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Key Points:
- A river's daily natural flow regime can be estimated without quantifying consumptive losses if there are enough gaging stations
- The flow regime of the northern branch of the Rio Grande is significantly altered in magnitude, timing, and variability
- The method by which natural streamflow is estimated can have significant effects on environmental flow recommendations

Supporting Information:
- Supporting Information S1

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Estimating the Natural Flow Regime of Rivers with Long-Standing Development: The Northern Branch of the Rio Grande

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Abstract An estimate of a river's natural flow regime is useful for water resource planning and ecosystem rehabilitation by providing insight into the predisturbance form and function of a river. The natural flow regime of most rivers has been perturbed by development during the 20th century and in some cases, before stream gaging began. The temporal resolution of natural flows estimated using traditional methods is typically not sufficient to evaluate cues that drive native ecosystem function. Additionally, these traditional methods are watershed specific and require large amounts of data to produce accurate results. We present a mass balance method that estimates natural flows at daily time step resolution for the northern branch of the Rio Grande, upstream from the Rio Conchos, that relies only on easily obtained streamflow data. Using an analytical change point method, we identified periods of the measured flow regime during the 20th century for comparison with the estimated natural flows. Our results highlight the significant deviation from natural conditions that occurred during the 20th century. The total annual flow of the northern branch is 95% lower than it would be in the absence of human use. The current 2 year flood has decreased by more than 60%, is shorter in duration, and peaks later in the year. When compared to unregulated flows estimated using traditional mass balance accounting methods, our approach provides similar results.

1. Introduction

It is widely accepted that native aquatic and riparian ecosystems are adapted to a river's natural flow regime (Bunn & Arthington, 2002; Karr, 1991; Olden & Naiman, 2010; Poff et al., 1997; Richter et al., 1996; Wohl et al., 2015). Thus, it is useful to estimate the magnitude, frequency, variability, and timing of flows that describe that regime, because those metrics can guide ecosystem rehabilitation programs that seek to protect or recover native ecosystems by manipulating streamflow. There are many strategies that seek to resolve competing utilitarian and ecosystem demands for streamflow by identifying the most important natural flow characteristics that need to be restored (Tharme, 2003). Most of these methods involve calculating metrics that compare the modern and natural flow regimes and therefore require an accurate and precise estimation of the natural streamflow.

Several approaches to estimating the components of the natural flow regime have been proposed. One method is to assume that all streams within a region have similar flow regimes and that the flow regime of an undeveloped river is broadly representative of nearby developed rivers. This approach includes methods such as calculating regional flow duration curves (Searcy, 1959). However, application of this method is limited, because less than 40% of the world's rivers are unaffected by water development (WCD, 2000). In some cases, managers and researchers calculate statistics by assuming that the flow regime measured by the oldest streamflow measurements approximates natural conditions (Richter et al., 1996, 1997). However, significant consumptive water use and flow regulation preceded gaging of many rivers in arid and semiarid regions with large population centers and whose water sources are in distant headwaters. In many of these exotic rivers, such as the Nile, Indus, and Yellow Rivers, Mediterranean streams in southern Europe, and the Rio Grande in North America, consumptive water use has occurred for more than a century and, in some cases, many centuries.

Natural flow estimates of monthly or annual volumes are often based on development of a water budget using traditional mass balance methods (NRCS, 2011; Prairie & Callejo, 2005; USACE, 1998; Wurbs et al., 1988). This approach uses estimates of consumptive losses, including irrigation diversions, and reservoir evaporation, to quantify streamflow depletions. The estimated depletions are adjusted for the operation of reservoirs and added to the measured streamflow at a gage located downstream from all depletions. This approach is typically used when forecasting annual yields for water supply, but requires extensive consumptive loss data to be accurate.

The various ecological approaches used to determine ecosystem streamflow requirements necessitate higher resolution natural flow estimates than those typically developed by the water budget approach described above. Estimates of natural flows with daily temporal resolution have been made by disaggregating monthly data, hydrologic modeling, or by interpolation from measurement stations where a large amount of daily data exist (Kumar et al., 2000; Sauer, 2002; Smakhtin, 1999; Wurbs & Hoffpauir, 2012; Wurbs & Sisson, 1999). However, in systems with long-standing water development, simulations are less useful because they cannot be verified by predevelopment streamflow data.

Here we describe and implement an alternate method for estimating the natural flow regime at daily time step resolution that relies on daily measured, rather than simulated, streamflow data. Our method uses the least disturbed streamflow measurements at the most upstream gages and identifies the location, magnitude, and timing of all downstream natural inflows. Natural inflows include ungaged increases in streamflow measured between two gages minus any known inflows from human development. The streamflow measured at the upstream-most gages, combined with the cumulative sum of all estimated natural inflows provide an estimate of the natural streamflow. This method is the inverse of typical water budgets where the cumulative sum of streamflow removed from the system is added to a downstream gage. The results of our method provide natural flows comparable to those estimated by traditional water budget accounting methods but have higher temporal resolution.

Our technique can be implemented in any river basin where daily streamflow is measured in the headwaters and major tributaries. To highlight the effectiveness of this method for determining the natural flow regime, we apply our method to the northern branch of the Rio Grande, upstream from its confluence with the Rio Conchos. This part of the river was over allocated by the late 1800s due to extensive infrastructure development that predates the earliest gaging. The Rio Grande has one of the longest, most complete records of continuous daily streamflow in the world with measurement sites in the headwaters of the main stem and tributaries as well as upstream and downstream from regions with major withdrawals. Using the results from our mass balance method, and a method for identifying change points in measured 20th century streamflows, we show that historical streamflow data are significantly different from natural conditions. Using a relatively simple alteration to the traditional water budget, we provide a temporally and spatially high-resolution estimate of the natural flows, and, for the first time, quantify the profound transformation of the northern branch of the Rio Grande.

