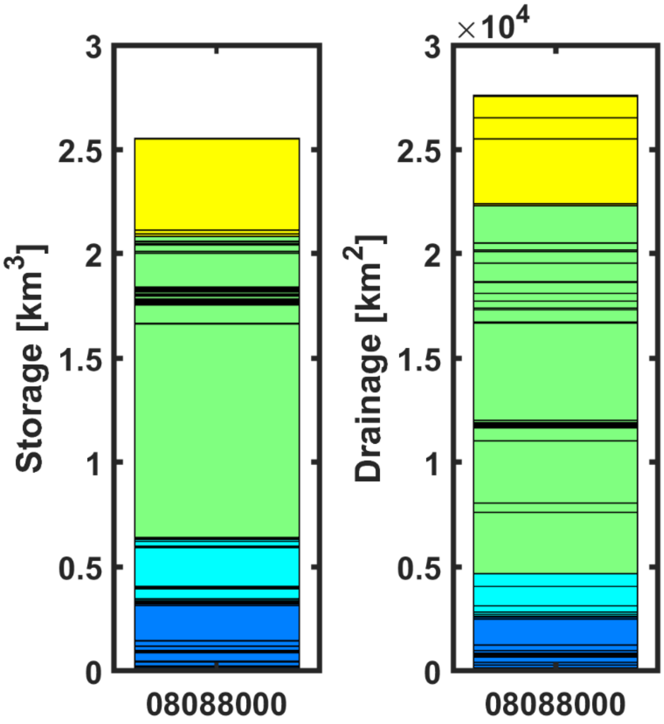


Figure 8. **Reservoir storage and drainage area**

For USGS 08088000 Brazos Rv nr South Bend, TX. Impoundment dates are: prior to 1940 (dark blue), 1940–1960 (light blue), 1960–1980 (green), and 1980–2000 (yellow). The last impoundment in the Upper Brazos was constructed in 1999 (Ingram Lake Dam). Source: USACE (2019).

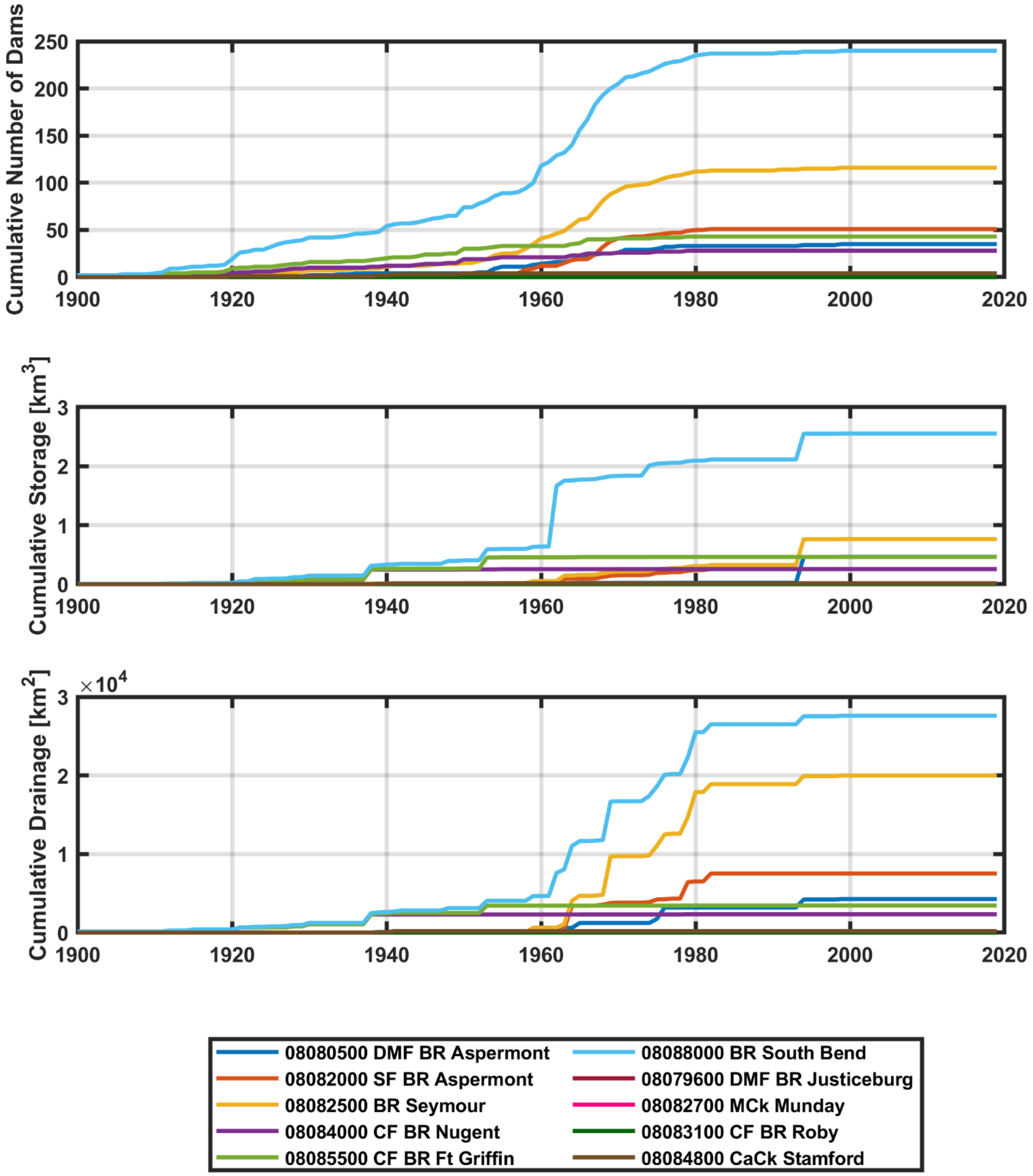


Figure 9. **Impoundment date, storage, and contributing area**

Many dams were constructed 1960–1980 following 1950s drought. Possum Kingdom Reservoir is not included as gauge 08088000 Brazos Rv nr South Bend, TX is located immediately upstream. Source: USACE (2019). Priority 1 and 2 gauges shown. (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River, MCk=Millers Creek, CaCk=California Creek).

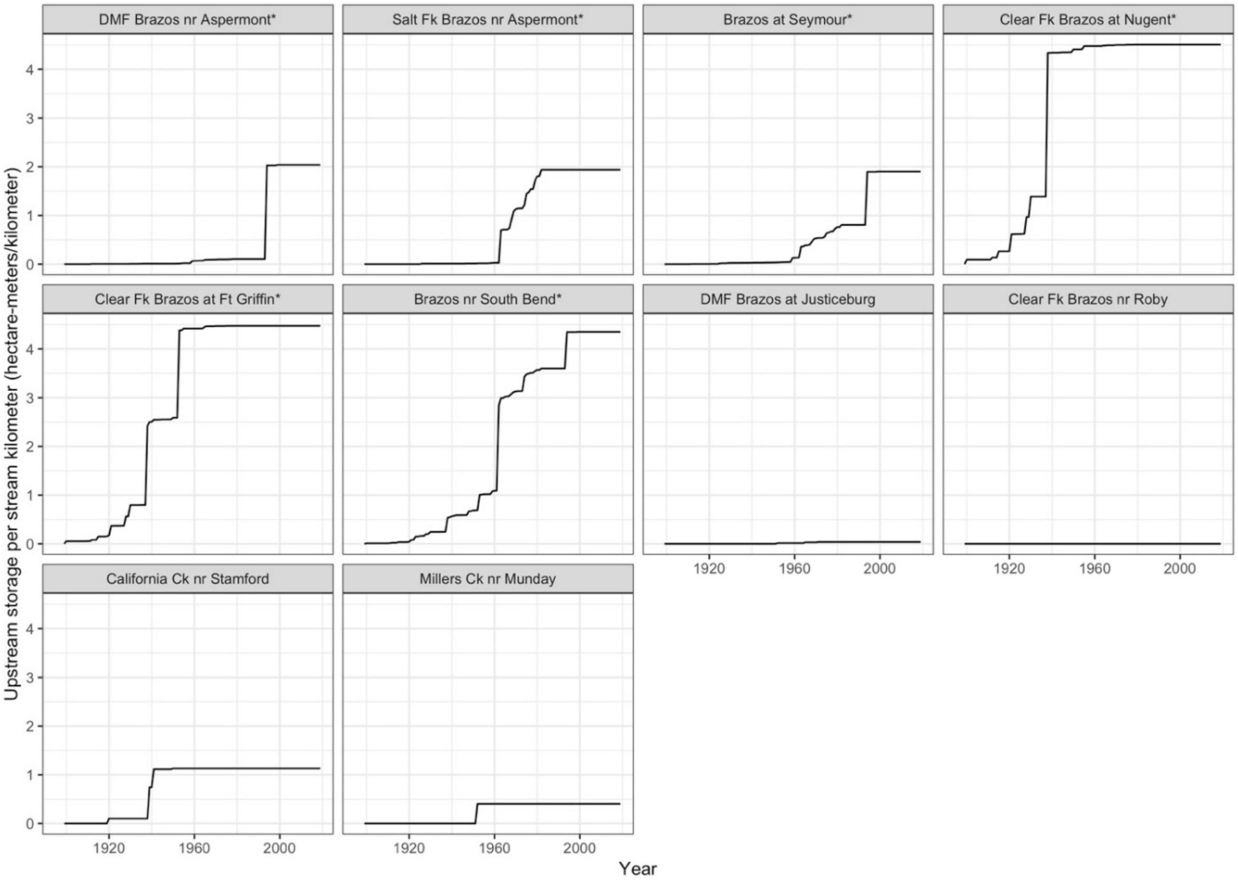


Figure 10. Cumulative upstream storage added per stream kilometer

Shown as (hectare-meters/kilometer). Calculated for each year 1900–2019 for each study gage in the UB basin. Priority study gages are indicated with an "*" at the end of their label name.

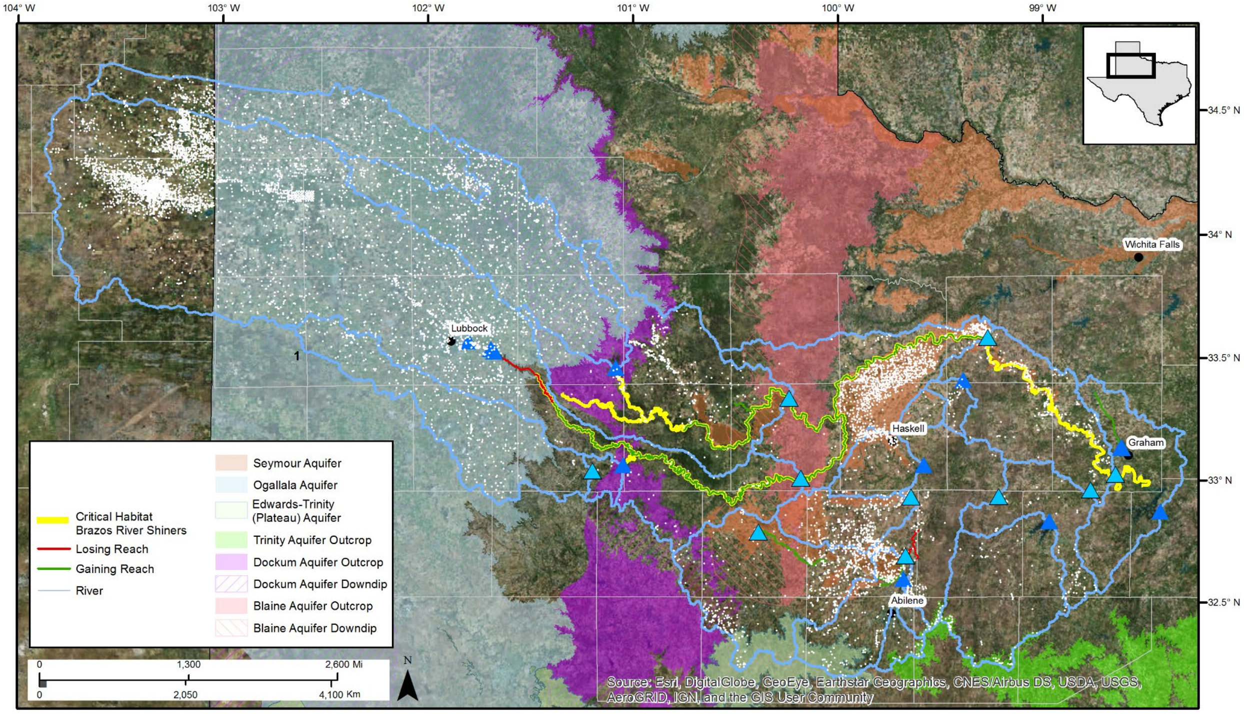


Figure 11. Well development

Groundwater wells from publicly available state databases in Texas and New Mexico. Source: (OSE, 2019; TWDB, 2019a).

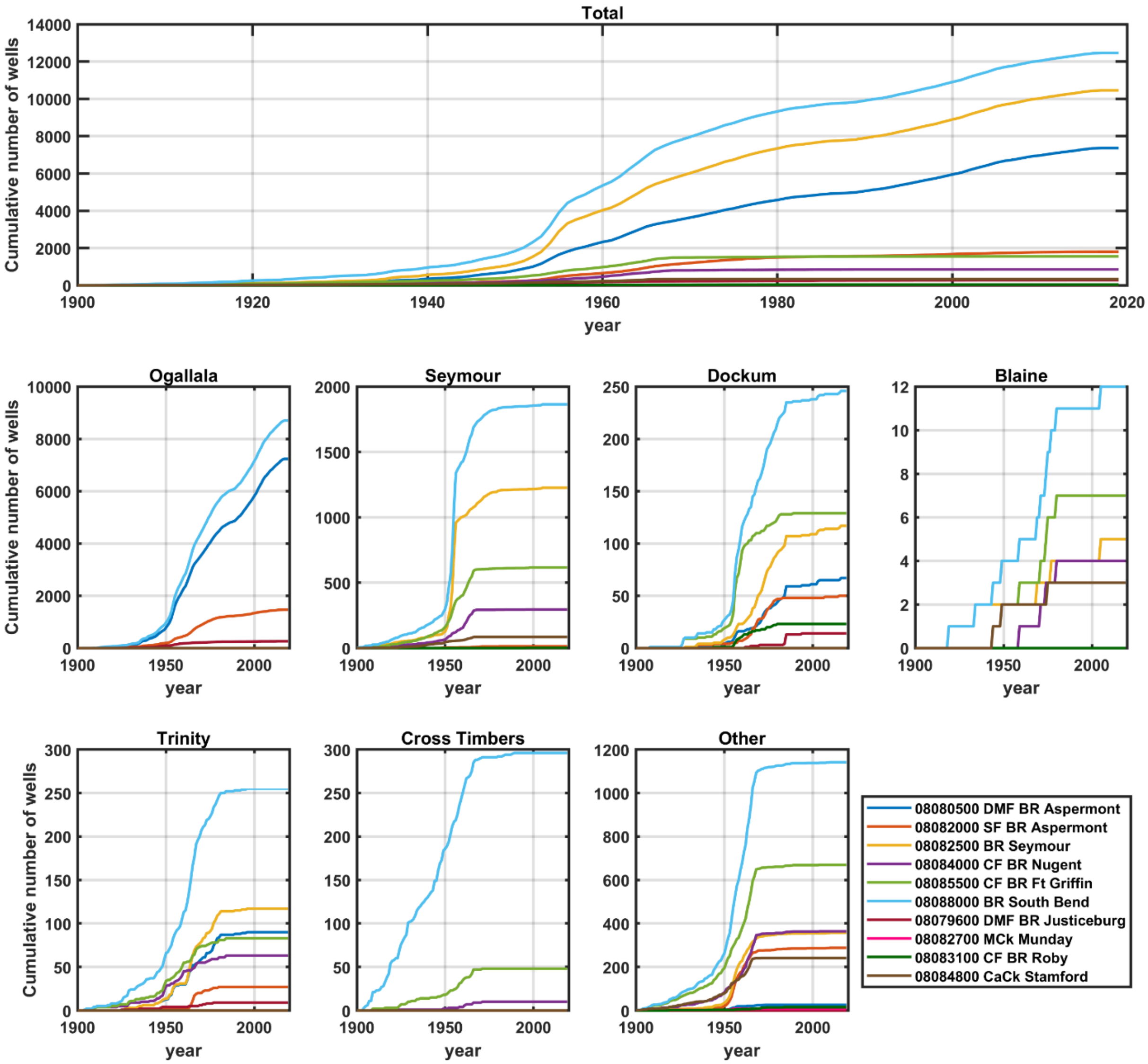


Figure 12. **Well development by study catchment and aquifer**

Groundwater wells from publicly available state databases in Texas and New Mexico. Source: (OSE, 2019; TWDB, 2019a). Priority 1 and 2 gauges shown (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River, MCk=Millers Creek, CaCk=California Creek).

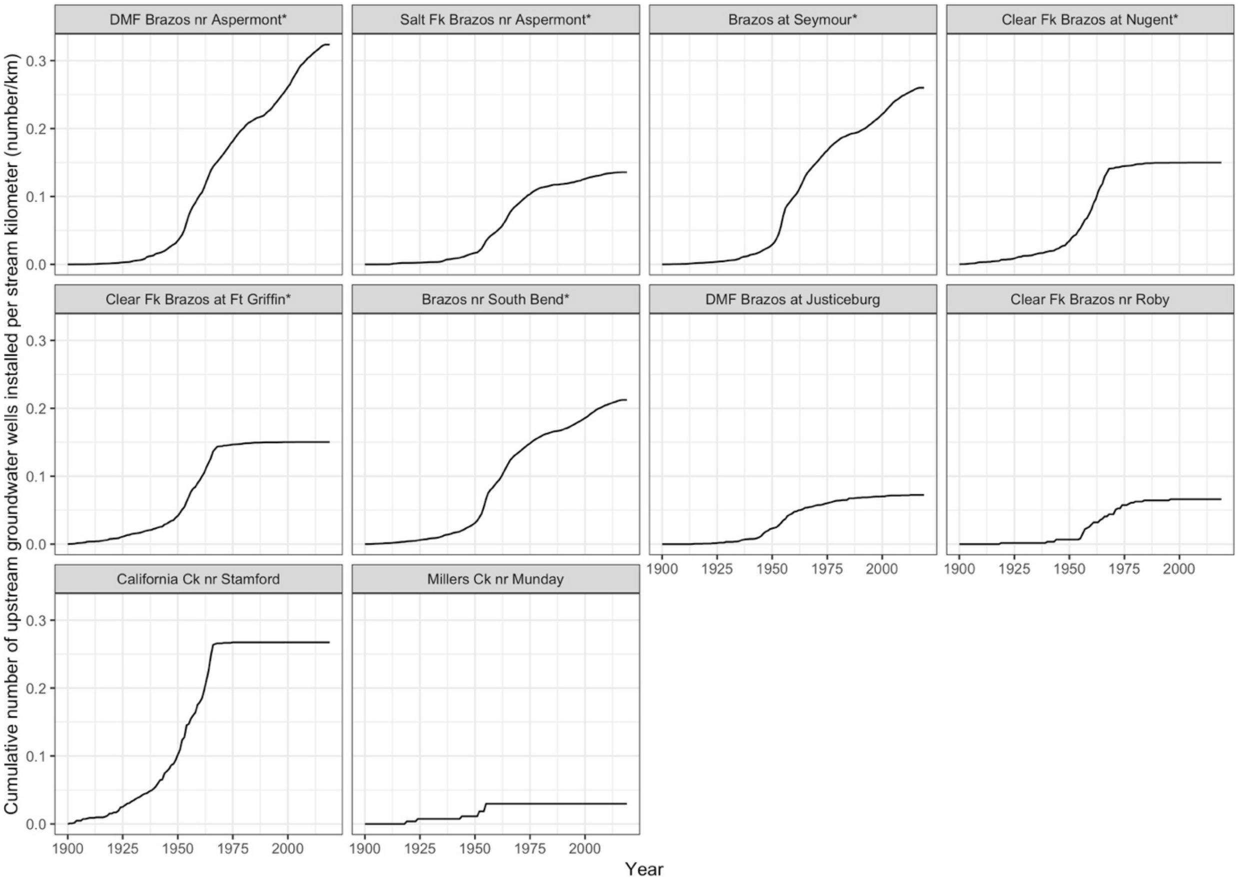


Figure 13. Cumulative number of upstream groundwater wells

Shown as installed per stream kilometer (wells/km). Calculated for each year 1900–2019, for each study gage in the UB basin.