2. Study Area

The Rio Grande, called the Río Bravo in Mexico, is more than 3,000 km long, making it the fifth longest river in North America. The river drains approximately 550,000 km^2 of eight states (Patiño-Gomez et al., 2007) in two countries (Figure 1a). The headwaters of the northern branch are more than 4,000 m above sea level in the southern Rocky Mountains, where most of the runoff is from snowmelt. Summer precipitation and the North American monsoon contribute additional late season flows. The San Juan, Sangre de Cristo, and Jemez Mountains receive as much as 1,200 mm of precipitation annually; in contrast, the semiarid lowlands receive as little as 100 mm annually (PRISM Climate Group, 2017). Before reaching Albuquerque, the Rio Grande accumulates flow from two large tributaries, the Conejos River and the Rio Chama. Between Albuquerque and Las Cruces, smaller tributaries, such as the Jemez River, Rio Puerco, and Rio Salado provide smaller amounts of streamflow, downstream from Las Cruces there are only a few small, ephemeral tributaries. The Rio Conchos is the largest tributary to the Rio Grande, originates in the Sierra Madre Occidental of Chihuahua, and enters the main stem near the border cities of Ojinaga and Presidio. The flow regime of the Rio Conchos is characteristic of a rainfall-dominated region. The flow regime of the lower Rio Grande, downstream of the Rio Conchos, reflects the combined influence of two climatically different headwaters (Gonzalez-Escorcia, 2017).

The most upstream gage analyzed in this study is near Del Norte (U.S. Geological Survey gage 8220000) (Figure 1b). This gage measures relatively natural inflows to the northern branch from the San Juan Mountains; however, the river is regulated by four, small reservoirs with total storage of less than 156×10^6 m^3,

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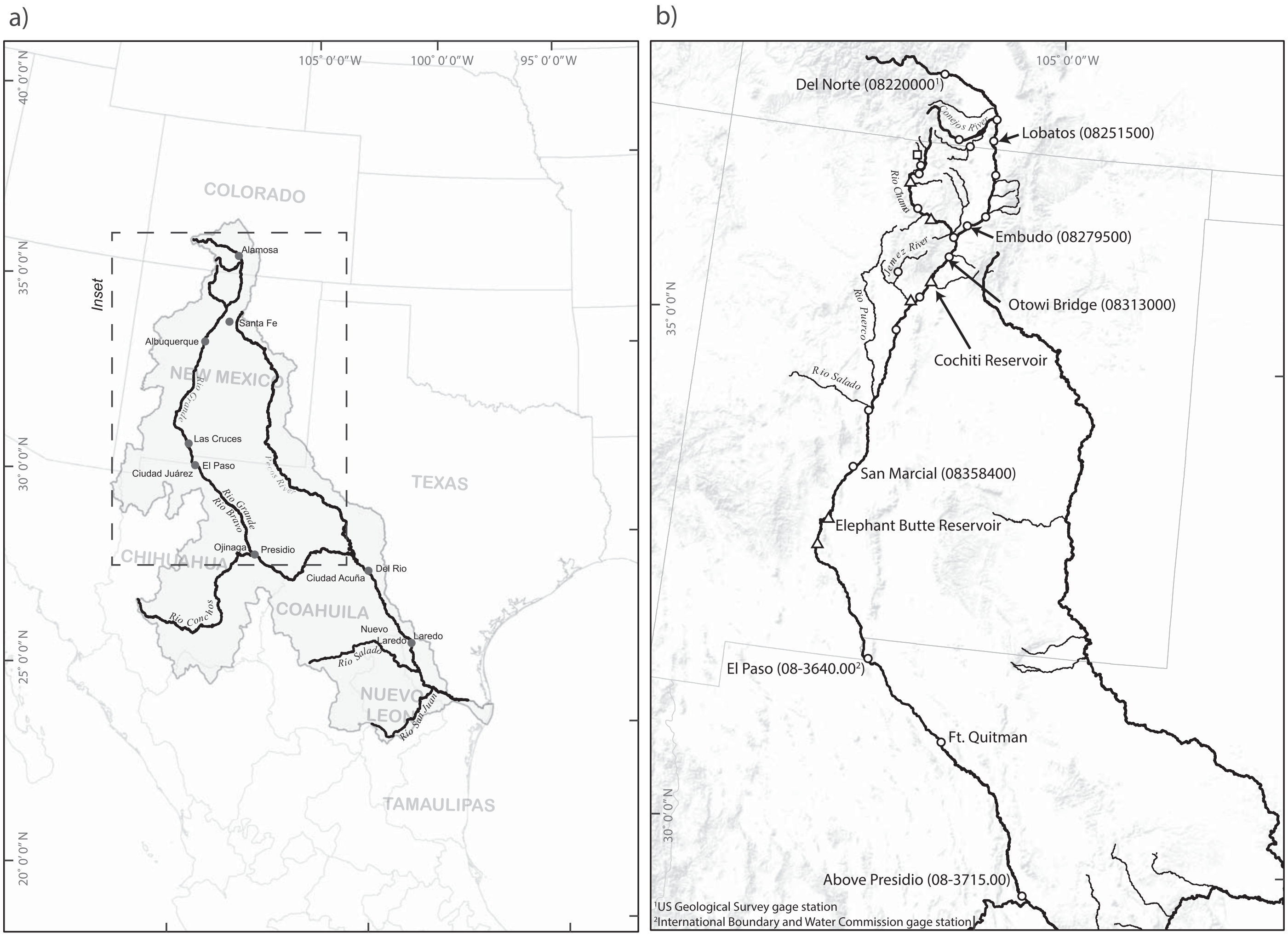