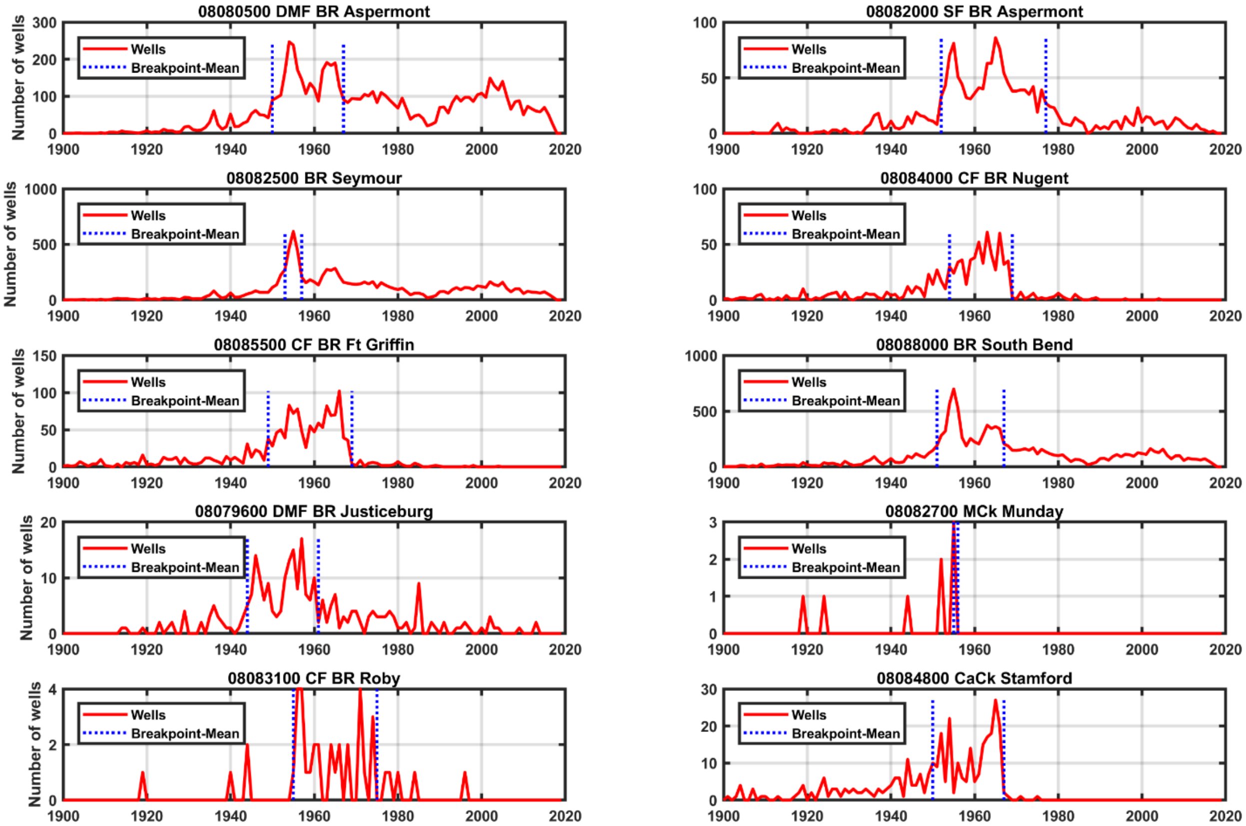


Figure 14. **Well development breakpoint analysis**

Priority 1 and 2 gauges shown (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River, MCk=Millers Creek, CaCk=California Creek).

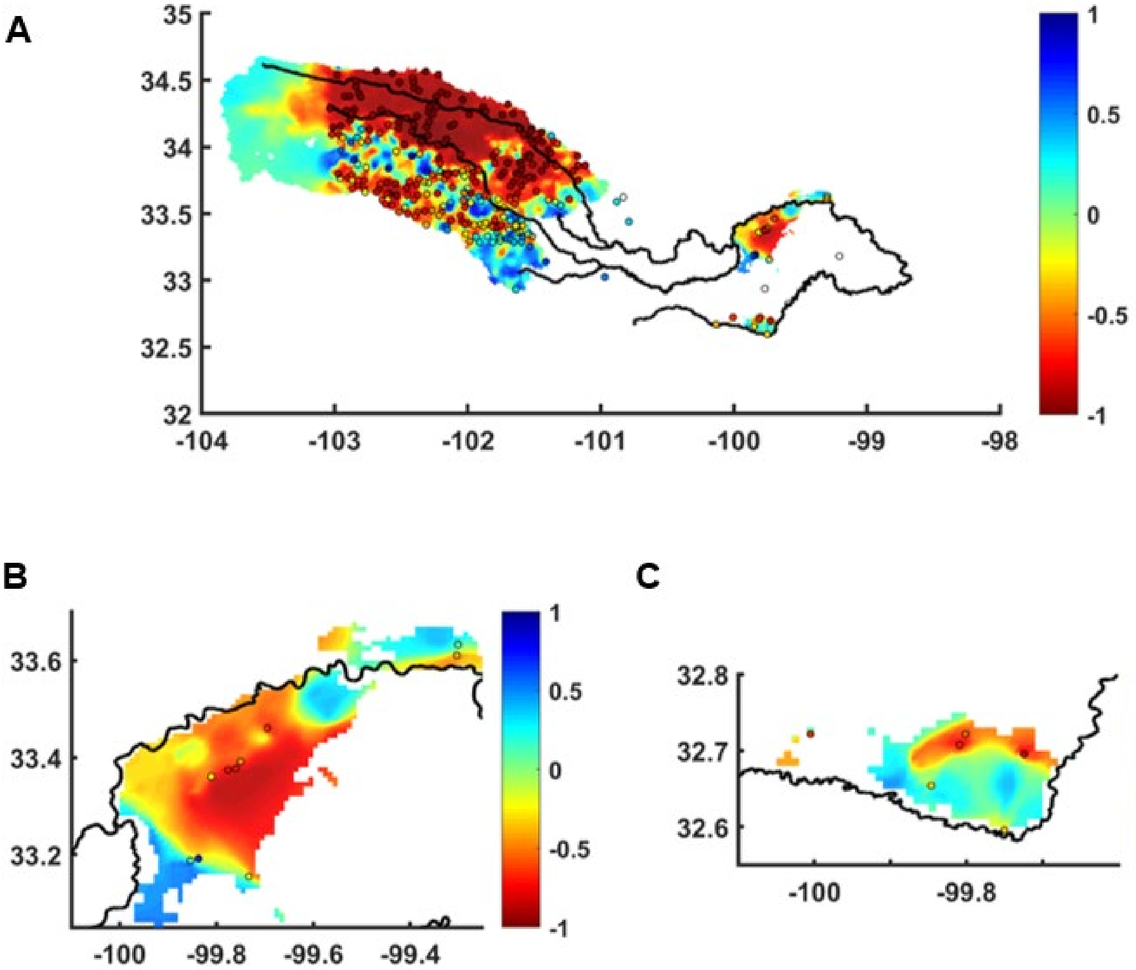


Figure 15. Gridded long-term groundwater level trends (1970–present)

Points represent individual wells with data prior to 1970 and post 2010. Source: (OSE, 2019; TWDB, 2019a). A. Ogallala Aquifer and Seymour Aquifer. B. Inset of northern pod of Seymour Aquifer. C. Inset of southern pod of Seymour Aquifer.

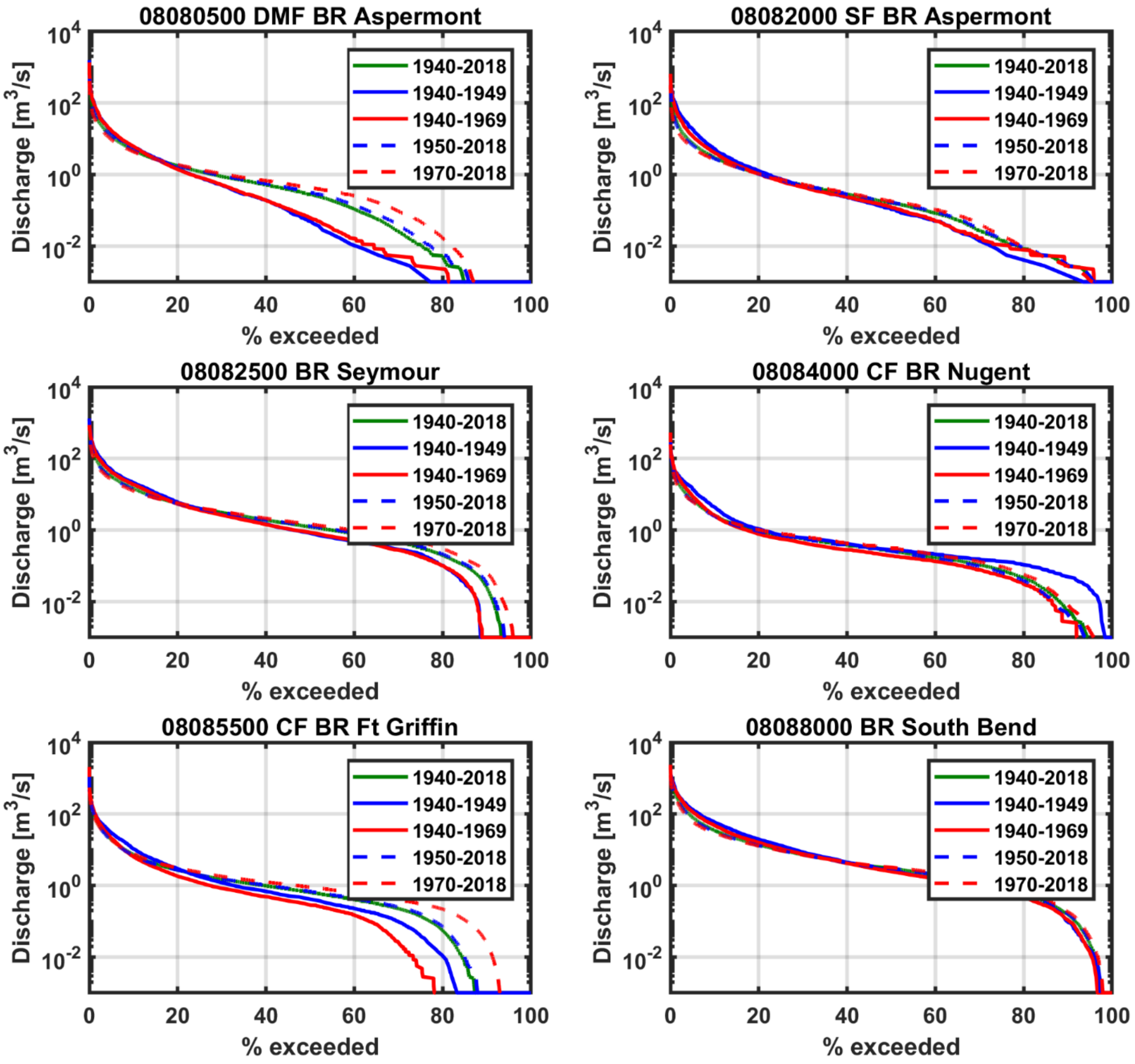


Figure 16. **Flow duration curves for selected gauges (annual streamflow)**

Time periods correspond to pre- and post-construction dates of major reservoirs in each catchment. Priority 1 gauges shown (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River).

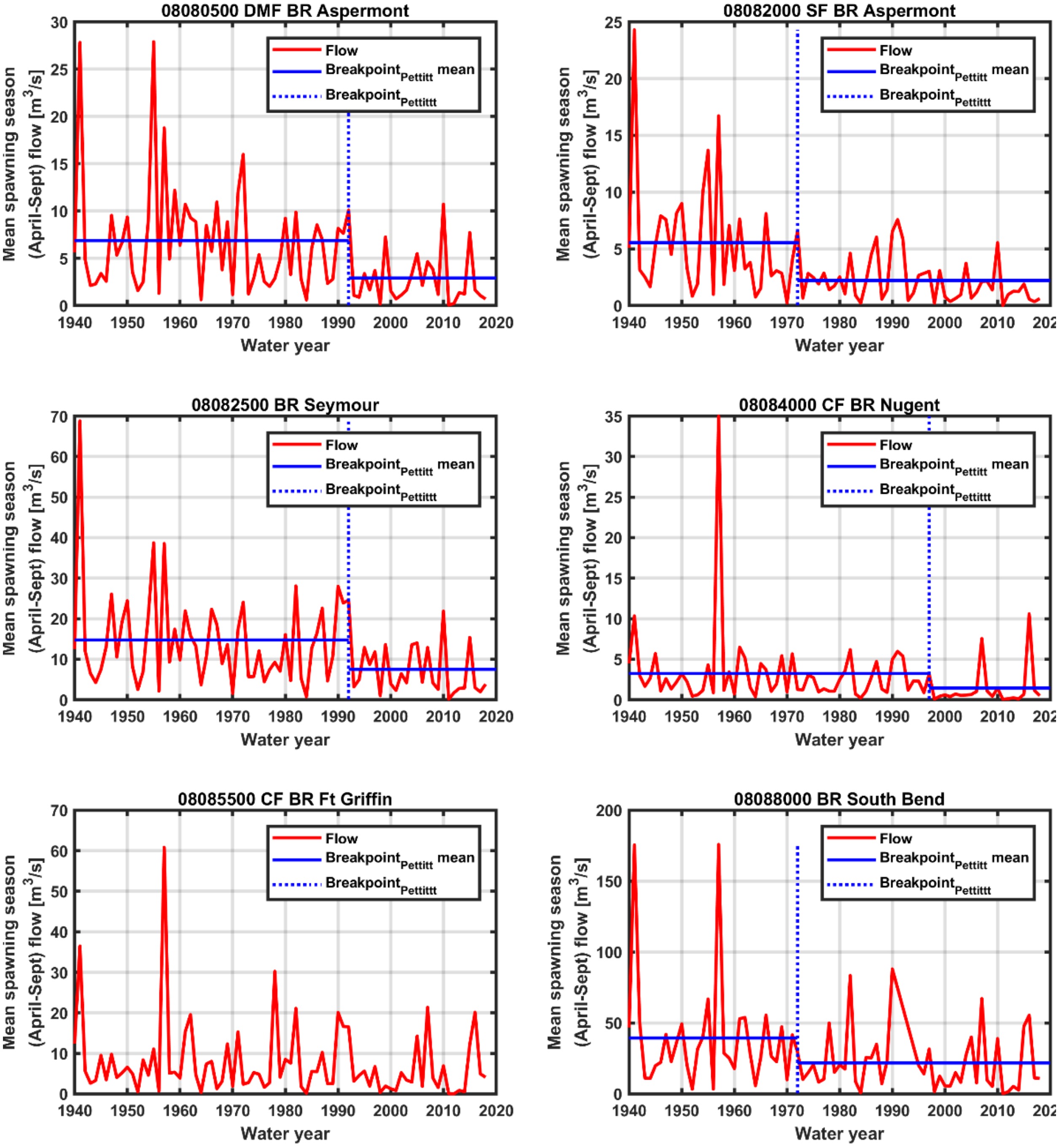


Figure 17. Breakpoint analysis for April–September spawning flows

Priority 1 gauges shown. (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River). Note that gauge 08085500 CF BR Ft Griffin does not have a statistically significant break point (Table 8).