Figure 1. Maps showing (a) the Rio Grande basin with major tributaries; and (b) inset of the northern branch of the Rio Grande with streamflow gages displayed as circles, reservoirs as triangles, and the San Juan-Chama Project trans-basin diversion as a square. Primary gages with a period of record to 1900 are labeled with station identification numbers; Ft. Quitman, Elephant Butte dam, and Cochiti dam are labeled for geographic reference.

and six small transmountain diversions import a negligible amount of water (RGCC, 2015). The downstream end of the study area is the gage near Ojinaga-Presidio (International Boundary and Water Commission gage 08–3715.00).

3. Background

The Rio Grande basin has a long record of human inhabitance and water use (Scurlock, 1998). Today, the river is a water source for approximately 10 million people and is used to irrigate more than 4,000 km^2. Long-term reconstructions of annual flow, estimated using tree ring analysis (Meko & Graybill, 1995; Smith & Stockton, 1981; Woodhouse et al., 2006, 2012), indicate that headwater runoff during the past five centuries has cyclically alternated between wetter and drier conditions. Each wet or dry period typically lasts 2–5 years (Woodhouse et al., 2012). There have been three extended periods of below average streamflow that lasted as much as 50 years and were caused by low snowmelt runoff exacerbated by dry monsoon conditions (Woodhouse et al., 2013). Nevertheless, the entire northern branch was perennial prior to the mid-1800s, even during extended dry periods (Scurlock, 1998). For much of the year, the river was typically large enough to impede overland travel such that crossing was only possible at fords or by ferry (Crimmins, 1933; Kelley, 1986; Scurlock, 1998). Early navigation accounts of the river describe an annual high flow entering the Gulf of Mexico whose duration extended from April to August (Crimmins, 1933; Kelley, 1986;

Scurlock, 1998) and must have been caused by snowmelt runoff in the northern branch combined with rainfall in the lower Rio Grande, including the Rio Conchos headwaters. The northern branch in central New Mexico was estimated to be several hundred meters wide and included braided segments (Kelley, 1986; Mueller, 1975; Scurlock, 1998; Stotz, 2000).

The earliest irrigation in the Rio Grande watershed was in northern New Mexico. The total area of irrigated land in New Mexico before 1850 was less than 610 km^2 (Scurlock, 1998; Wozniak, 1998). Large-scale development of the northern branch began around 1850 to support the growing agricultural industry and more intensively after the *Desert Land Act of 1877*. The greatest expansion of irrigated lands occurred in the San Luis Valley in Colorado. By 1900, consumptive water use in the San Luis Valley exceeded all other parts of the watershed. As a result, downstream users in New Mexico, Texas, and Chihuahua experienced water shortages that led to international and interstate disputes (Mueller, 1975; Scurlock, 1998). Systematic stream gaging began in 1888 at Embudo in an effort to determine the available water supply in response to Mexico's formal complaints about the magnitude of upstream consumption. This gage is the oldest in the U.S., and the Rio Grande was the first U.S. river to be comprehensively measured (Frazier & Heckler, 1972). Between 1890 and 1900, six other gages were established on the northern branch to provide data that informed binational negotiations and culminated in the *Convention between the United States and Mexico for the Equitable Distribution of the Waters of the Rio Grande* in 1906, and the *Rio Grande Compact* signed by Colorado, New Mexico, and Texas in 1938.

Drought and declining streamflow also fostered a growing interest in water storage projects. Agricultural regions in southern New Mexico and along the international border in the Ciudad Juarez-El Paso Valley were especially susceptible to low water supply during droughts. Low flows perturbed the sediment mass balance into surplus (sensu Schmidt & Wilcock, 2008) which caused decreased channel capacity, bed aggradation, increased flood risk, and decreased irrigation efficiency (Everitt, 1993; Mueller, 1975; Scurlock, 1998; Swanson et al., 2011). Elephant Butte was the first major dam built on the northern branch and was completed in 1915 as part of the Rio Grande Project (RGP) in order to store water for distribution to U.S. and Mexican users; Caballo Reservoir, also part of the RGP, was completed in 1938 (Kelly et al., 2007). Reservoir releases were entirely diverted in the Ciudad Juarez-El Paso Valley leaving only irrigation return flow further downstream. Between 1940 and 1980, several dams were constructed by the U.S. Army Corps of Engineers (USACE) on tributaries of the northern branch to control flooding and trap sediment inputs (Kelly et al., 2007). Cochiti Dam was the centerpiece of this flood control and sediment mitigation plan whose purpose was to intentionally perturb the sediment mass balance of the northern branch in central New Mexico into deficit (Lagasse, 1981).

Today, the northern branch is single threaded, and much of the river in central New Mexico is lined by levees or is divided into floodways and conveyance channels. There is 8,270 $\times$ 10^6 m^3 of active storage capacity in three primary reservoirs on the main stem and numerous reservoirs on tributaries. Flows are augmented by diverting water from the adjacent San Juan River in northwestern New Mexico. Streamflow is allocated in compliance with the Rio Grande Compact and the 1906 Convention that necessitate extensive streamflow accounting. There are more than 30 USGS gaging stations on the northern branch and its tributaries, and the IBWC maintains gages downstream from Ciudad Juarez-El Paso. The Bureau of Reclamation and the Army Corps of Engineers report daily storage data for all reservoirs and estimate monthly evaporation. In the last decade, an increasing number of irrigation canals have been gaged to quantify conveyance losses. These data are compiled annually by the Rio Grande Compact Commission (RGCC) to monitor distribution of water in the basin and Compact compliance. The RGCC reports annual deviations of measured flow from Compact requirements for the gage at San Marcial, upstream from Elephant Butte Reservoir, and the gage at Lobatos, near the border between Colorado and New Mexico.

4. Methods

We compiled mean daily discharge data for 33 gages established before 1950, daily storage data for seven reservoirs, and the daily volume of water imported to the Rio Chama from the San Juan River via the San Juan-Chama Project (Figure 2). For the period between 1900 and 2010 at the 33 gages, less than 7% of the streamflow data were labeled as estimated in the USGS National Water Information System (NWIS) database. Using these data, we developed a model that estimated the conveyed flow from each gage to the

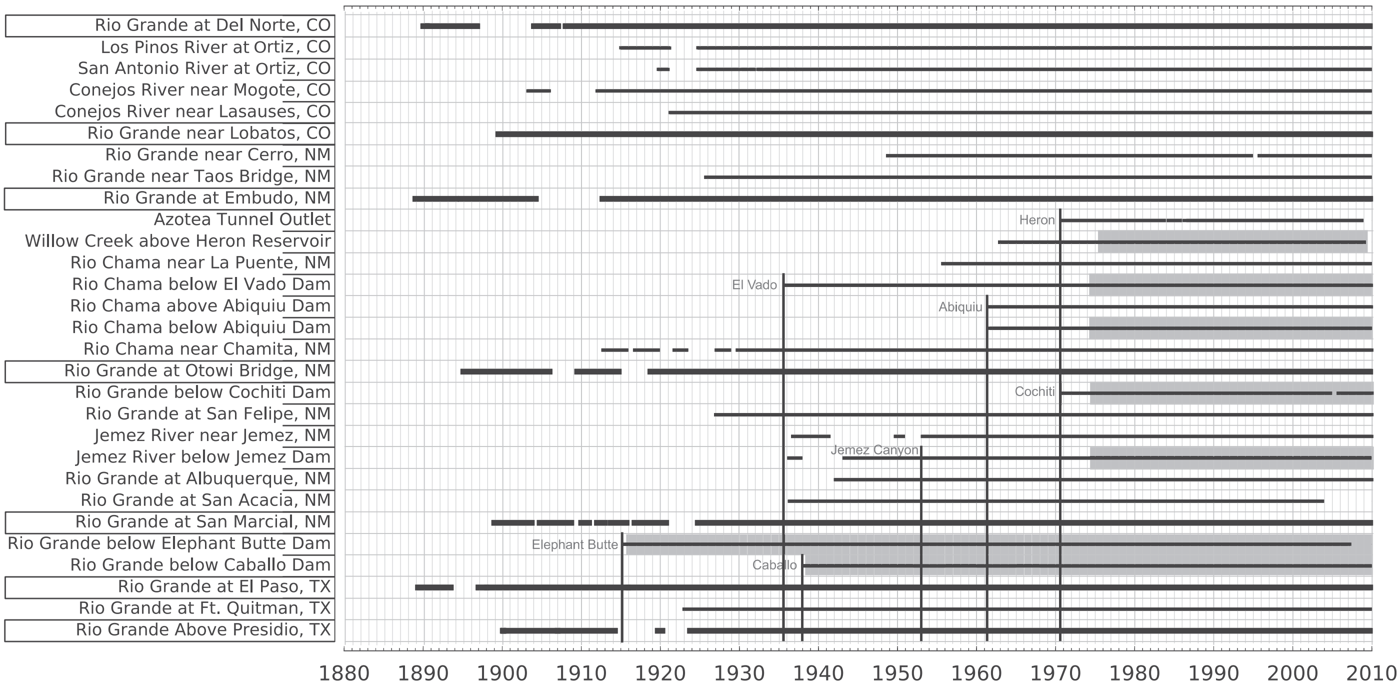

Figure 2. Diagram showing duration of gaging at each site used in mass balance model. Horizontal lines represent available data for each gage, vertical lines mark the closure of reservoirs. Shaded rectangles represent available storage data used in mass balance model. Primary long-term gages that have a record to 1900 or earlier are bolded with boxes around the labels.

next downstream gage, accounting for any gaged tributary inflows and ungaged flows. Our primary focus was to define an ecologically relevant estimate of the daily natural flow; therefore, sources of unnatural inflow that had a negligible effect on the annual hydrograph, such as waste water discharge, were ignored. The cumulative sum of all estimated natural ungaged flows on the main stem and tributaries, plus measured flow at the upstream-most gages, equaled the natural flow at the next downstream gage. We used the daily data to estimate travel times for each segment and adjusted down-stream estimates accordingly. This procedure was repeated for each couplet of gages on the main stem and on all tributaries with two or more gages. We summarized the natural flow regime by calculating the interquartile range of all flows for each day for the period of our calculations, and we calculated metrics that described the annual peak flood; including magnitude, date of peak, duration, and flood-hydrograph symmetry. To quantify changes in the flow regime, we compared the results of our model to the measured streamflow between 1900 and 2010 at seven gages distributed throughout the watershed (Figure 2). However, water development projects and management practices have caused abrupt changes in average streamflows during the 20th century. To make an accurate comparison, we defined periods of consistent streamflow using an analytical change point method and quantified the difference between measured and estimated natural flows for each period. .