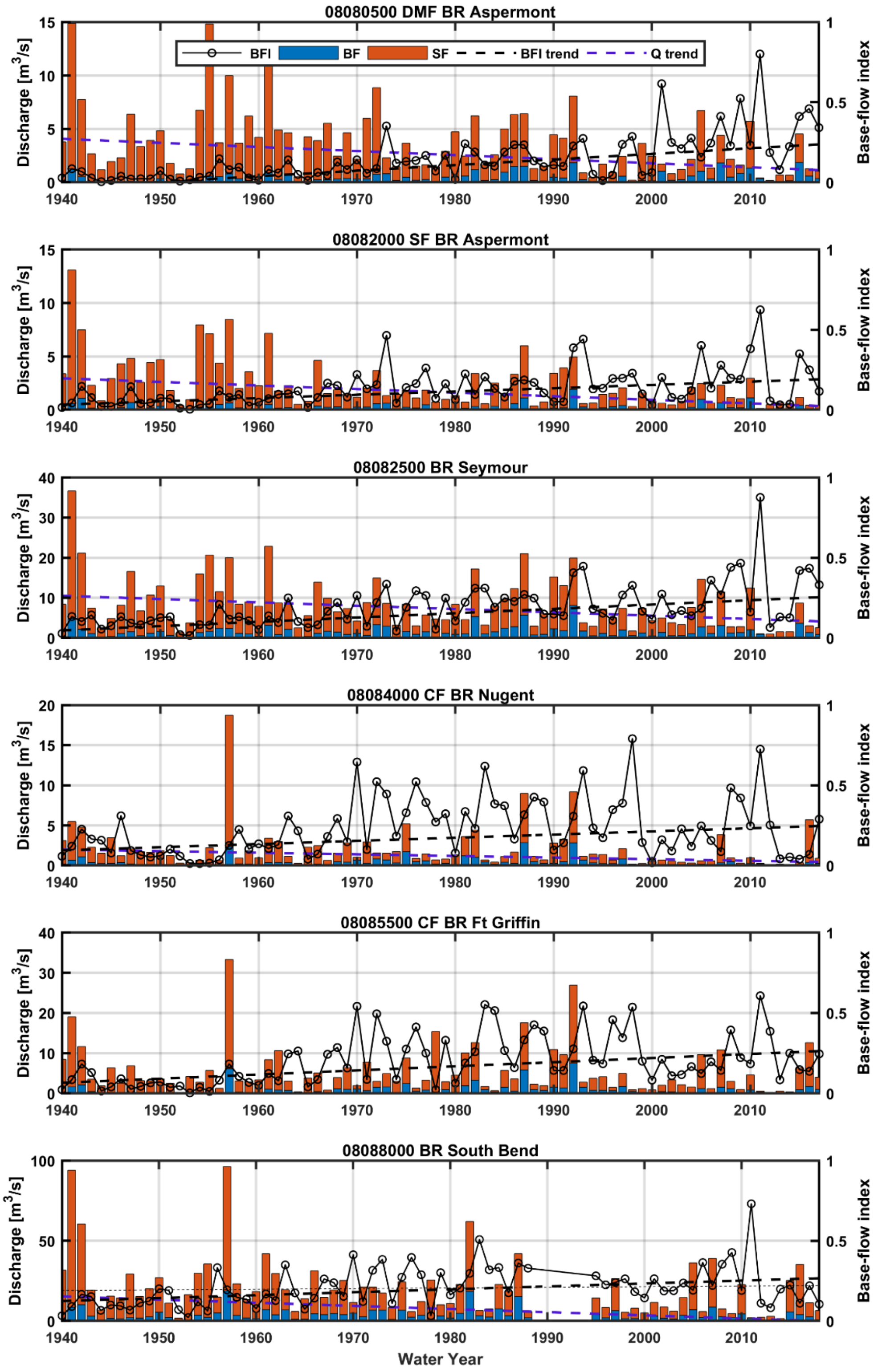


Figure 18. **Streamflow, baseflow, and baseflow index**

Trends shown as dashed lines. (DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River)

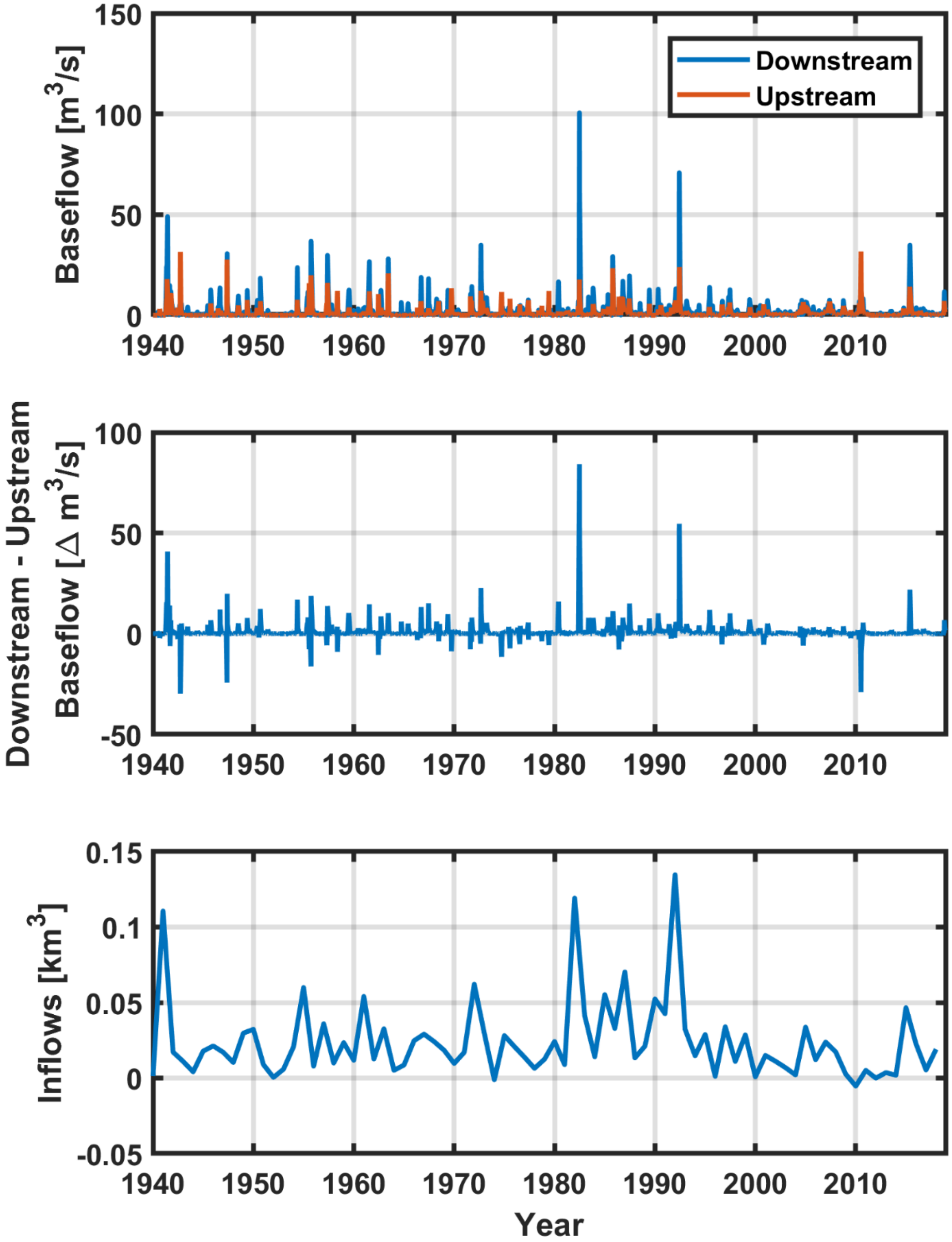


Figure 19. **Baseflow and Inflows from Groundwater (and Ungauged Catchments)**

For most years the stream gains flows between DMF and SF Aspermont gauges and Seymour.

11 Tables

Table 1. Study gages in the UB basin

Priority: 1. Gauges with long, continuous records previous studies used to evaluate environmental flows this study focuses on (REFS), 2. Gauges with shorter, but continuous, records (results for which included in Supporting Information), 3. Gauges with short, discontinuous records with limited analyses by this study.

Site Number	**Gage Site Name**	**Gauge Priority**	**Drainage Area (km^2)**	**Record Length (years)**	**Surface Water or Groundwater Development?**
08080500	DMF Brazos River near Aspermont, TX	1	22,782	94	Yes
08082000	Salt Fork Brazos River near Aspermont, TX	1	13,287	95	Yes
08082500	Brazos River at Seymour, TX	1	40,243	95	Yes
08084000	Clear Fork Brazos River at Nugent, TX	1	5,695	94	Yes
08085500	Clear Fork Brazos River at Fort Griffin, TX	1	10,329	95	Yes
08088000	Brazos River near South Bend, TX	1	58,723	81	Yes
08084800	California Creek near Stamford, TX	2	1,238	56	Yes
08079600	DMF Brazos River near Justiceburg, TX	2	3,797	58	Limited
08083100	Clear Fork Brazos River near Roby, TX	2	591	57	Limited
08082700	Millers Creek near Munday, TX	2	269	56	Limited

Table 2. Major reservoirs in UB basin

Reservoir	Gauge Corresponding to Reservoir (if available)	Latitude	Longitude	Impound. Date	Stream	Storage (km^3)	Contrib. Area (km^2)
Possum Kingdom Reservoir	08088500 Possum Kingdom Lk nr Graford, TX	32.872364	-98.425880	3/21/1941	Brazos River	1.68	36,338
Hubbard Creek Reservoir	08086400 Hubbard Ck Res nr Breckenridge, TX	32.831507	-98.967847	12/18/1962	Clear Fork Brazos River	1.02	2,810
Lake Alan Henry	08079700 Lk Alan Henry Res nr Justiceburg, TX	33.062778	-101.047220	1/1/1994	Double Mountain Forks Brazos River	0.44	1,023
Lake Stamford	08084500 Lk Stamford nr Haskell, TX	33.062500	-99.579167	6/30/1953	Clear Fork Brazos River	0.19	953
Fort Phantom Hill Reservoir	08083500 Ft Phantom Hill Res nr Nugent, TX	32.596111	-99.680278	10/30/1938	Clear Fork Brazos River	0.17	1,217
Millers Creek Reservoir	08082800 Millers Ck Res nr Bomarton, TX	33.408889	-99.388611	7/1/1974	Brazos	0.16	622
White River Reservoir	08080910 White Rv Res nr Spur, TX	33.457778	-101.083611	10/30/1963	Salt Fork Brazos River	0.09	1,785
Lake Ransom Canyon	-	33.524484	-101.678187	1965	Double Mountain Forks Brazos River	-	-
Buffalo Springs Lake	-	33.533563	-101.694882	9/15/1959	Double Mountain Forks Brazos River	-	-
Canyon Lakes 1–6	-	33.565631	-101.802281	1970s	Double Mountain Forks Brazos River	-	-
Lake Eddleman	-	33.131762	-98.611328	12/31/1929	Salt Creek	-	-
Lake Graham	-	33.133153	-98.617235	12/31/1929	Salt Creek	-	-

Note: Reservoirs sorted by storage volume (USACE, 2019) … USGS stream gauges (USGS, 2019)

Table 3. Annual streamflow metrics calculated for gauges

Abbreviation	Definitions
WYMean	Mean annual daily flow (cms) calculated for the water year
WYMedian	Median annual daily flow (cms) calculated for the water year
WYMax	Maximum annual daily flow (cms) calculated for the water year
WYMin	Minimum annual daily flow (cms) calculated for the water year
WYP10	10th percentile annual daily flow (cms)
WYP90	90th percentile annual daily flow (cms)
SpawnMean	Mean spawning season (April-Sept) daily flow (cms) calculated for the water year
SpawnMedian	Median spawning season (April-Sept) daily flow (cms) calculated for the water year
SpawnMax	Maximum spawning season (April-Sept) daily flow (cms) calculated for the water year
SpawnMin	Minimum spawning season (April-Sept) daily flow (cms) calculated for the water year
SpawnP10	10th percentile spawning season (April-Sept) daily flow (cms)
SpawnP90	90th percentile spawning season (April-Sept) daily flow (cms)
zerodays_summer	Number of zero-flow days per spawning season (May - September)
zerodays_wy	Number of zero-flow days per water year
wyMin_1_Day	1-day minimum flow for the water year (cms)
wyMin_1_Day_DoY	Day of the year of the 1-day minimum flow for the water year
wyMin_1_Day_Date	Date of the 1-day minimum flow for the water year

Abbreviation	Definitions
wyMin_7_Day	7-day minimum flow for the water year (cms)
wyMin_7_Day_DoY	Day of the year of the 7-day minimum flow for the water year
wyMin_7_Day_Date	Date of the 7-day minimum flow for the water year
wyMin_30_Day	30-day minimum flow for the water year (cms)
wyMin_30_Day_DoY	Day of the year of the 30-day minimum flow for the water year
wyMin_30_Day_Date	Date of the 30-day minimum flow for the water year
spawnMin_1_Day	1-day minimum flow for the spawning season (April–Sept) (cms)
spawnMin_1_Day_DoY	Day of the year of the 1-day minimum flow for the spawning season (April–Sept)
spawnMin_1_Day_Date	Date of the 1-day minimum flow for the spawning season (April–Sept)
spawnMin_7_Day	7-day minimum flow for the spawning season (April–Sept) (cms)
spawnMin_7_Day_DoY	Day of the year of the 7-day minimum flow for the spawning season (April–Sept)
spawnMin_7_Day_Date	Date of the 7-day minimum flow for the spawning season (April–Sept)
spawnMin_30_Day	30-day minimum flow for the spawning season (April–Sept) (cms)
spawnMin_30_Day_DoY	Day of the year of the 30-day minimum flow for the spawning season (April–Sept)
spawnMin_30_Day_Date	Date of the 30-day minimum flow for the spawning season (April–Sept)
instpk_date	Date of the annual instantaneous peak flow
instpk_julainday	Julian day of the annual instantaneous peak flow
instpk_cms	Annual instantaneous peak flow (cms)

Abbreviation	Definitions
instpk_cms	Annual instantaneous peak flow (cms)

Note: cms = m^3s^{-1}

Table 4. Climate variables calculated for study area

Source: NOAA (2019b)

Short name	Definition
WY precip	Total annual precipitation (cm) for the water year
WY mean temp	Mean temperature (C) for the water year
WY PDSI	Mean Palmer drought severity index (PDSI) for the water year
WY-1 precip	Total annual precipitation (mm) for the previous water year
WY-1 mean temp	Mean temperature (C) for the previous water year
WY-1 PDSI	Mean Palmer drought severity index (PDSI) for the previous water year
Mean temp prev fall	Mean temperature (C) for the previous fall (September–November)
Mean temp prev winter	Mean temperature (C) for the previous winter (December–February)
Mean temp spring	Mean temperature (C) for this year's spring (March–May)
Mean temp summer	Mean temperature (C) for this year's summer (June–August)
Mean PDSI prev fall	PDSI for the previous fall (September–November)
Mean PDSI prev winter	PDSI for the previous winter (December–February)
Mean PDSI spring	PDSI for this year's spring (March–May)
Mean PDSI summer	PDSI for this year's summer (June– August)
Total precip prev fall	Total precipitation (cm) for the previous fall (September–November)

Short name	Definition
Total precip prev winter	Total precipitation (cm) for the previous winter (December–February)
Total precip spring	Total precipitation (cm) for this year's spring (March–May)
Total precip summer	Total precipitation (cm) for this year's summer (June– August)

Table 5. Breakpoint analysis for climate Variables

	Pettitt				Buishand Range				Standard Normal Homogeneity			
Climate variable	pvalue	year	mean 1	mean 2	pvalue	year	mean 1	mean 2	pvalue	year	mean 1	mean 2
precip_wy [mm]	0.482	1956	537.7	597.6	0.560	1984	568.0	612.6	0.724	1956	537.69	597.64
meant_wy [C]	**0.003**	1997	16.9	17.6	**<0.001**	1997	16.9	17.6	**<0.001**	1997	16.87	17.61
pdsi_wy	0.429	1967	-0.567	0.277	0.260	1967	-0.567	0.277	0.728	1956	-0.84	0.18
meant_PrevFall [C]	0.073	1998	17.3	18.0	**0.029**	1998	17.3	18.0	**0.036**	1998	17.28	18.04
meant_PrevWinter [C]	**0.007**	1989	5.9	6.9	**0.009**	1989	5.9	6.9	**0.012**	1991	5.96	6.96
meant_Spring [C]	**0.036**	1997	16.7	17.6	0.102	1999	16.7	17.7	**0.012**	1999	16.71	17.71
meant_Summer [C]	0.316	1958	28.0	27.4	**0.030**	1997	27.4	27.9	0.267	2009	27.46	28.30
pdsi_PrevFall	0.204	1957	-1.146	0.243	0.083	1957	-1.146	0.243	0.389	1957	-1.15	0.24
pdsi_PrevWinter	0.621	1967	-0.584	0.217	0.390	1967	-0.584	0.217	0.783	1957	-0.84	0.14
pdsi_Spring	0.635	1967	-0.598	0.157	0.388	1967	-0.598	0.157	0.889	1956	-0.84	0.09
pdsi_Summer	0.759	1956	-0.927	0.316	0.459	1956	-0.927	0.316	0.772	1942	2.98	0.07
precip_PrevFall [mm]	0.418	1957	132.0	162.4	0.323	1957	132.0	162.4	0.564	1957	131.98	162.38
precip_PrevWinter [mm]	0.447	1979	64.7	78.7	0.268	1982	64.8	79.4	0.762	1982	64.80	79.44
precip_Spring [mm]	1.314	1967	167.2	169.6	0.829	1958	184.8	165.1	0.759	2014	166.33	201.32
precip_Summer [mm]	0.334	1984	177.8	202.5	0.547	1958	161.5	197.3	0.464	1958	161.46	197.35
precip_wy [mm]	0.482	1956	537.7	597.6	0.560	1984	568.0	612.6	0.724	1956	537.69	597.64

Notes: Mean 1 is the mean prior to the break point and mean 2 is the mean after the breakpoint. Bold indicates statistically significant value (p value<0.05) and corresponding breakpoint year.

Table 6. Breakpoint analysis for climate variables

	Chow Test With Linear Change Point					
Climate Variable	pvalue	year	b1	m1	b2	m2
precip_wy [mm]	0.087	1957	23295	-11.68	444.82	0.079
meant_wy [C]	**<0.001**	1957	-99.28	0.060	-27.90	0.023
pdsi_wy	**0.003**	1957	566.86	-0.291	28.46	-0.014
meant_PrevFall [C]	**0.003**	1968	21.83	-0.002	-52.60	0.035
meant_PrevWinter [C]	**0.006**	1958	-112.98	0.061	-60.14	0.033
meant_Spring [C]	0.250	1968	-32.27	0.025	-46.73	0.032
meant_Summer [C]	**0.008**	1959	-91.46	0.061	-5.41	0.017
pdsi_PrevFall	**0.010**	1958	447.06	-0.230	42.88	-0.021
pdsi_PrevWinter	**0.032**	1958	433.20	-0.223	14.58	-0.007
pdsi_Spring	**0.048**	1957	445.05	-0.229	19.28	-0.010
pdsi_Summer	0.078	1957	497.7	-0.256	24.06	-0.012
precip_PrevFall [mm]	0.109	1958	4436.8	-2.207	1131	-0.486
precip_PrevWinter [mm]	0.198	1985	467.2	-0.204	2071	-0.995
precip_Spring [mm]	0.316	2015	288.9	-0.061	142851	-70.739
precip_Summer [mm]	0.070	1958	9058.4	-4.565	223	-0.013

Note: Bold indicates statistically significant value and corresponding breakpoint year.

Table 7. Breakpoint analysis for groundwater Wells

					Mean Breakpoint				
Gauge	Catchment	Primary Aquifers	Wells (*n*)	Catchment Area (km^2)	Breakpoint Year 1	Breakpoint Year 2	mean1	mean2	mean3
08088000	Brazos Rv nr South Bend	Ogallala Seymour	12,467	58,914	1951	1967	39.0	331.5	98.2
08082500	Brazos Rv at Seymour	Ogallala Seymour	10,456	40,351	1953	1957	33.3	400.6	113.2
08080500	DMF Brazos Rv nr Aspermont	Ogallala Dockum	7,366	22,997	1950	1967	15.6	147.7	77.2
08082000	Salt Fk Brazos Rv nr Aspermont	Ogallala Dockum	1,802	13,167	1952	1977	5.0	46.3	9.1
08085500	Clear Fk Brazos Rv at Ft Griffin	Seymour	1,552	10,425	1949	1969	8.0	53.5	1.4
08084000	Clear Fk Brazos Rv at Nugent	Seymour Trinity	853	5,788	1954	1969	5.1	34.7	1.0
08084800	California Ck nr Stamford	Seymour	331	1,244	1950	1967	2.5	11.8	0.1
08079600	DMF Brazos Rv at Justiceburg	Ogallala	275	3,349	1944	1961	0.8	8.3	1.6
08083100	Clear Fk Brazos Rv nr Roby	Dockum Trinity Seymour	39	590	1955	1975	0.1	1.4	0.1
08082700	Millers Ck nr Munday	Seymour	8	276	1955	1956	0.1	1.5	0.0

Note: Orange=furthest downstream, blue=upstream of Seymour, green=Clear Fork Brazos River drainage, gray=drains east side Seymour Aquifer.

Table 8. Breakpoint analysis: mean summer spawning flows (April–September)

	Pettitt				Buishand Range				Standard Normal Homogeneity			
Site	pvalue	Breakpoint year	mean 1	mean 2	pvalue	Breakpoint year	mean 1	mean 2	pvalue	Breakpoint year	mean 1	mean 2
08080500 DMF BR Aspermont	**<0.001**	1992	6.87	2.91	**0.018**	1972	8.00	3.93	**0.007**	1972	8.00	3.93
08082000 SF BR Aspermont	**<0.001**	1972	5.55	2.21	**0.003**	1961	6.64	2.45	**<0.001**	1961	6.64	2.45
08082500 BR Seymour	0.006	1992	14.74	7.51	0.128	1992	14.74	7.51	**0.003**	1941	40.65	12.14
08084000 CF BR Nugent	**0.001**	1997	3.23	1.46	0.550	1971	3.90	2.03	0.435	1962	4.34	2.14
08085500 CF BR Ft Griffin	0.212	1992	8.81	5.46	0.760	1992	8.81	5.46	0.151	1941	24.45	7.51
08088000 BR South Bend	0.025	1972	39.40	21.88	0.287	1969	40.64	22.61	**0.003**	1941	111.16	29.26

Note: Bold indicates statistically significant value and corresponding breakpoint year.

Table 9. Baseflow, storm flow, total flow statistics: Priority 1 gages

	Site	08080500 DMF Brazos Rv Aspermont	08082000 Salt Fk Brazos Rv Aspermont,	08082500 Brazos Rv Seymour	08084000 Clear Fk Brazos Rv Nugent	08085500 Clear Fk Brazos Rv Ft Griffin	8088000 Brazos Rv South Bend
BFI	max	0.8	0.624	0.876	0.791	0.607	0.731
	max yr	2011	2011	2011	1998	2011	2011
	min	0.005	0.005	0.015	0.012	0.003	0.022
	min yr	1944	1953	1953	1954	1953	1953
	mean	0.149	0.139	0.192	0.227	0.202	0.21
	median	0.101	0.111	0.149	0.169	0.163	0.19
BF [m^3/s]	max	1.866	1.923	8.088	2.844	7.464	18.712
	max yr	2015	1992	1992	1987	1992	1957
	min	0.005	0.004	0.028	0.003	0.011	0.119
	min yr	1944	1953	1952	2014	1952	1952
	mean	0.443	0.285	1.481	0.398	0.932	3.769
	median	0.281	0.19	1.108	0.239	0.525	2.649
SF [m^3/s]	max	14.234	12.527	31.767	16.396	27.217	85.49
	max yr	1955	1941	1941	1957	1957	1941
	min	0.086	0.055	0.129	0.038	0.069	0.536
	min yr	2011	2011	2011	1998	2012	2011
	mean	3.208	2.144	6.961	1.604	4.417	16.231
	median	2.365	1.426	6.128	0.832	2.99	12.809
Q [m^3/s]	max	14.869	13.101	36.651	18.734	33.328	96.239
	max yr	1941	1941	1941	1957	1957	1957
	min	0.189	0.148	0.965	0.059	0.113	1.449
	min yr	2012	2011	2012	2014	2012	2014
	mean	3.651	2.428	8.442	2.002	5.349	19.999
	median	2.63	1.688	7.359	1.227	3.368	15.257

Note: BFI=base flow index, BF=base flow, SF=storm flow, Q=total streamflow.

Table 10. Baseflow, storm flow, total flow statistics: Priority 1 gages

	Site	08080500 DMF BR Aspermont	08082000 SF BR Aspermont	08082500 BR Seymour	08084000 CF BR Nugent	08085500 CF BR Ft Griffin	08088000 BR South Bend
BFI	p-value	**<0.001**	**<0.001**	**<0.001**	**0.013**	**<0.001**	**<0.001**
	tau	0.518	0.358	0.398	0.193	0.345	0.28158
	sen	0.003	0.002	0.003	0.002	0.003	0.002
BF [m^3/s]	p-value	**0.012**	0.403	0.654	0.407	**0.047**	0.577
	tau	0.193	-0.065	0.035	-0.064	0.154	-0.045
	sen	0.004	-0.001	0.002	-0.001	0.005	-0.007
SF [m^3/s]	p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.034**	**<0.001**
	tau	-0.329	-0.411	-0.325	-0.312	-0.164	-0.299
	sen	-0.042	-0.033	-0.083	-0.016	-0.029	-0.179
Q [m^3/s]	p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.088	**<0.001**
	tau	-0.269	-0.371	-0.277	-0.301	-0.132	-0.276
	sen	-0.038	-0.034	-0.083	-0.020	-0.027	-0.196

Note: Bold indicates statistically significant value. DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, BR=Brazos River, CF=Clear Fork Brazos River

Table 11. Mixed-effects regression models for streamflow metrics

Analysis includes UB basin with climate and human effects. Random effects were water year within site, to account for the time series within each gage site. Fixed-effect predictor variables included total water year precipitation (precip_wy), mean water year temperature (meant_wy), water year PDSI (pdsi_wy), PDSI for the previous fall (pdsi_PrevFall), PDSI for the previous winter (pdsi_PrevWinter), PDSI for the spring (pdsi_spring), PDSI for the summer (pdsi_Summer), upstream storage per river kilometer (storage_hamkm), and the number of ground water wells per upstream river kilometer (wells_km).

Note: Tables shown on subsequent pages.

Table 11A. Zero-flow days per year (gauges = 7, impacted)

Variable	**Value**	**Std error**	**DF**	**t-value**	**P-value**
(Intercept)	**-4.34**	**1.82**	**572.00**	**-2.39**	**0.017**
precip_wy	0.00	0.01	572.00	-0.33	0.741
meant_wy	**0.42**	**0.11**	**572.00**	**3.96**	**<0.001**
pdsi_wy	-0.08	0.46	572.00	-0.17	0.864
pdsi_PrevFall	**-0.37**	**0.09**	**572.00**	**-4.36**	**<0.001**
pdsi_PrevWinter	0.25	0.15	572.00	1.65	0.099
pdsi_Spring	0.19	0.14	572.00	1.37	0.170
pdsi_Summer	**-0.35**	**0.14**	**572.00**	**-2.57**	**0.011**
storage_hamkm	**0.17**	**0.08**	**572.00**	**2.14**	**0.033**
wells_km	**-10.01**	**1.18**	**572.00**	**-8.46**	**<0.001**

Table 11B. Zero-flow days per spawning season (April–Sept; gauges = 7, impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	2.50	1.77	574.00	1.41	0.158
precip_wy	0.005	0.01	574.00	0.43	0.668
meant_wy	-0.02	0.11	574.00	-0.17	0.867
pdsi_wy	-0.62	0.51	574.00	-1.20	0.229
pdsi_PrevFall	-0.08	0.10	574.00	-0.81	0.420
pdsi_PrevWinter	**0.32**	**0.15**	**574.00**	**2.10**	**0.036**
pdsi_Spring	**0.31**	**0.16**	**574.00**	**1.96**	**0.051**
pdsi_Summer	**-0.29**	**0.14**	**574.00**	**-2.00**	**0.046**
storage_hamkm	0.10	0.06	574.00	1.53	0.127
wells_km	**-3.58**	**0.86**	**574.00**	**-4.14**	**<0.001**

Table 121C. Water year mean daily flow (gauges = 7, impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	0.55	0.93	574.00	0.59	0.558
precip_wy	0.01	0.01	574.00	1.06	0.288
meant_wy	0.06	0.05	574.00	1.11	0.268
pdsi_wy	**0.63**	**0.23**	**574.00**	**2.81**	**0.005**
pdsi_PrevFall	-0.04	0.04	574.00	-0.96	0.336
pdsi_PrevWinter	**-0.24**	**0.07**	**574.00**	**-3.27**	**0.001**
pdsi_Spring	**-0.25**	**0.07**	**574.00**	**-3.67**	**<0.001**
pdsi_Summer	0.06	0.07	574.00	0.85	0.395
storage_hamkm	**-0.14**	**0.04**	**574.00**	**-3.61**	**<0.001**
wells_km	**-4.15**	**0.59**	**574.00**	**-7.03**	**<0.001**

Table 11D. Spawning season (April–Sept) mean daily flow (gauges = 7, impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	0.92	1.09	574.00	0.84	0.401
precip_wy	**0.01**	**0.01**	**574.00**	**2.06**	**0.040**
meant_wy	0.03	0.06	574.00	0.50	0.621
pdsi_wy	**0.77**	**0.27**	**574.00**	**2.84**	**0.005**
pdsi_PrevFall	-0.03	0.05	574.00	-0.56	0.573
pdsi_PrevWinter	**-0.43**	**0.09**	**574.00**	**-4.88**	**<0.001**
pdsi_Spring	**-0.39**	**0.08**	**574.00**	**-4.66**	**<0.001**
pdsi_Summer	0.14	0.08	574.00	1.69	0.092
storage_hamkm	**-0.14**	**0.05**	**574.00**	**-3.00**	**0.003**
wells_km	**-5.40**	**0.70**	**574.00**	**-7.68**	**<0.001**

Table 11E. Annual instantaneous peak flow (gauges = 7, impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	**6.10**	**1.11**	**576.00**	**5.49**	**0.000**
precip_wy	0.01	0.01	576.00	1.06	0.288
meant_wy	-0.01	0.06	576.00	-0.21	0.831
pdsi_wy	**0.89**	**0.28**	**576.00**	**3.15**	**0.002**
pdsi_PrevFall	**-0.11**	**0.05**	**576.00**	**-2.07**	**0.039**
pdsi_PrevWinter	**-0.34**	**0.09**	**576.00**	**-3.62**	**<0.001**
pdsi_Spring	**-0.30**	**0.09**	**576.00**	**-3.43**	**0.001**
pdsi_Summer	-0.09	0.09	576.00	-1.11	0.266
storage_hamkm	**-0.09**	**0.05**	**576.00**	**-1.92**	**0.056**
wells_km	**-7.30**	**0.72**	**576.00**	**-10.08**	**<0.001**

Table 11F. Zero-flow days per year (gages = 3, un-impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	**4.98**	**0.32**	**163**	**15.54**	**<0.001**
pdsi_wy	**-0.16**	**0.06**	**163**	**-2.62**	**0.010**
pdsi_PrevFall	**-0.08**	**0.04**	**163**	**-2.06**	**0.041**
pdsi_PrevWinter	0.12	0.07	163	1.65	0.100

Table 11G. Zero-flow days per spawning season (April–Sept) (gauges = 3, un-impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	**4.32**	**0.33**	**163**	**13.14**	**<0.001**
pdsi_wy	**-0.34**	**0.10**	**163**	**-3.58**	**0.001**
pdsi_PrevWinter	**0.22**	**0.07**	**163**	**3.09**	**0.002**
pdsi_PrevFall	-0.04	0.04	163	-0.93	0.353
pdsi_Spring	0.08	0.08	163	0.90	0.367

Table 11H. Water year mean daily flow (gauges = 3, un-impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	**-3.93**	**0.85**	**163**	**-4.64**	**<0.001**
precip_wy	**0.04**	**0.01**	**163**	**3.18**	**0.002**
pdsi_wy	0.07	0.16	163	0.46	0.648
pdsi_PrevFall	0.06	0.06	163	0.98	0.328
pdsi_PrevWinter	-0.09	0.13	163	-0.73	0.466

Table 11I. Spawning season (April–Sept) mean daily flow (gauges = 3, un-impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	**-3.30**	**0.92**	**163**	**-3.59**	**0.000**
precip_wy	**0.03**	**0.01**	**163**	**2.37**	**0.019**
pdsi_wy	**0.66**	**0.24**	**163**	**2.73**	**0.007**
pdsi_PrevWinter	**-0.32**	**0.14**	**163**	**-2.30**	**0.023**
pdsi_Spring	**-0.32**	**0.12**	**163**	**-2.61**	**0.010**

Table 11J. Annual instantaneous peak flow (gauges = 3, un-impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	1.16	1.21	163	0.96	0.337
precip_wy	**0.04**	**0.02**	**163**	**2.44**	**0.016**
pdsi_wy	0.09	0.22	163	0.41	0.679
pdsi_PrevWinter	-0.12	0.17	163	-0.70	0.485

Table 11K. Brazos River at Seymour mean spawning season flow (April–Sept) (gauge = 1, impacted)

Variable	Value	Std error	DF	t-value	P-value
(Intercept)	1.56	2.24	85	0.70	0.488
precip_wy	**0.03**	**0.01**	**85**	**2.33**	**0.022**
meant_wy	-0.03	0.13	85	-0.23	0.818
pdsi_wy	0.37	0.52	85	0.71	0.482
pdsi_PrevFall	0.03	0.10	85	0.28	0.779
pdsi_PrevWinter	**-0.36**	**0.17**	**85**	**-2.18**	**0.032**
pdsi_Spring	-0.21	0.16	85	-1.33	0.189
pdsi_Summer	0.12	0.15	85	0.78	0.439
storage_hamkm	-0.24	0.21	85	-1.11	0.270
wells_km	**-3.67**	**1.68**	**85**	**-2.19**	**0.032**

Table 11L. Brazos River at Seymour mean spawning season flow (May–Sept) (gauge = 1, impacted)

Variable	**Value**	**Std error**	**DF**	**t-value**	**P-value**
(Intercept)	2.46	2.46	85	1.00	0.320
precip_wy	**0.04**	**0.01**	**85**	**2.46**	**0.016**
meant_wy	-0.10	0.14	85	-0.68	0.499
pdsi_wy	0.34	0.57	85	0.59	0.557
pdsi_PrevFall	0.02	0.11	85	0.23	0.822
pdsi_PrevWinter	**-0.34**	**0.18**	**85**	**-1.87**	**0.065**
pdsi_Spring	-0.26	0.17	85	-1.51	0.134
pdsi_Summer	0.15	0.17	85	0.87	0.384
storage_hamkm	-0.27	0.23	85	-1.16	0.249
wells_km	**-3.48**	**1.85**	**85**	**-1.89**	**0.063**

12 Supporting Information

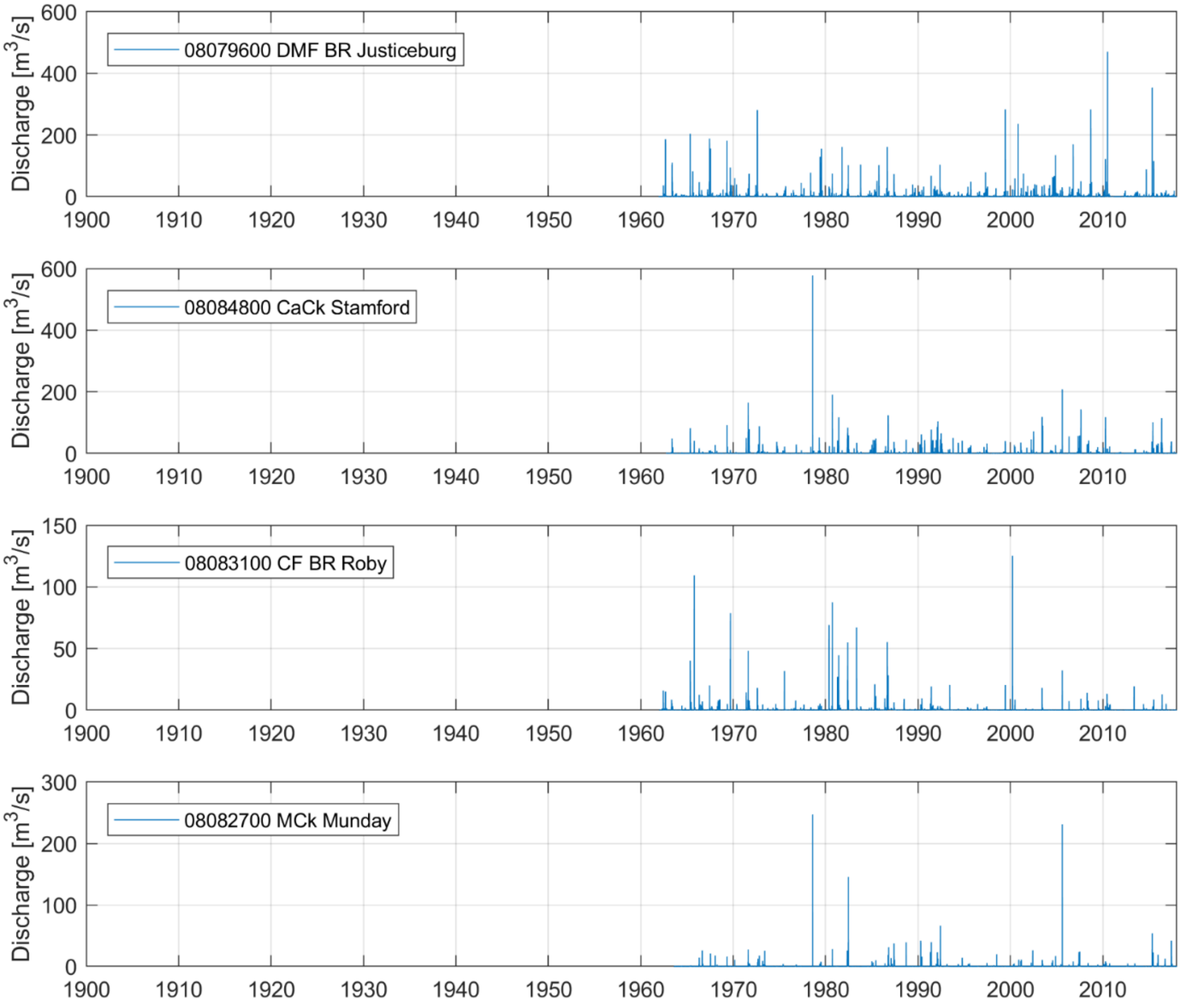


Figure SI 1. **Streamflow at Priority 2 gauges**

Source: (USGS, 2019)