4.1. Mass Balance Model

Our model employed a mass balance equation based on changes in storage for a control volume, calculated as the difference between inflows and outflows

$$\frac{dS}{dt} = I - O \quad (1)$$

where S is storage, t is time, I is inflow, and O is outflow. We defined a control volume as the river segment between each gaging station couplet and identified two types of control volumes—primary and secondary. Each type was determined by geography and period of record. The primary control volumes were bracketed by the seven long-term gages, and the secondary control volumes were a subset within the larger scale primary control volumes. Thus, the secondary control volumes occurred within the primary control volumes, and their period of record was shorter than the long-term gages. Inflows (I) in equation (1) were a function of upstream discharge (Q_U), groundwater inflow (G_I), tributary inflows (T), precipitation (P), and irrigation return flow (R). Outflows (O) were a function of downstream discharge (Q_D), groundwater outflow (G_O), evapotranspiration (E), and diversions (D). Our data set included measured, or estimated, daily values of Q_U, Q_D, T, and changes in reservoir storage. We assumed that dS/dt within a control volume was zero unless a segment included a reservoir. All other variables (G_I, G_O, P, E, R, D) were considered unknown.

We replaced I and O in equation (1) with the known input/output variables and solved for the net gain or loss in streamflow (δ), referred to as ungaged flows

$$\delta = \left(\frac{dS}{dt} + Q_D\right) - (Q_U + T) \quad (2)$$

$$\delta = f(G_T,\ P_T,\ D_T)$$

$$G_T = [G_I - G_O]$$

$$P_T = [P - E]$$

$$D_T = [R - D]$$

We used an incremental version of equation (3) for daily time steps

$$\delta_{ij} = \left(\Delta S_{ij} + Q_{Dij}\right) - \left(Q_{Uij} + T_{ij}\right) \quad (3)$$

$$i = (1,\ 2,\ 3, \ldots, 12)\ \ month$$

$$j = (1,\ 2,\ 3,\ \ldots,\ n)\ \ day\ \ of\ \ the\ \ month$$

Equation (3) was applied to each day between 1900 and 2010 to calculate δ for all primary and secondary control volumes on the main stem and tributaries.

We used the sign of the ungaged flows as an indicator of the timing and duration of consumptive losses. Where $\delta > 0$, we estimated that there was a net increase in streamflow within the control volume; where $\delta < 0$, there was a net loss of streamflow. Because specific components of the ungaged flows (e.g., return flow and diversions) were unknown, we analyzed δ_{ij} on a case-by-case basis to estimate if negative values were natural conveyance losses or human-caused consumptive loss. We defined human-caused consumptive loss as any period where δ_{ij} was consecutively negative for more than 30 days. For most gages, consecutive losses occurred between April and October, because irrigation withdrawals were the primary consumptive use. We removed the human-caused consumptive losses by assuming zero during periods of consecutive negative values

$$\delta^*_{ij} = \begin{cases} \delta_{ij} \ \ if \ \ \delta_{ij} \geq 0 \\ 0 \ \ if \ \ \delta_{ij} < 0 \end{cases} \quad (4)$$

If we did not observe any periods of consecutive negative values, δ was assumed to adequately represent the natural ungaged flows for the control volume, in which case $\delta^*_{ij} = \delta_{ij}$. To ensure that our estimated annual flood peaks occurred on the correct date at each gage, we estimated the mean travel time (t_R), in days, using representative peaks in the measured annual hydrographs for each year. Flood peaks covered a range of discharges and durations such that we assumed the mean of these values adequately captured the variability of travel times, rather than using a discharge-dependent function for travel times. We used the estimated mean travel time to shift downstream discharge data to align with upstream discharges for each control volume. These time-adjusted daily discharges were then used to calculate the time-adjusted ungaged flows $(\delta^*_{ij-t_R})$. We did not adjust for travel time in control volumes containing reservoirs, or in cases where $\delta^*_{ij} = \delta_{ij}$.

The time-adjusted natural streamflow estimate (Q^*_{ij}) for any control volume (N) was the cumulative sum of the time-adjusted ungaged flows ($\delta^*_{ij-t_R}$) for all upstream control volumes, plus an initial discharge input $\left(Q_{0ij}\right)$ and the sum of all upstream tributaries (T_{ij}). The final incremental equation for any control volume (N) was therefore

$$Q^*_{ij} = \sum_{m=1}^{N} \left(\delta_{mij-t_R}\right) + \sum_{m=1}^{N} \left(T_{m_{ij}}\right) + Q_{0ij} \quad (5)$$

To determine the natural streamflow $\left(Q_{ij}\right)$ at a gage, we shifted the time-adjusted natural streamflow by a coefficient (θ), in days, where (θ) was the cumulative sum of upstream mean travel times (t_R) for any control volume (N)

$$\theta = \sum_{m=1}^{N} \left(t_{R_m} \right) \tag{6}$$

The initial input $\left(Q_{0ij}\right)$ was the discharge measured near Del Norte.

Most gages used in our model had different periods of record that created blocks of time with different amounts of missing data. When data were missing for a short-term gage, we expanded the spatial extent of the secondary control volume to incorporate the nearest short-term gage with data. When there were missing data at a long-term gage, we assumed that flow at this gage was equal to that of the nearest upstream gage where data were available. We treated tributary inflow as ungaged input in the case of missing tributary data. Further explanation of the calculations within each primary control volume is provided in the supporting information Text S2–S7.