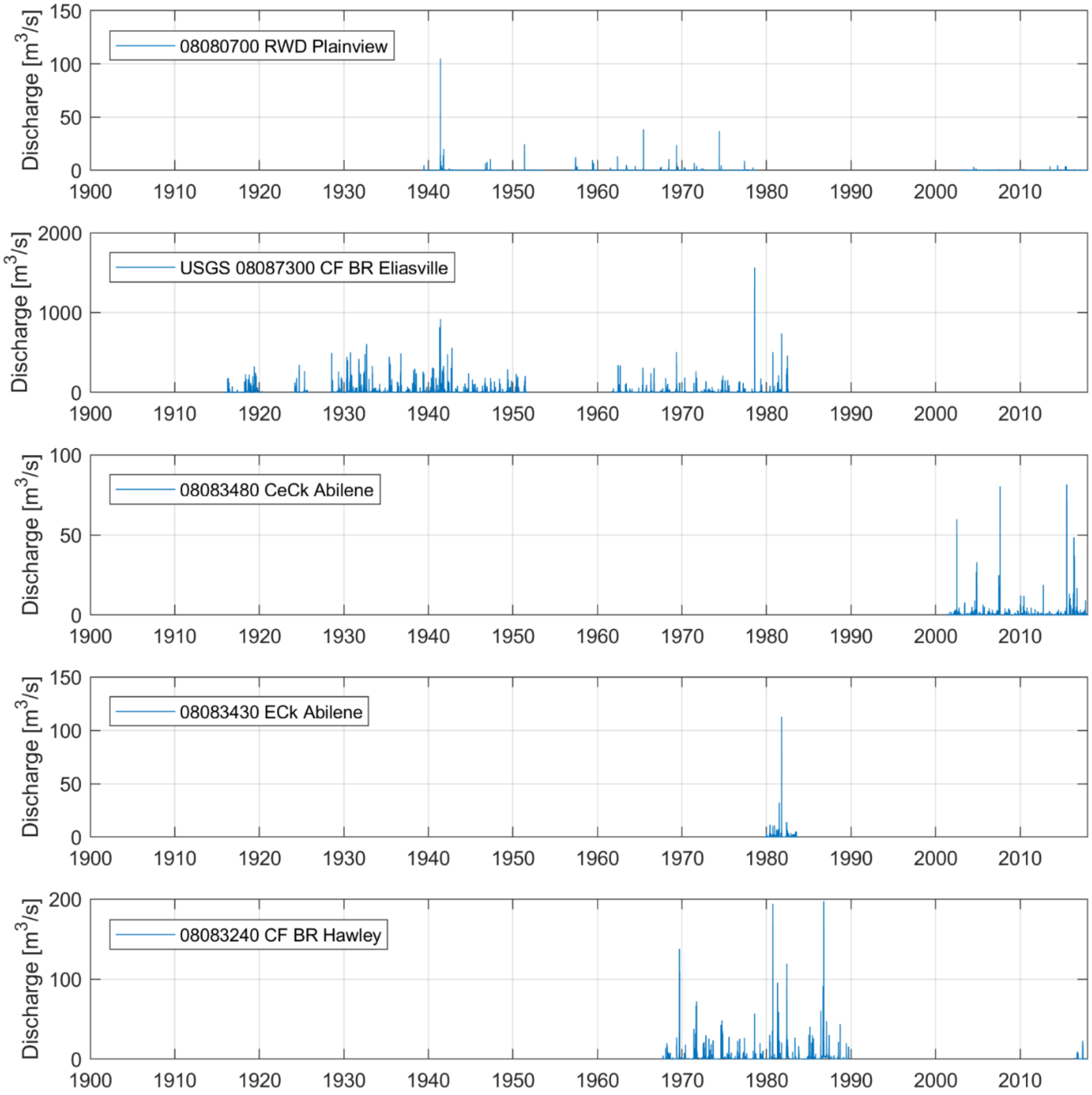


Figure SI 2. Streamflow at Priority 3 gauges

Source: (USGS, 2019)

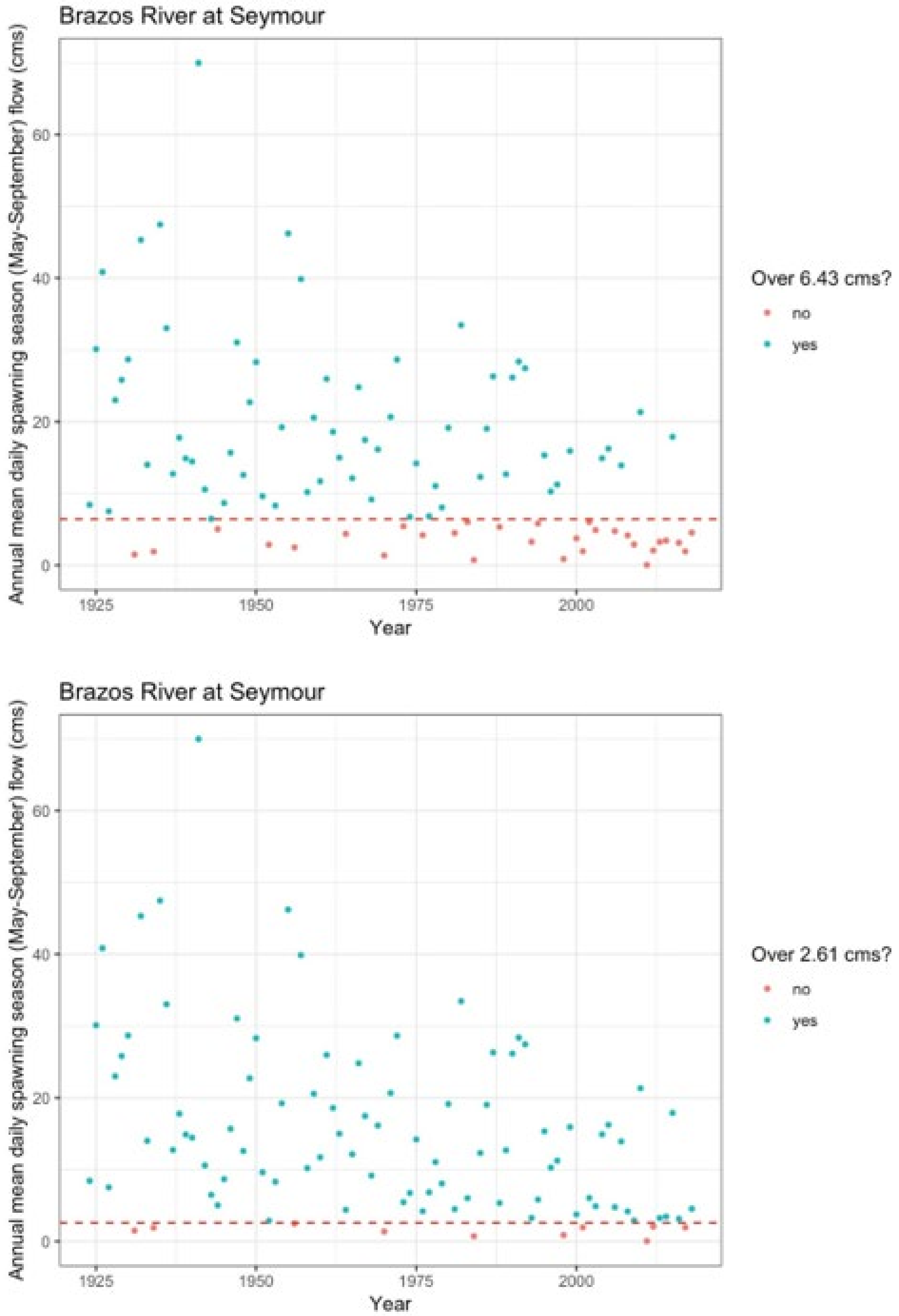


Figure SI 3. Mean spawning season (May–Sept.) streamflow

Analysis for at Seymour gauge. Upper panel indicates whether mean daily flow is above 6.43 m^3s^{-1} (227 cfs) streamflow. Lower panel indicates wither mean daily flow is above 2.61 m^3s^{-1} (92 cfs) over the streamflow record 1924–2019. Source: (USGS, 2019)

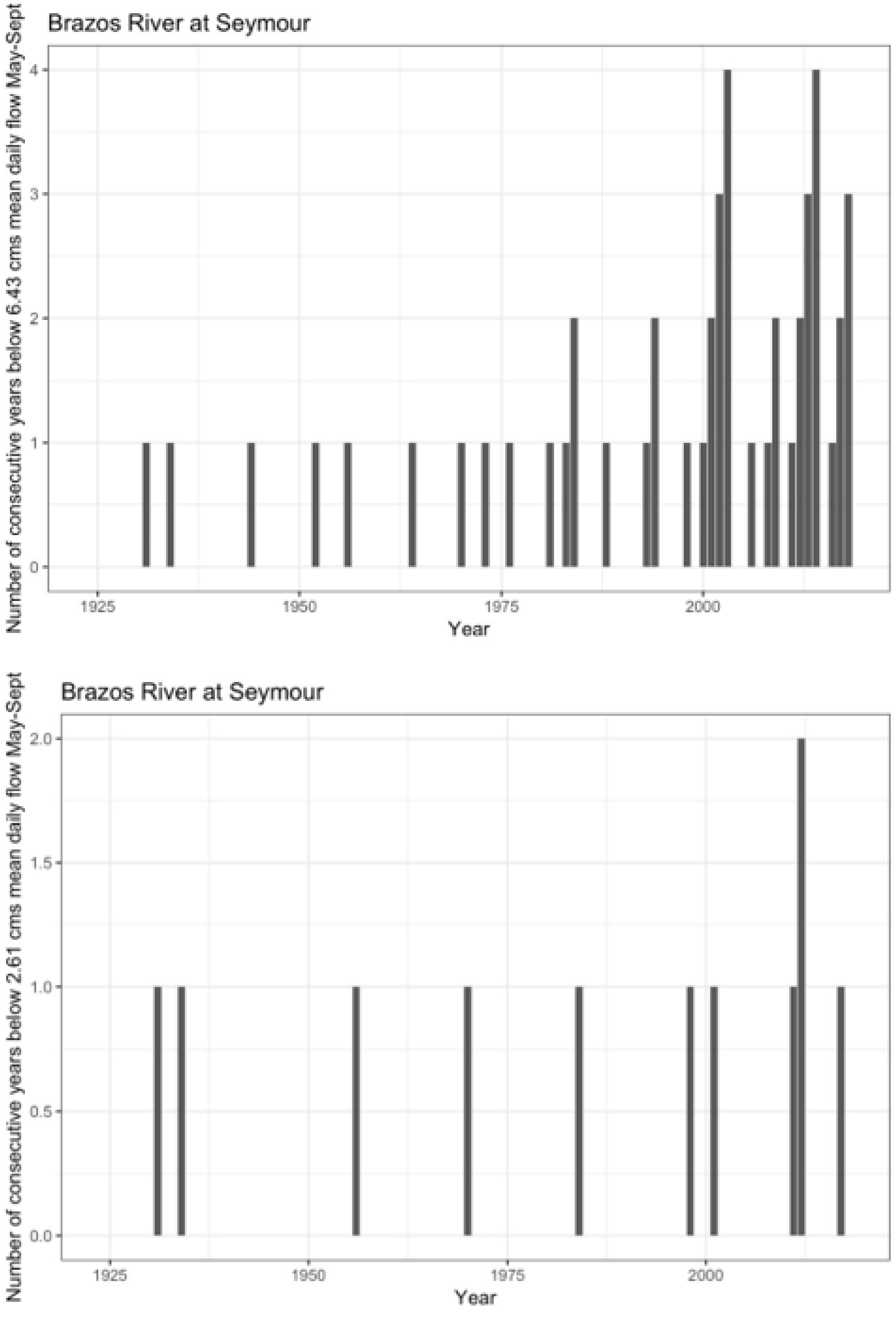


Figure SI 4. Consecutive years mean daily streamflow below threshold

Flow thresholds of biological importance to focal species are 6.43 m^3s^{-1} (227 cfs; upper panel) and 2.61 m^3s^{-1} (92 cfs; lower panel) for the Brazos River at Seymour over the flow record (1924–2019) (Durham and Wilde, 2009a; Durham and Wilde, 2009b).

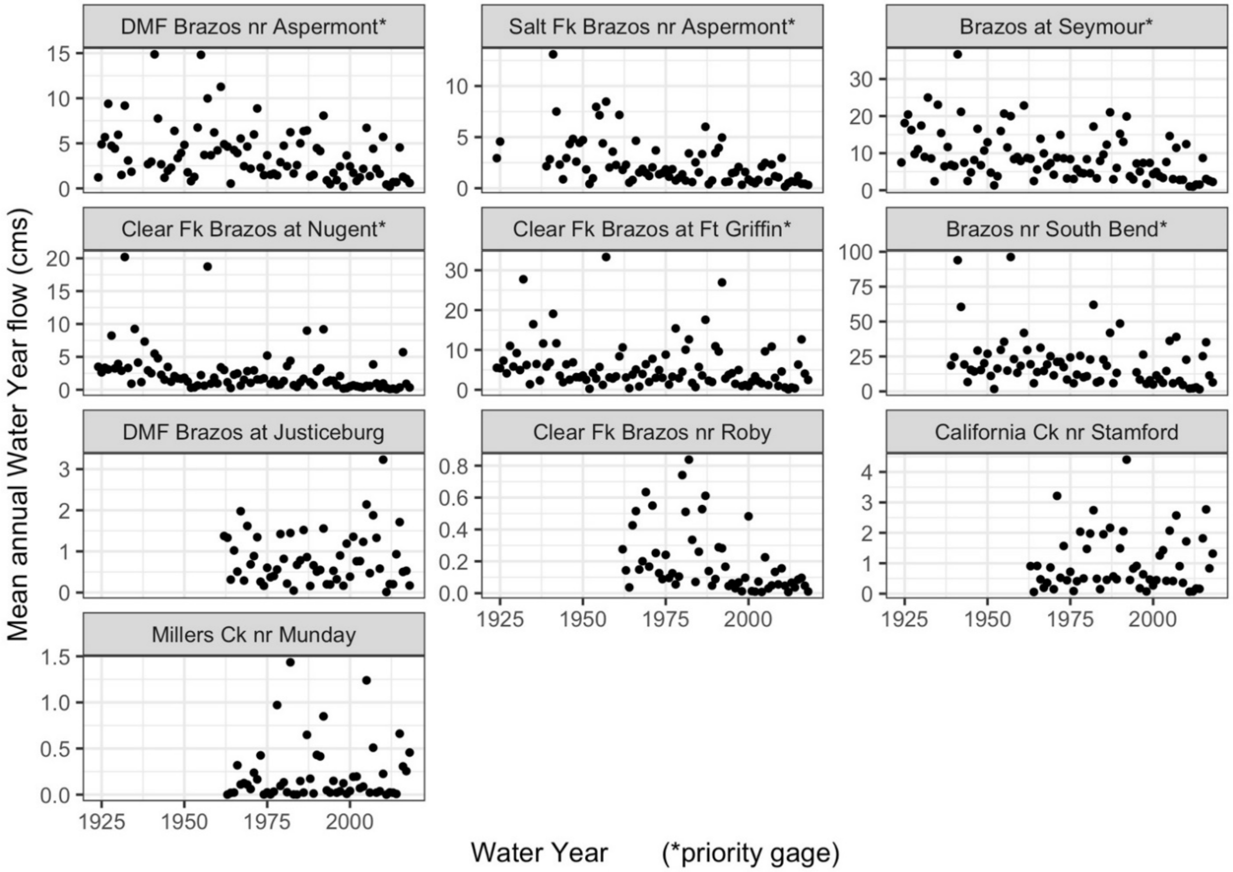


Figure SI 5. **Mean annual streamflow (cms): Priority 1 and 2 gauges**

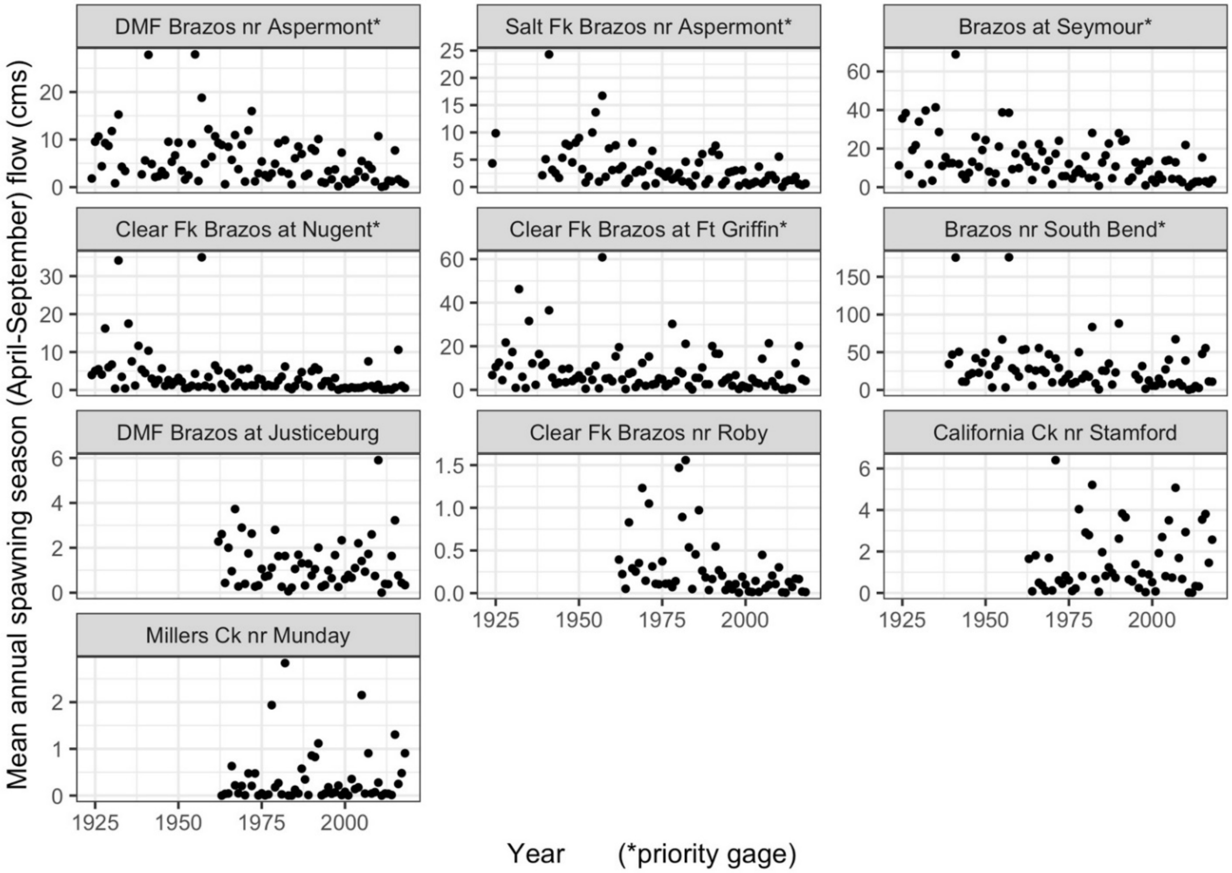


Figure SI 6. Mean annual spawning season streamflow (April–September)

For Priority 1 and 2 gauges

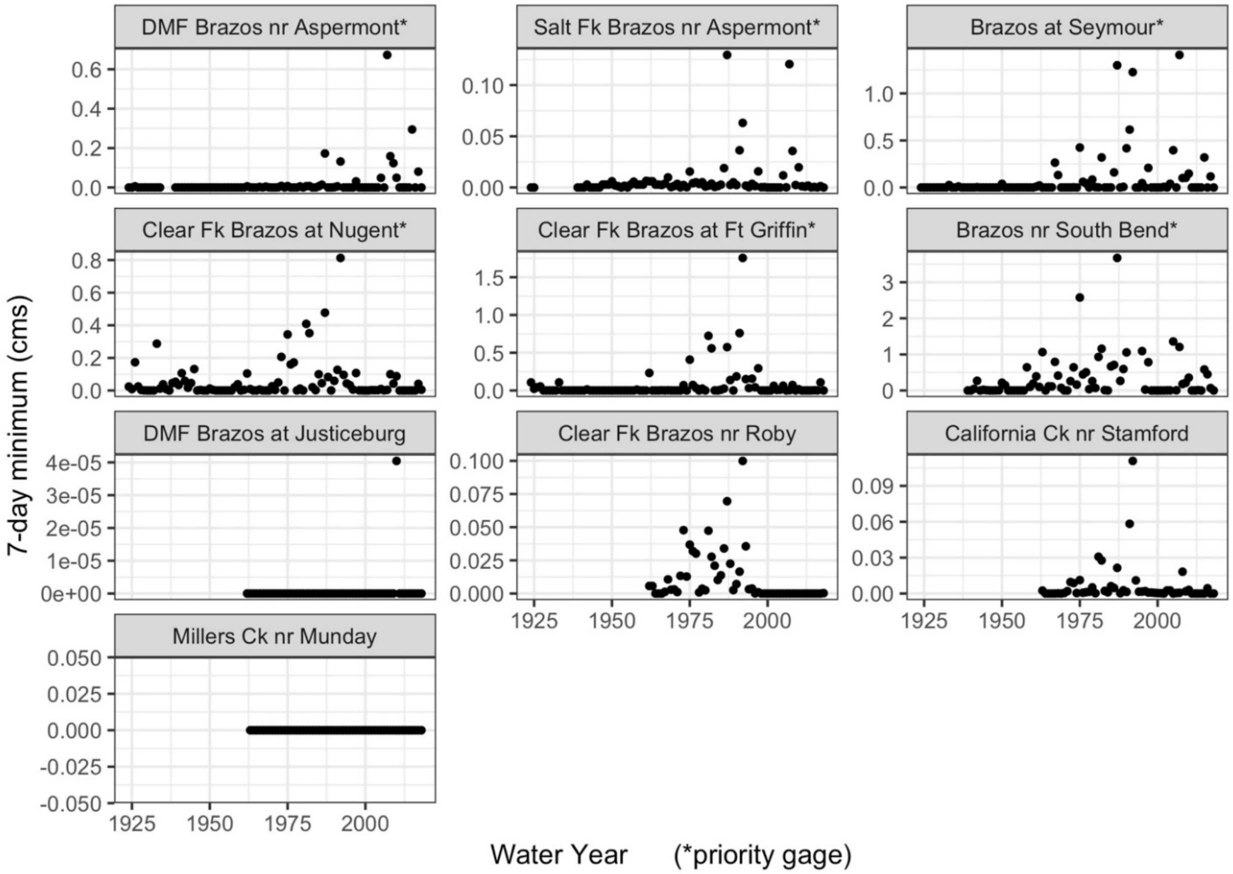


Figure SI 7. Annual 7-Day minimum streamflow (cms)

For Priority 1 and 2 gauges

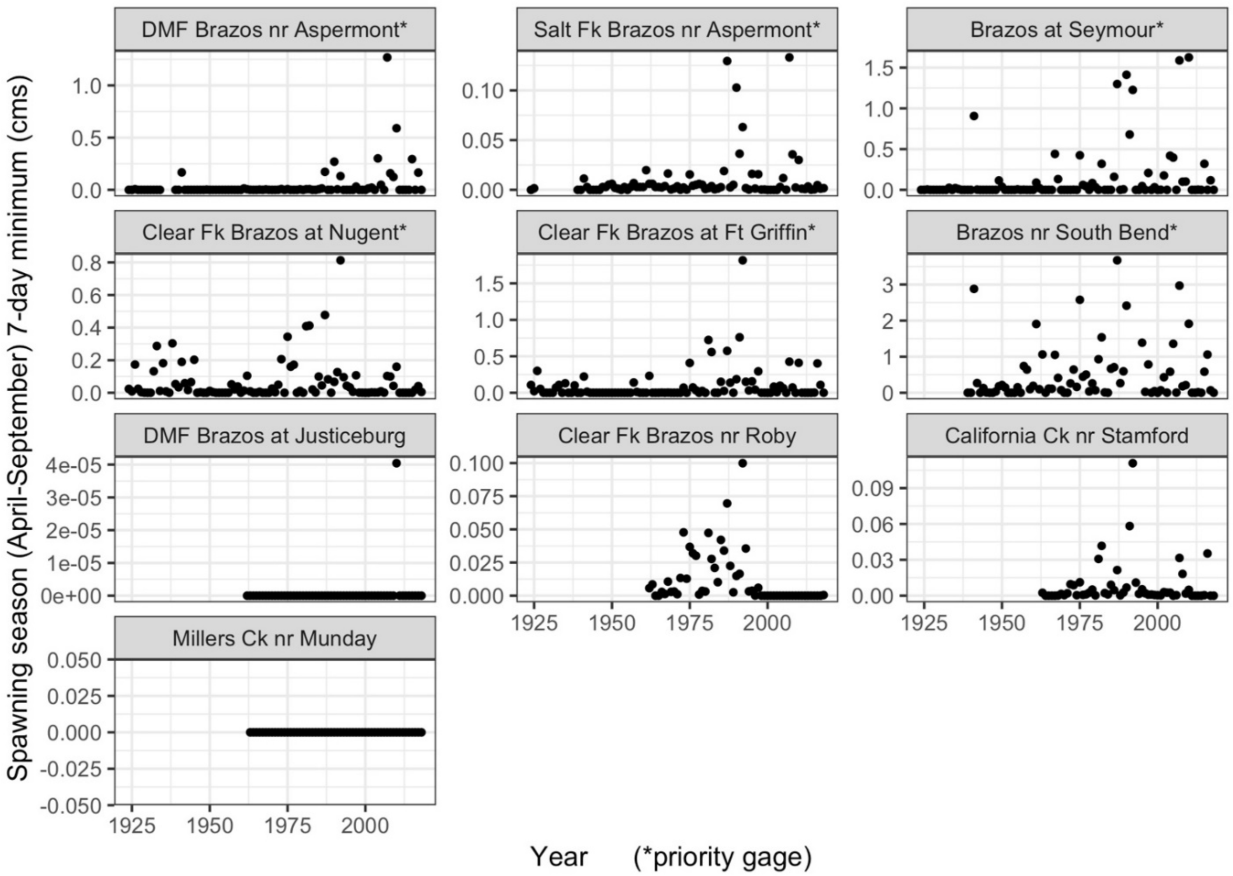


Figure SI 8. Annual 7-Day min. spawning season (Apr.–Sept.) streamflow

For Priority 1 and 2 gauges

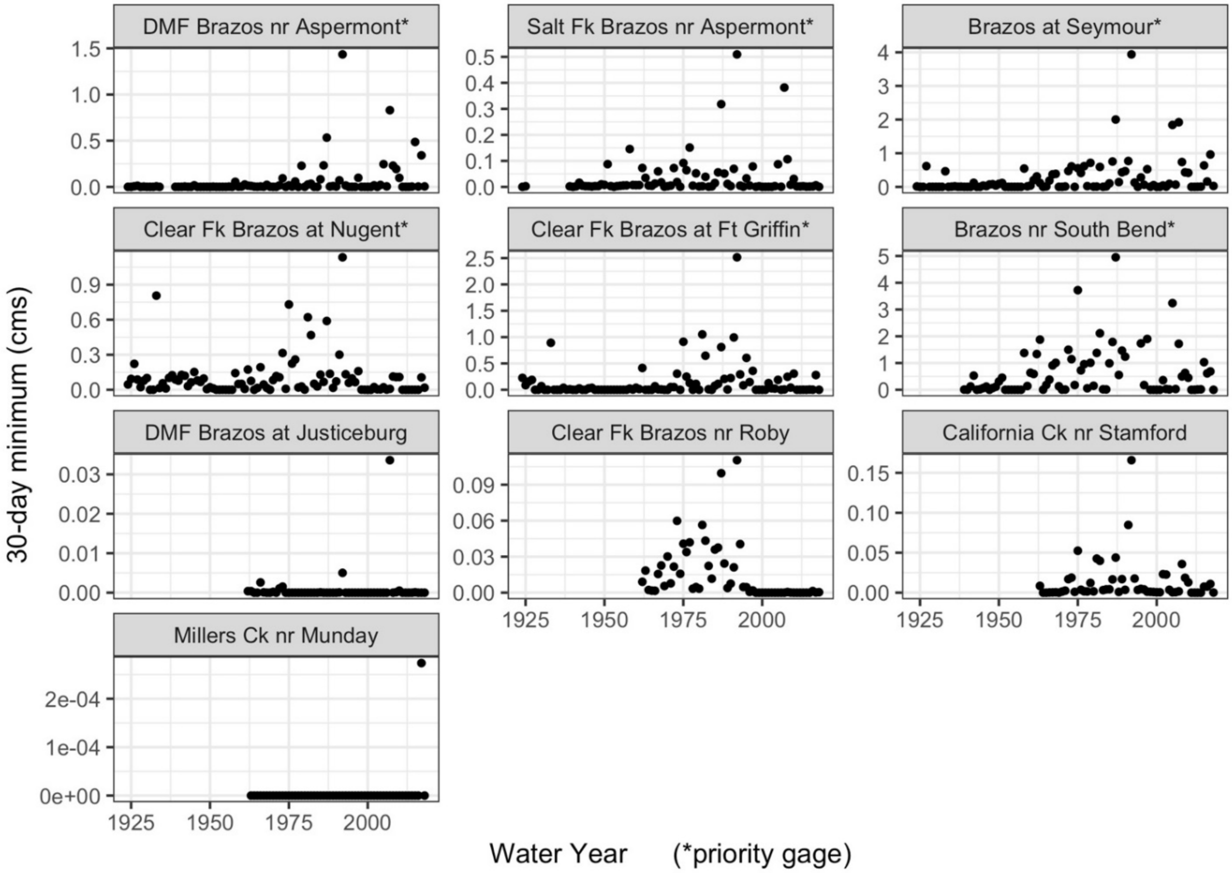


Figure SI 9. Annual 30-Day minimum streamflow: Priority 1 and 2 gauges

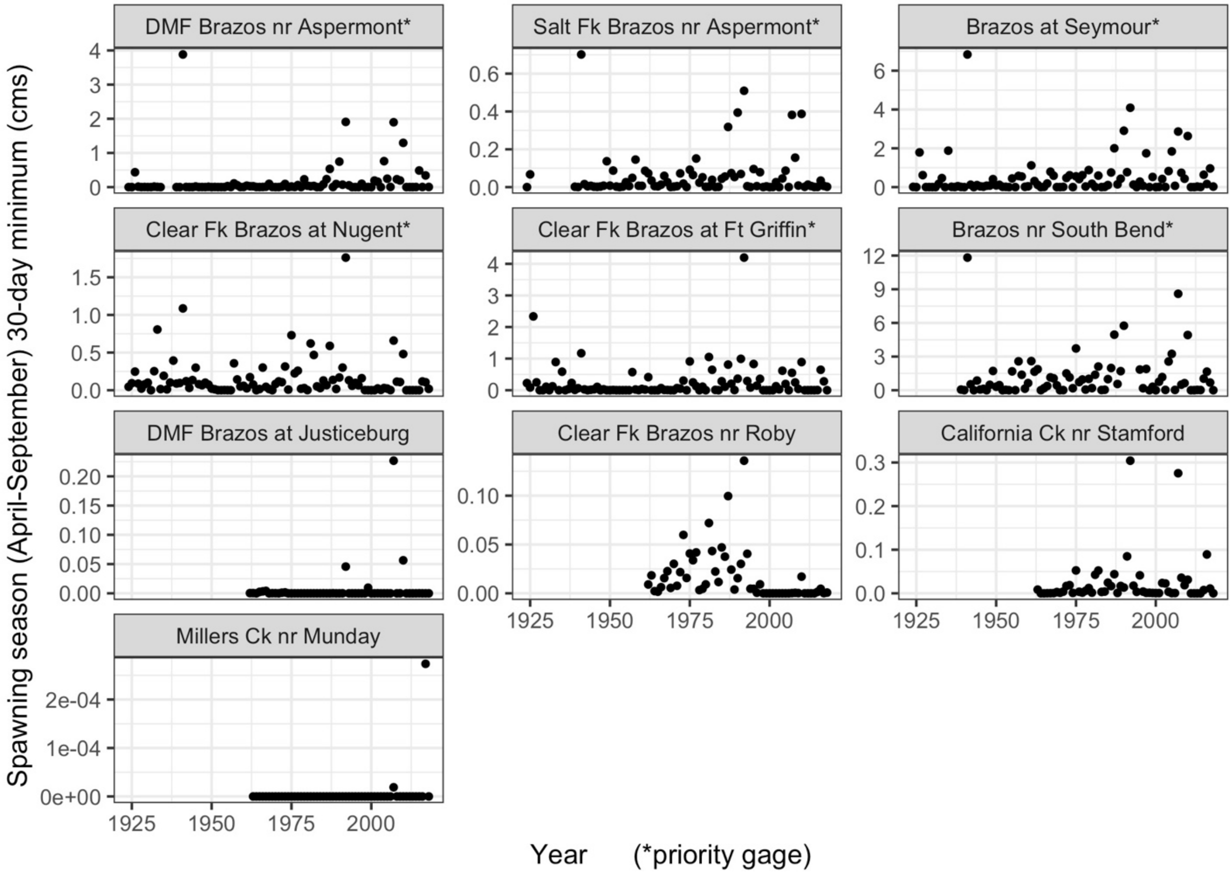


Figure SI 10. Annual 30-day min. spawn. season (Apr.–Sept.) streamflow

For Priority 1 and 2 gauges

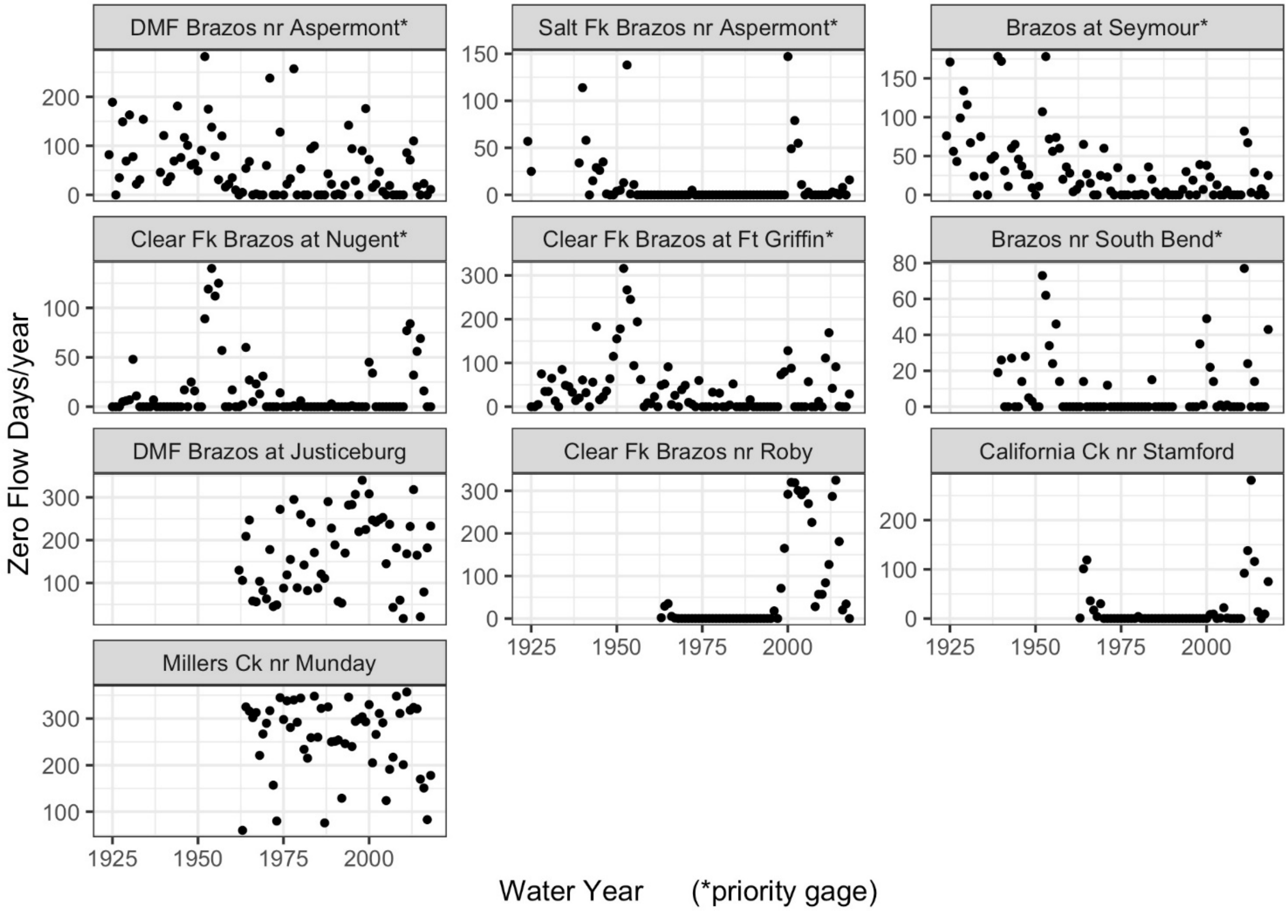
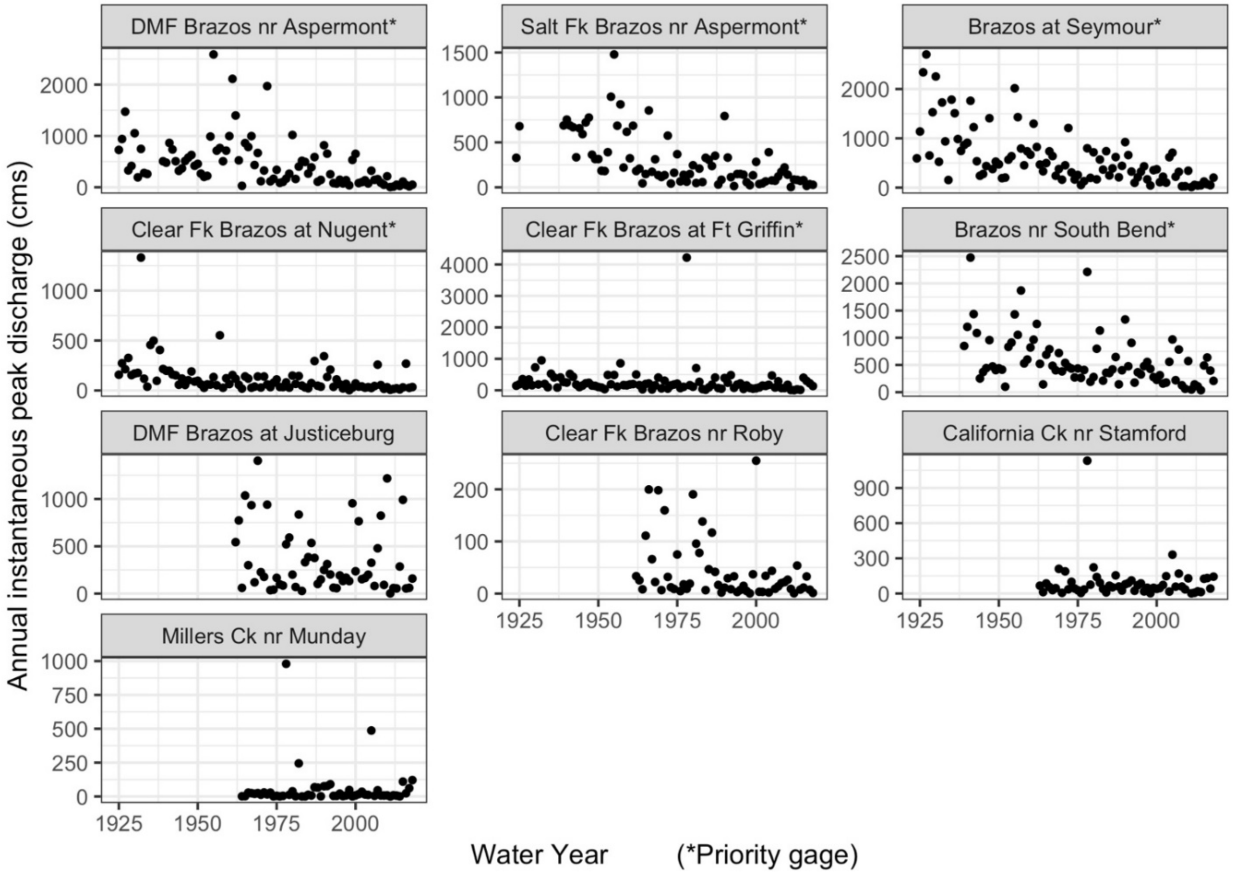