The number of secondary control volumes within a primary control volume affected the accuracy of our natural flow estimates. The size and number of secondary control volumes depended on the number of short-term gages in the study area and their period of record. We defined the ungaged area of each secondary control volume as the difference between total drainage area at the downstream gage and total drainage area at the upstream gage. Within each primary control volume, we calculated the average of the secondary control volumes' ungaged areas (p) for all years. In years when there were no secondary control volumes, p equaled the drainage area of the primary control volume. We used p as a metric to calculate upper and lower error bands for our natural flow estimates. The lower error band was the estimated natural flow calculated without using secondary control volumes, or when p was equal to the primary control volume drainage area. This represented the least accurate estimates using only the seven long-term gages, no reservoir data, and treating all tributaries as ungaged inflows. The upper error band was calculated using the upper 95% confidence interval of a linear regression between annual estimated natural flows and annual measured flows for years with minimum values of p. This represented the most accurate estimates using all gages and reservoir data. For additional details and results on our uncertainty calculations see supporting information Text S1; Figures S10, S13, S16, S19, S23, and S27.

When ungaged flows were consecutively negative and adjusted to equal zero, we assumed no transmission losses due to bed infiltration, bank storage, or evapotranspiration of the riparian zone. We conducted a sensitivity analysis using a variety of transmission loss magnitudes and found a negligible effect on our estimates at most gages. We used a range of transmission loss values that included riparian evapotranspiration and open water evaporation. The range of losses were estimated by Reclamation and other water supply studies for central New Mexico (SSPA, 2000; RGCC, 2015; Thomson, 2012; USBR, 2017). Analyses by Reclamation acknowledge variations in transmission losses with discharge and season. Estimates of annual transmission loss for the region are between 0.9×10^6 and 1.5×10^6 m^3/km (SSPA, 2000). Although these losses are expected to be greater in the southern part of the study area, they still represent a small proportion of the natural flow. We used constant values between 0.01% and 0.05% loss per kilometer and observed little effect on our estimates. Based on the evapotranspiration and open water evaporation rates discussed earlier, these percentages represent realistic losses. Values greater than 0.05% noticeably changed our estimates at the furthest downstream gages, but these high transmission losses would be unrealistic during conditions produced by the magnitude of estimated, natural discharges. Discussion and graphs summarizing the results of this sensitivity analysis for each primary gage are presented in the supporting information Text S1; Figures S10, S13, S16, S19, S23, and S27.

4.2. Flood Peak Characteristics

We calculated four metrics of the estimated natural streamflow and measured streamflow that described the characteristics of the annual peak flood. These metrics included the magnitude and date of the maximum mean daily discharge value for the year, the duration of the maximum annual flood, and the shape, or symmetry, of the annual flood peak. The duration of the flood was calculated as the number of consecutive days that discharge was greater than the 40th exceedance probability (e.g., the 60th percentile) of each annual, flow duration curve, because this threshold best described the start and end dates of the annual snowmelt flood. The symmetry of the maximum annual flood peak was calculated as the ratio of rate of rise (dQ_r/dt) to the recession rate (dQ_f/dt) of each annual flood. We calculated the rate of rise as the change in discharge between the start of the flood and the peak divided by the number of intervening days. The recession rate was calculated as the change in discharge between the peak and the end of the flood, divided by the number of intervening days. Values greater than 1 represented a flood that rose over a shorter duration and receded over a longer duration. If values were less than 1, then the flood receded faster than it rose. A value of 1 indicated a flood with identical rise and recession rates.

4.3. Change Point and Trend Analysis

We identified periods when measured flows were consistent using a change point detection method applied to the average annual flow data. Hereafter, we refer to the periods of consistent measured flow characteristics as individual regimes. Abrupt changes from one regime to another typically occurred during a period of 1–5 years; these transitional times are referred to as change points. For the northern branch, change points in the measured flow were mostly caused by the completion of a dam or a fundamental change in administrative water management. To identify change points, we used a Bayesian model for a single shift in the mean before and after a point (Berger, 1985; Perreault et al., 2000a; Xiong & Guo, 2004), assuming there was one change point in a time ordered data set and no change in variance before and after the change point. Given a time series with ordered observations $X=(x_1, x_2, x_3, \ldots, x_n)$, the data set was partitioned into $X_\tau=(x_1, x_2, x_3, \ldots, x_\tau)$ and $X_{\tau+1}=(x_{\tau+1}, x_{\tau+2}, x_{\tau+3}, \ldots, x_{\tau+n})$ assuming there was one unknown change point, τ. The random variables in the model were the mean of the data set before and after the change point, $\bar{Q}_a$ and $\bar{Q}_b$, respectively, and the change point τ. Under Bayes Theorem, the joint posterior distribution was calculated as

$$P(\bar{Q}_a, \bar{Q}_b, \tau|X) \propto P(X|\bar{Q}_a, \bar{Q}_b, \tau) \cdot P(\bar{Q}_a, \bar{Q}_b, \tau) \quad (7)$$

The marginal distributions of the random variables $\bar{Q}_a$, $\bar{Q}_b$, and τ were integrated from the joint posterior distribution $P(\bar{Q}_a, \bar{Q}_b, \tau|X)$ using Monte Carlo methods.