Figure SI 11. Annual zero-flow days: Priority 1 and 2 gauges



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125 **Figure SI 12. Annual instantaneous peak discharge**

126 For Priority 1 and 2 gauges

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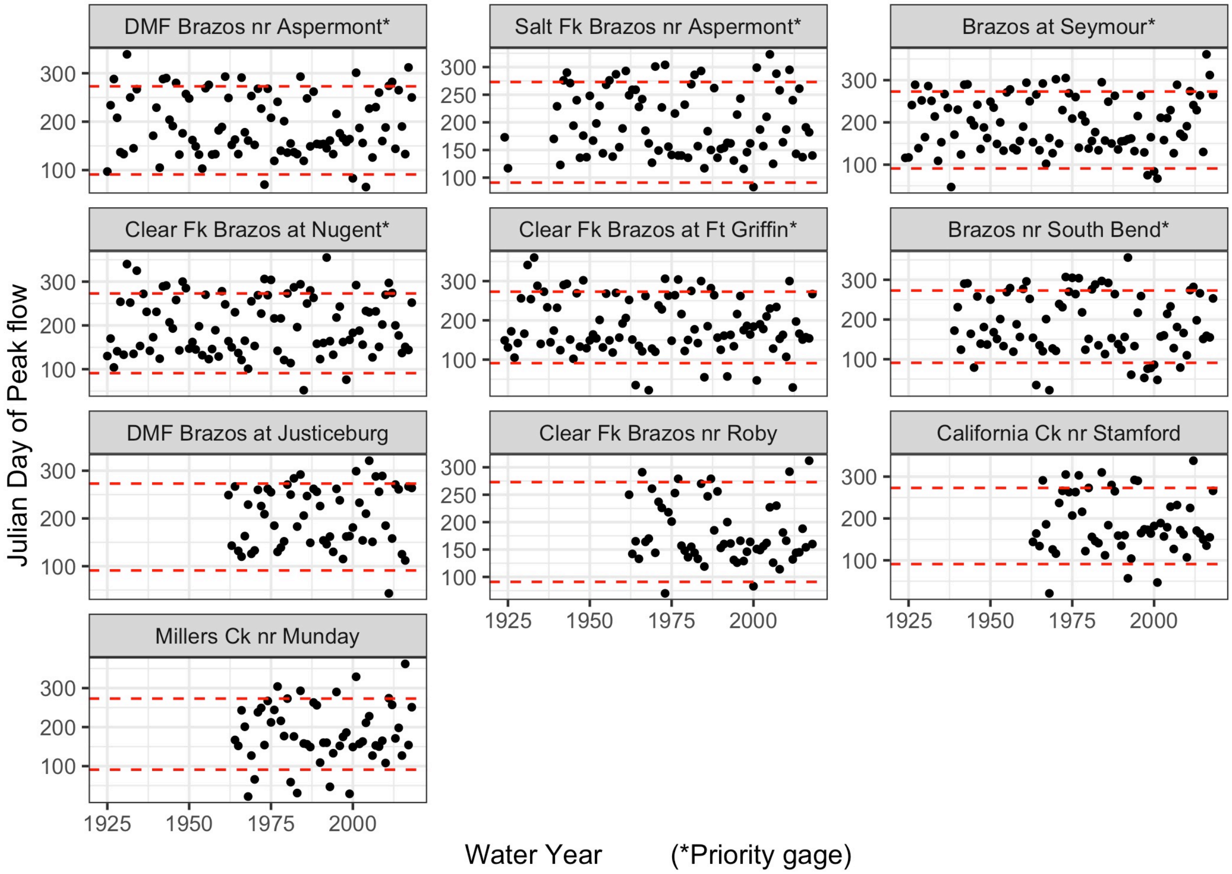

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129 **Figure SI 13. Peak streamflow Julian day (day of the year)**