The Bayesian model only applies to normally distributed, independent data sets. Daily discharge values are typically not independent and have significant autocorrelation. Therefore, we created three independent annual data sets that were used for detecting change points, the most important of which was the mean annual discharge. The other two data sets characterized the variability of the flow in each year: the value of the lowest measured flow in each year (annual minimum flow) and the value of the maximum mean daily discharge in each year (annual maximum flood). Each of these time series had skewed distributions, including mean annual discharge. We assumed that each series fit a log-normal distribution, and we log transformed all data before applying the change point model. Visual inspection of each time series distribution confirmed that they were approximately normally distributed. When a change point was identified, we determined the significance of the difference between $\bar{Q}_a$ and $\bar{Q}_b$ using a two-sided *t* test with a null hypothesis of $\bar{Q}_a=\bar{Q}_b$. To account for multiple change points, we iteratively repeated this procedure for the periods before and after all possible change points. Any change point with a difference in means not significant at $\alpha=0.05$ was discarded. The change point model was applied using the statistical language R (R Development Core Team, 2008) with the "bcp" package for Bayesian change point analysis (Erdman & Emerson, 2007).

We used a nonparametric Mann-Kendall trend test (Kendall, 1975; Mann, 1945) to identify gradual changes in the three annual flow data sets for the entire period of record. This test is superior to similar parametric tests for skewed data, missing values, and seasonality; all of which are encountered in natural hydroclimatic time series. If a trend was detected in an annual time series with no change points, it was considered gradually changing. Annual time series with change points always had significant trends. To determine if the observed changes were influenced by abrupt change points or gradual change, we adjusted the time series by deducting the mean of the data before the change point ($\bar{Q}_a$) from each value (X_n), and the mean of the data after the change point ($\bar{Q}_b$) from each value ($X_{\tau+n}$) (Xiong & Guo, 2004). We disregarded any long-term gradual changes if there were no significant trends after adjusting for sudden change points.

Our estimated natural flows represent the streamflow conditions that would exist without human influence. Therefore, the change points associated with water development and management should not be detected in our estimates. The presence of change points or slow progressive changes in the estimated natural flow regime thus provides insight into large-scale climate drivers of streamflow. To confirm that our method truly corrects for human influences, we applied the Bayesian change point model and Mann-Kendall test to our estimated natural flows with the same assumptions and hypotheses used for the measured flows.

We distinguished both gradual and sudden changes in annual flow regime characteristics at the seven long-term gages using the Bayesian model and Mann-Kendall test together. Both the Mann-Kendall and

Bayesian change point methods are well suited for time series data and have been widely adapted for hydrologic data analysis (Berger, 1985; Crawford et al., 1983; Hirsch et al., 1982; Hirsch & Slack, 1984; Perreault et al., 2000a, 2000b; Steele et al., 1974; Xiong & Guo, 2004; Yue et al., 2002).

5. Results

5.1. 20th Century Flow Regime Changes

Using the analytical techniques described above, we identified changes in annual flow characteristics at the seven long-term gages. As described below, the annual flow characteristics at some downstream gages changed abruptly 1–4 times but never changed abruptly at some upstream gages (Table 1). The abrupt changes at downstream gages were likely the result of the complex patterns and requirements of water use, infrastructure operation, and administrative agreements. See the supporting information Figures S1–S7 and Tables S1–S14 for additional change point results, including exact *p* values for Mann-Kendall and *t* tests.

The mean annual flow of the Rio Grande near Del Norte gradually decreased throughout the 20th century at a rate of 0.05 m^3/s/yr, with no abrupt changes in the average mean annual flow. The average magnitude of the annual maximum flood flows did not change, but the average magnitude of the minimum flows abruptly decreased around 1930 from an average of 5.2 m^3/s to an average of 3.4 m^3/s.

Downstream from the San Luis Valley in northern New Mexico, measured streamflow near Lobatos and at Embudo significantly decreased after 1949, such that an early 20th century and a late 20th century flow

Table 1
Summary of the Periods of Change Identified During the 20th Century

	Annual max	Annual mean	Annual min	Median flood duration	Median flood date
Del Norte, CO					
Long-term trends (1900–2010)	*None*	−0.05 m^3/s/yr	*None*		
Early 20th century (1900–1929)	*No change*	*No change*	5.2 m^3/s		
Late 20th century (1931–2010)	*points*	*points*	3.4 m^3/s		
Lobatos, CO					
Early 20th century (1900–1948)	139 m^3/s	21 m^3/s	*No change*	74 days	5/24
Late 20th century (1950–2010)	57 m^3/s	11 m^3/s	*points*	80 days	5/21
Embudo, NM					
Early 20th century (1900–1948)	159 m^3/s	29 m^3/s	*No change*	83 days	5/22
Late 20th century (1950–2010)	87 m^3/s	21 m^3/s	*points*	93 days	5/19
Otowi Bridge, NM					
Long-term trends (1900–2010)	*None*	−0.1 m^3/s/yr	0.03 m^3/s/yr		
Early 20th century (1900–1948)	273 m^3/s	*No change*	*No change*	89 days	5/16
Late 20th century (1950–2010)	135 m^3/s	*points*	*points*	89 days	5/19
San Marcial, NM					
Early 20th century (1900–1948)	322 m^3/s	41 m^3/s		75 days	5/12
Late 20th century (1950–2010)	119 m^3/s	27 m^3/s		73 days	5/23
El Paso, TX					
Early 20th century pre-Elephant Butte (1900–1911)	280 m^3/s	35 m^3/s		77 days	5/31
Early 20th century post-Elephant Butte (1913–1943)	110 m^3/s	23 m^3/s		46 days	7/17
Late 20th century (1951–2010)	53 m^3/s			65 days[a]	7/29
Late 20th century drought (1951–1984)	*No change*	11 m^3/s			
Late 20th century high flows (1985–2010)	*points*	18 m^3/s			
Near Presidio, TX					
Early 20th century pre-Elephant Butte (1900–1911)	187 m^3/s	24 m^3/s		85 days	6/12
Early 20th century post-Elephant Butte (1913–1949)	76 m^3/s	10 m^3/s		50 days	8/11
Late 20th century drought (1951–1968)	18 m^3/s	0.8 m^3/s		35 days[a]	8/20
Late 20th century high flows (1984–2010)	35 m^3/s	9.2 m^3/s		71 days[a]	9/16