130 For Priority 1 and 2 gauges

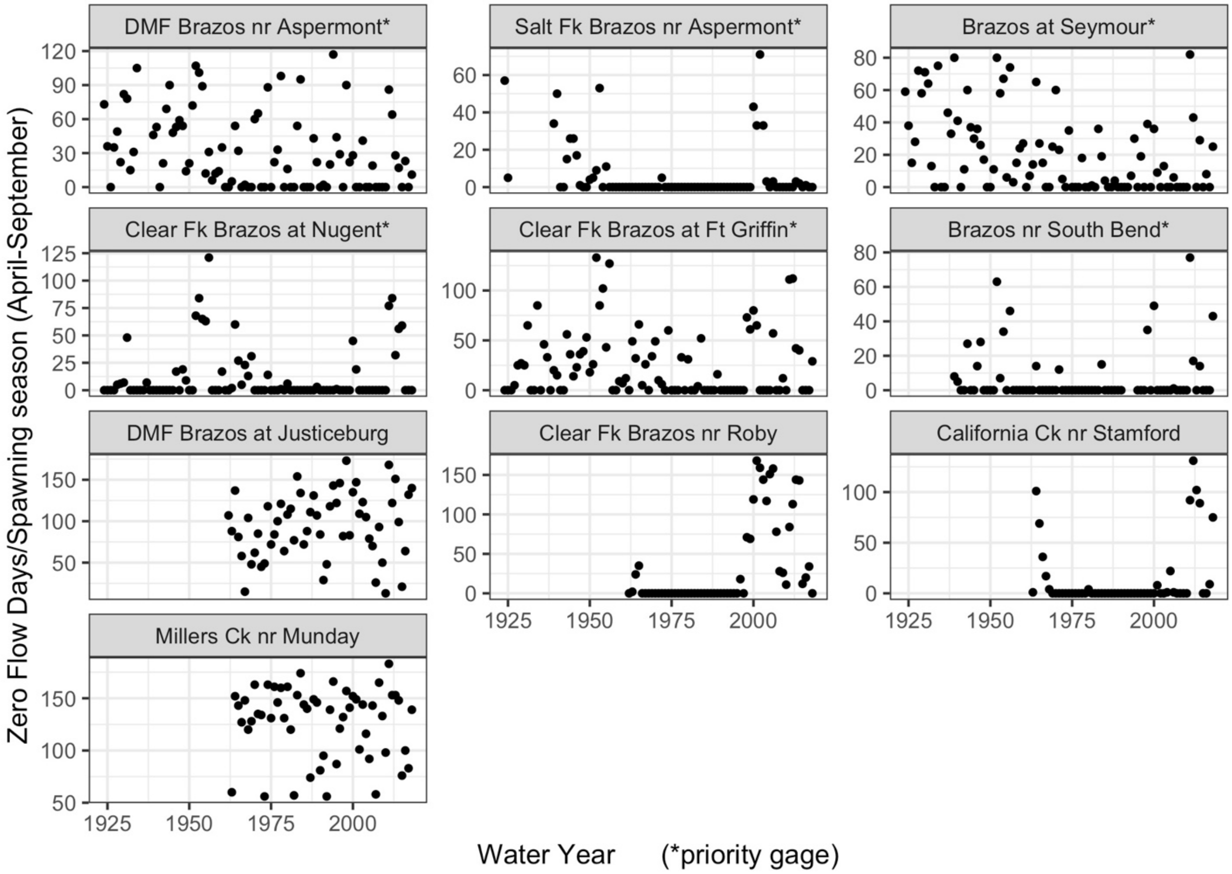

Figure SI 14. Annual zero-flow days during (Apr.–Sept.) spawning season

For Priority 1 and 2 gauges

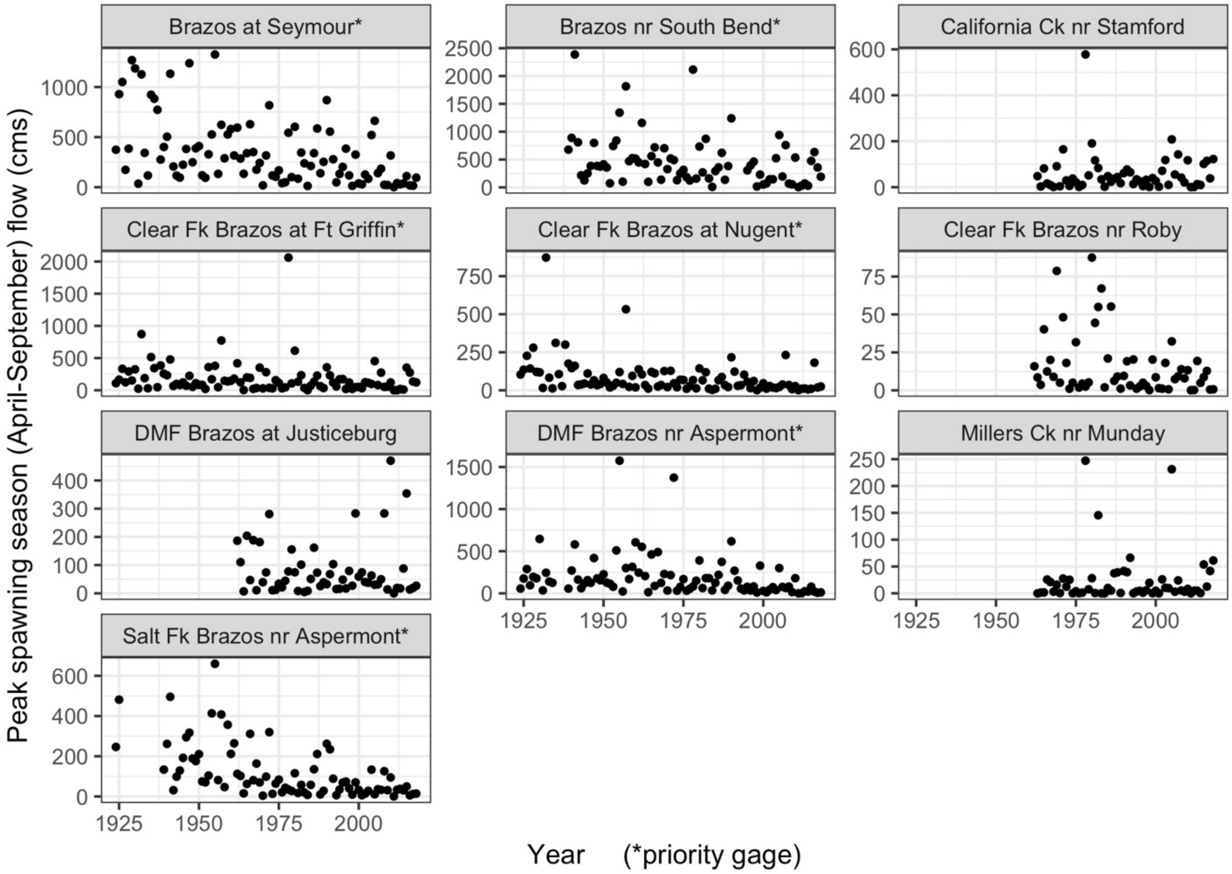

Figure SI 15. Annual peak spawning season (April–September) streamflow

For Priority 1 and 2 gauges

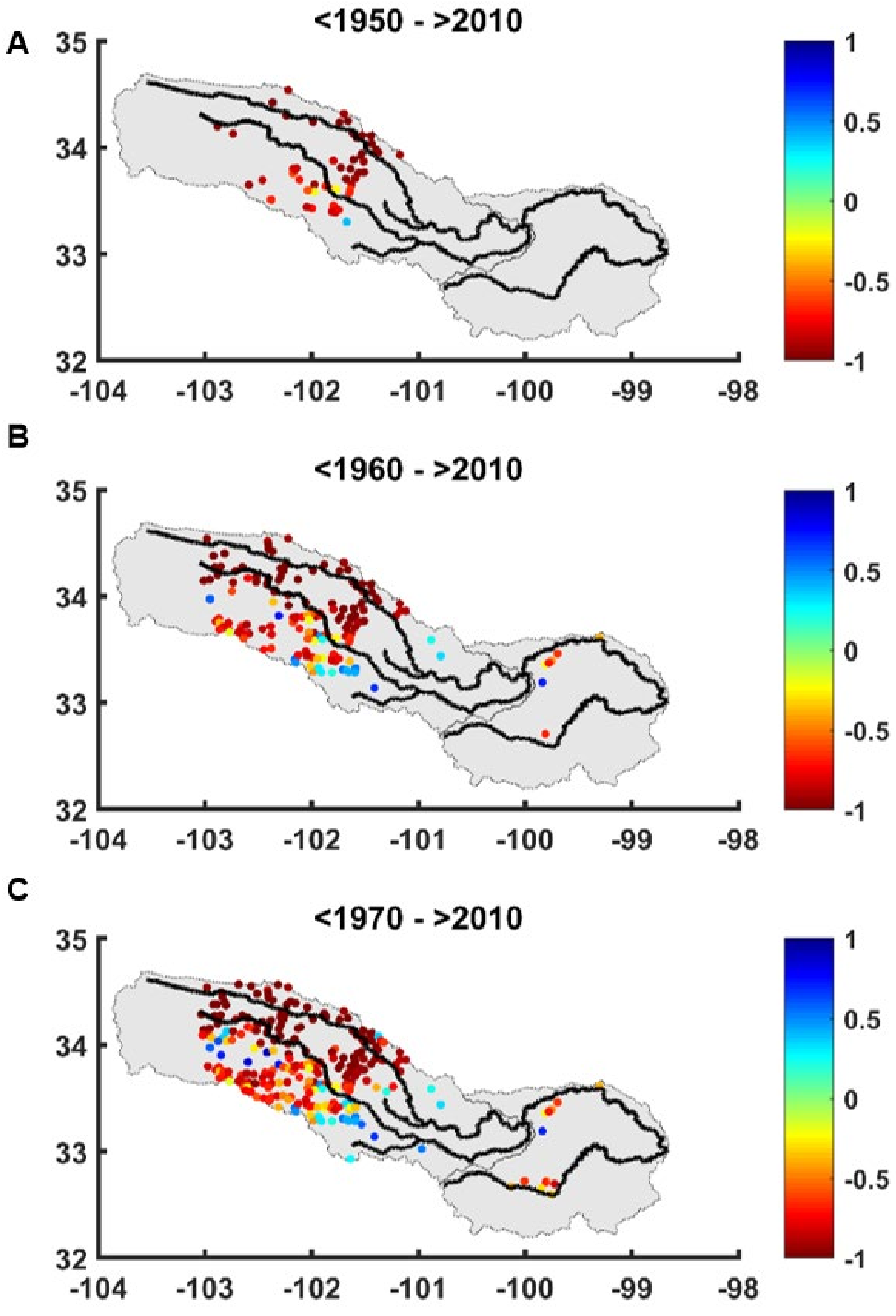

Figure SI 16. Long-term groundwater level trends for individual wells

A. Pre-1950 to post-2010. B. Pre-1960 to post-2010. C. Pre-1970 to post-2010.

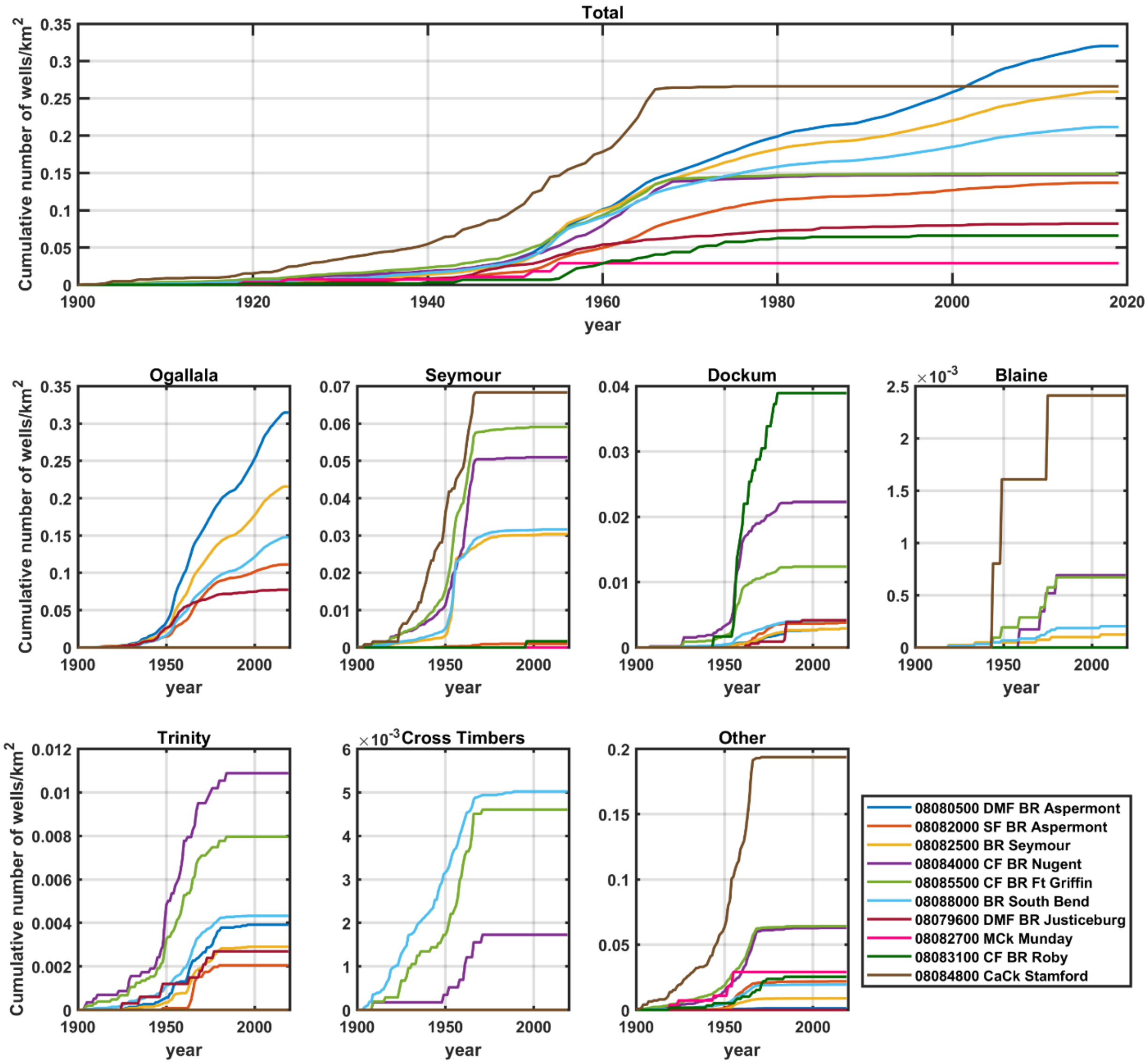

Figure SI 17. Well development

Results normalized by study catchment and separated by aquifer. Source: (OSE, 2019; TWDB, 2019a).

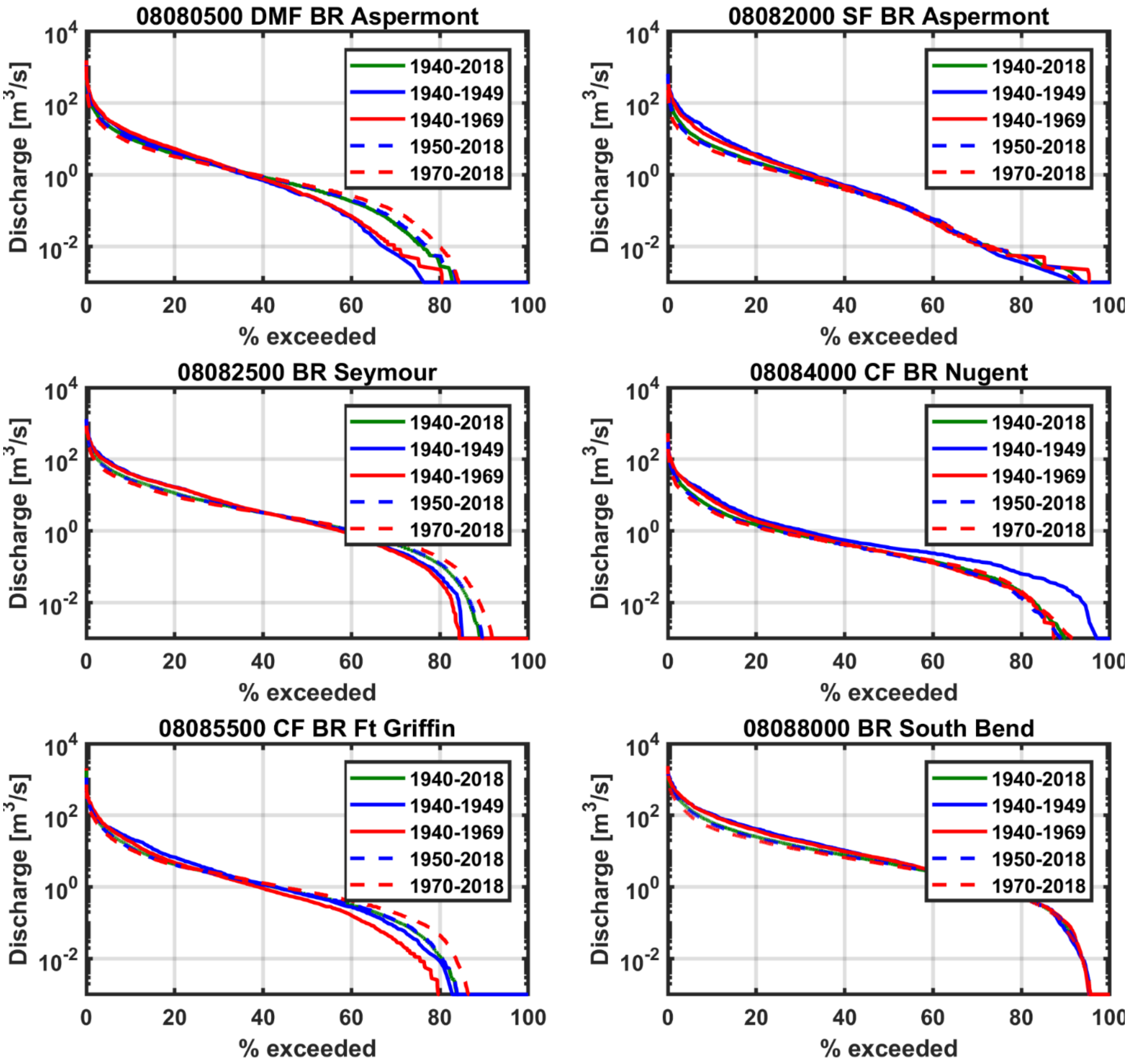

Figure SI 18. Flow duration curves during spawning season (Apr.–Sept.)

For Priority 1 and 2 gauges. Time periods correspond to pre- and post-construction dates of major reservoirs in each catchment. Fish population models suggest a mean summer (May–September) discharge of 6.43 m^3/s to maintain Smalleye Shiner populations and 2.61 m^3/s to maintain Sharpnose Shiners (Durham and Wilde, 2009a; Durham and Wilde, 2009b)

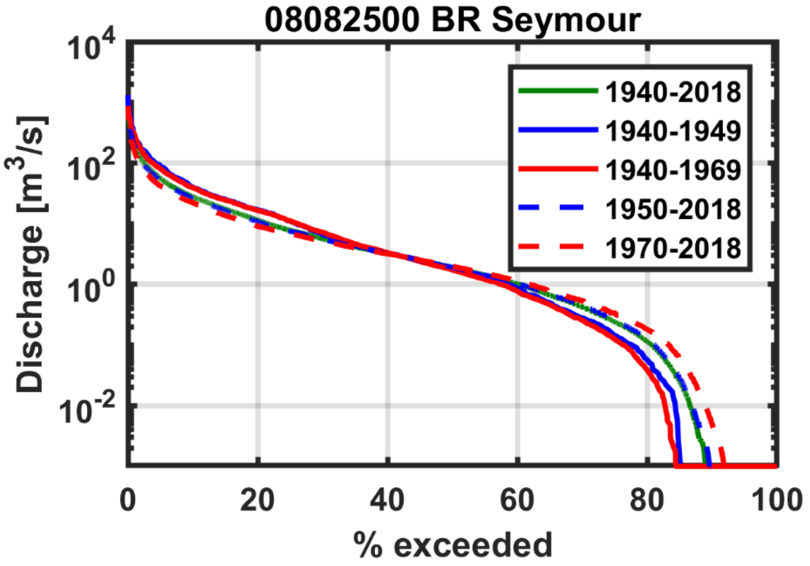

Figure SI 19. **Flow duration curve during spawning season (May–Sept.)** For Seymour, TX. Time periods correspond to pre- and post-construction dates of major reservoirs in each catchment. Fish population models suggest a mean summer (May–September) discharge of 6.43 m^3/s to maintain Smalleye Shiner populations and 2.61 m^3/s to maintain Sharpnose Shiners (Durham and Wilde, 2009a; Durham and Wilde, 2009b)

Table SI 1. Primary land cover for selected catchments

Source: Homer et al. (2015). Notes: Values presented as percent of catchment. BR=Brazos River, DMF=Double Mountain Forks Brazos River, SF=Salt Fork Brazos River, CF BR=Clear Fork Brazos River, CaCk=California Creek, MCk=Millers Creek.

Gauge	Cultivated Crops	Shrub/ Scrub	Herb-aceous	Dev-eloped	Forest	Open Water/ Wetland	Hay/ Pasture	Barren	Drainage Area (km2)
08088000 BR South Bend	37.7	36.0	19.8	3.7	1.5	0.8	0.3	0.2	58,723
08082500 BR Seymour	43.6	36.3	14.8	3.7	0.3	0.8	0.3	0.3	40,243
08080500 DMF BR Aspermont	42.8	36.6	15.0	4.3	0.2	0.6	0.3	0.3	22,782
08082000 SF BR Aspermont	46.7	32.3	16.1	3.0	0.1	1.1	0.4	0.3	13,287
08085500 CF BR Ft Griffin	32.8	44.2	13.7	4.8	3.6	0.7	0.2	0.0	10,329
08084000 CF BR Nugent	30.1	52.2	4.8	6.3	5.8	0.6	0.2	0.1	5,695
08079600 DMF BR Justiceburg	59.0	20.2	14.4	3.6	0.3	1.4	0.3	0.9	3,797
08084800 CaCk Stamford	68.4	24.9	1.2	4.4	0.4	0.4	0.3	0.0	1,238
08083100 CF BR Roby	50.6	33.5	11.1	3.8	0.7	0.1	0.1	0.1	591
8082700 MCk Munday	56.3	17.3	23.2	2.2	0.3	0.2	0.5	0.0	269

Table SI 2. Additional information regarding study stream gauges

Priority: 1. Gauges with long, continuous records, Priority 2: Gauges with shorter, but continuous, records, Priority 3: Gauges with short, discontinuous records with limited analyses by this study.

USGS Gauge	Latitude	Longitude	Start Year	Drain. Area mi2	Contrib. Area mi2	Stream	Priority	Comments
08080500 DMF Brazos Rv nr Aspermont, TX	33.008160	-100.180700	1925	22,782	4,828	Double Mountain Forks	1	Downstream of Lake Alan Henry (1/1/1994) and Lubbock-area lakes: e.g., Ransom Canyon (1965), Buffalo Springs Lake (9/15/1959), Canyon Lake 1 (1975), Canyon Lake 3 (1976), and Canyon Lake 6 (1976). Gains Lubbock waste water effluent (includes imported groundwater. Historic spring discharge along Caprock Escarpment greatly reduced due to groundwater withdrawals. Headwaters in Ogallala Aquifer.
08082000 Salt Fk Brazos Rv nr Aspermont, TX	33.333980	-100.238200	1924	13,287	6,465	Salt Fork Brazos River	1	Downstream of White River Reservoir (10/30/1963). Groundwater depletion has reduced spring flows. Saline seeps increase salinity. Headwaters in Ogallala Aquifer.
08082500 Brazos Rv at Seymour, TX	33.580930	-99.267600	1924	40,243	15,467	Brazos River	1	Mean May-September discharge correlates with Sharpnose and Smalleye shiner population. Downstream of Seymour Aquifer.
08084000 Clear Fk Brazos Rv at Nugent, TX	32.690120	-99.669500	1925	5,695	5,695	Clear Fork Brazos River	1	Downstream of Fort Phantom Hill (10/30/1938). Gains Abilene wastewater effluent, some is imported surface water from 1. Hubbard Creek Reservoir (up to 30 MGD), 2. O.H. Ivie Reservoir (up to 12 MGD, interbasin transfer from Colorado River, and 3. Possum Kingdom Reservoir (during

USGS Gauge	Latitude	Longitude	Start Year	Drain. Area mi2	Contrib. Area mi2	Stream	Priority	Comments
								extreme droughts). Downstream of Seymour Aquifer.
08085500 Clear Fk Brazos Rv at Ft Griffin, TX	32.932980	-99.215400	1924	10,329	10,329	Clear Fork Brazos River	1	Downstream of Lake Stamford (6/30/1953) and Seymour Aquifer.
08088000 Brazos Rv nr South Bend, TX	33.024167	-98.643600	1938	58,723	33,947	Brazos River	1	Last gauge upstream of Possum Kingdom Reservoir (3/21/1941), integrates effects of all upstream impoundments and groundwater pumping.
08079600 DMF Brazos Rv at Justiceburg, TX	33.038333	-101.197220	1961	3,797	632	Double Mountain Forks Brazos River	2	Upstream of Lake Alan Henry. Headwaters in Ogallala Aquifer.
08082700 Millers Ck nr Munday, TX	33.329167	-99.464722	1963	269	269	Brazos River	2	Upstream of Millers Creek Reservoir. Headwaters include east side of Seymour Aquifer.
08083100 Clear Fk Brazos Rv nr Roby, TX	32.787610	-100.388700	1962	591	591	Clear Fork Brazos River	2	Headwaters include Seymour and Blaine aquifers.

USGS Gauge	Latitude	Longitude	Start Year	Drain. Area mi2	Contrib. Area mi2	Stream	Priority	Comments
08084800 California Ck nr Stamford, TX	32.930940	-99.642600	1963	1,238	1,238	Clear Fork Brazos River	2	Headwaters include Seymour and Blaine aquifers.
08080700 Running Water Draw at Plainview, TX	34.178889	-101.702222	1939	3,344	989	Salt Fork	3	Upstream of White River Reservoir in Ogallala Aquifer.
08083240 Clear Fk Brazos Rv at Hwy 83 nr Hawley, TX	32.598500	-99.814556	1967	3,667	3,667	Clear Fork Brazos River	3	Upstream of Fort Phantom Hill. Headwaters in Seymour and Blaine aquifers.
08083430 Elm Ck at Abilene, TX	32.507306	-99.741028	1979	1,093	1,093	Clear Fork Brazos River	3	Urbanized Abilene location. Short record.
08083480 Cedar Ck at IH 20, Abilene, TX	32.486611	-99.714556	2001	352	352	Clear Fork Brazos River	3	Urbanized Abilene location. Short record.
08087300 Clear Fk Brazos Rv at Eliasville, TX	32.960683	-98.766700	1915	14,755	14,755	Clear Fork Brazos River	3	Downstream-most Clear Fork gage.

Table SI 3. Baseflow, storm flow, total flow statistics

For Priority 2 gauges.

	Site	08079600 DMF BR Justiceburg	08084800 CaCk Stamford	08083100 CF BR Roby	08082700 MCk Munday
BFI	max	0.191	0.718	0.842	0.417
	max yr	2011	2011	1998	2011
	min	0	0.003	0.001	0
	min yr	2004	2013	2005	1978
	mean	0.017	0.141	0.272	0.04
	median	0.009	0.11	0.219	0.017
BF	max	0.193	0.652	0.342	0.106
	max yr	2010	1992	1987	1982
	min	0	0	0	0
	min yr	1998/2013	2013	2002	1964
	mean	0.013	0.108	0.045	0.008
	median	0.004	0.063	0.027	0.001
SF	max	3.037	3.752	0.724	1.328
	max yr	2010	1992	1980	1982
	min	0.011	0.019	0.002	0
	min yr	2011	2011	1998	2011
	mean	0.801	0.895	0.152	0.202
	median	0.629	0.484	0.072	0.091
Q	max	3.23	4.404	0.838	1.435
	max yr	2010	1992	1982	1982
	min	0.013	0.066	0.008	0
	min yr	2011	2011	2004	2011
	mean	0.814	1.003	0.196	0.21
	median	0.632	0.546	0.101	0.091

Note: BFI=base flow index, BF=base flow, SF=storm flow, Q=total streamflow.

Table SI 4. Baseflow, storm flow, and total flow(Q) trends

For Priority 1 & 2 Gauges using 1964 as a start date

	site	08080500 DMF BR Aspermont	08082000 SF BR Aspermont	08082500 BR Seymour	08084000 CF BR Nugent	08085500 CF BR Ft Griffin	08088000 BR South Bend	08079600 DMF BR Justiceburg	08084800 CaCk Stamford	08083100 CF BR Roby	8082700 MCk Munday
BFI	p-value	**<0.001**	0.245	**0.023**	0.245	0.811	0.829	0.571	0.303	0.052	0.870
	tau	0.386	0.110	0.213	-0.110	-0.023	-0.022	-0.054	-0.097	-0.182	0.016
	sen	0.005	0.001	0.002	-0.002	0.000	0.000	0.000	-0.001	-0.003	0.000
BF	p-value	0.210	0.245	0.881	**0.004**	0.371	0.115	0.576	0.917	**<0.001**	0.748
	tau	0.118	-0.110	-0.015	-0.269	-0.085	-0.156	-0.053	0.010	-0.398	0.031
	sen	0.004	-0.002	-0.001	-0.006	-0.005	-0.030	0.000	0.000	-0.001	0.000
SF	p-value	**0.003**	**0.018**	**0.005**	**0.010**	0.317	0.057	0.743	0.743	**0.007**	0.952
	tau	-0.282	-0.222	-0.263	-0.241	-0.094	-0.189	0.031	0.031	-0.254	0.006
	sen	-0.039	-0.014	-0.069	-0.014	-0.020	-0.126	0.002	0.001	-0.002	0.000
Q	p-value	**0.012**	**0.032**	**0.014**	**<0.001**	0.199	**0.041**	0.743	0.929	**<0.001**	0.988
	tau	-0.236	-0.202	-0.231	-0.312	-0.121	-0.202	0.031	0.009	-0.360	-0.002
	sen	-0.037	-0.016	-0.069	-0.026	-0.036	-0.164	0.002	0.000	-0.004	0.000

Notes: Bold values are statistically significant. BFI=base flow index, BF=base flow, SF=storm flow, Q=total streamflow.