Note. All metrics are given as average values for the given time period unless labeled otherwise.
[a]These durations describe the longest observed period of consecutive flows that had an exceedance probability $\geq$ 0.4 in a given year; thus, these durations are not describing an actual flood peak but the period of the highest flows that included the largest flood spike of the year. The actual peak would be much shorter in duration.

regime can be distinguished. Mean annual flow of the late 20th century was at least 45% less than it was in the early 20th century. Average annual maximum floods in the late 20th century were 59% less than in the early part of the century near Lobatos and 45% less at Embudo. The average annual minimum flows did not change at either gage. The abrupt shift in 1949 was likely caused by a combination of the construction of Platoro Reservoir on the Conejos River and large consumptive losses in the San Luis Valley during very low flow years in the 1950s and 1960s. The depletion of streamflow between Del Norte and Lobatos was large even during the early 20th century, such that the mean annual and maximum flows near Lobatos were less than at any other gage in the watershed. The measured flows between Lobatos and Embudo typically increased due to ungaged tributary inputs.

Downstream from Embudo, the Rio Chama enters the Rio Grande and relatively natural snowmelt runoff from the southernmost portion of the San Juan Mountains augments the main stem flows. At Otowi Bridge, located downstream from the Rio Chama, there were no change points in the measured mean annual and minimum flow data sets. Mean annual flows gradually decreased at an average rate of 0.1 m^3/s/yr, and annual minimum flows gradually increased at an average rate of 0.03 m^3/s/yr during the 20th century. However, annual maximum flows decreased abruptly in 1949 by 51%, from an average of 273 m^3/s to an average of 135 m^3/s. This change point was the same time as near Lobatos and at Embudo; therefore, we distinguished the same early and late 20th century regimes as the two upstream gages.

The San Marcial gaging station was established in the 1890s and measures inflow of the Rio Grande into Elephant Butte Reservoir. This gage is downstream from large irrigated areas in central New Mexico, and the measured flows are greatly affected by consumptive losses. Here we also distinguished an early 20th century regime and a late 20th century regime, but the change point between the two periods occurred during a 5 year transition between 1945 and 1949. After 1949, average mean annual flow was 34% less than in the early 20th century, and annual maximum flows were 63% less. Annual minimum flows were frequently zero and could not be analyzed using the statistical techniques of this study.

Downstream from Elephant Butte Dam, there were more change points because of different RGP operating rules and consumptive use patterns in southern New Mexico, Texas, and Chihuahua. The measured streamflow at El Paso reflects the releases from RGP reservoirs and consumptive use of the Mesilla Valley in southern New Mexico. The observed streamflow near Presidio reflects the additional influence of consumptive use in the Ciudad Juarez-El Paso Valley. Measured streamflow decreased after 1912, decreased again in the 1940s, and recovered somewhat thereafter. We distinguished four periods in the streamflow record at El Paso and near Presidio; the early 20th century pre-Elephant Butte regime (1900–1911), early 20th century post-Elephant Butte regime (1913–1943 at El Paso; 1913–1949 near Presidio), late 20th century drought (1951–1984 at El Paso; 1951–1968 near Presidio), and the late 20th century high flow regime (1985–2010 at El Paso; 1984–2010 near Presidio). In the early 20th century, mean annual flow decreased by 34% at El Paso and 58% near Presidio after construction of Elephant Butte Dam. Annual maximum floods decreased by 61% at El Paso and 59% near Presidio. Mean annual flow decreased by an additional 52% at El Paso and 92% near Presidio during the late 20th century drought. Annual maximum flood flows during the late 20th century drought decreased by 52% at El Paso and 76% near Presidio. During the late 20th century high flow period, mean annual flows increased to approximately those of the early 20th century post-Elephant Butte regime, although the average flood flows at El Paso did not increase. Even though annual flood flows increased near Presidio, their magnitude was still approximately half the magnitude of flood flows during the early 20th century post-Elephant Butte regime. Annual minimum flows downstream from Elephant Butte were frequently zero and could not be analyzed using the statistical techniques of this study.

The changes in streamflow that occurred downstream from Elephant Butte after 1950 are due to operation of the RGP. To provide insight into the role of water management in shaping the late 20th century regime, we compared the periods of abrupt change in the flow regime at El Paso and near Presidio to the mean annual storage and total annual release of Elephant Butte Reservoir (Figure 3a). Near Presidio, the abrupt decline in streamflow around 1950 coincided with declining reservoir volumes, and the abrupt increase in streamflow occurred when storage of water increased after 1980. Reservoir releases were below average between 1949 and 1984, but were higher than annual storage (Figure 3a), indicating a change in operating rules to deplete storage in an attempt to meet downstream demands. We also compared the cumulative difference between measured annual flows and mandated annual flows reported by the RGCC at Lobatos and San Marcial (Figure 3b). A negative cumulative difference translates to a deficit of inflows to Elephant

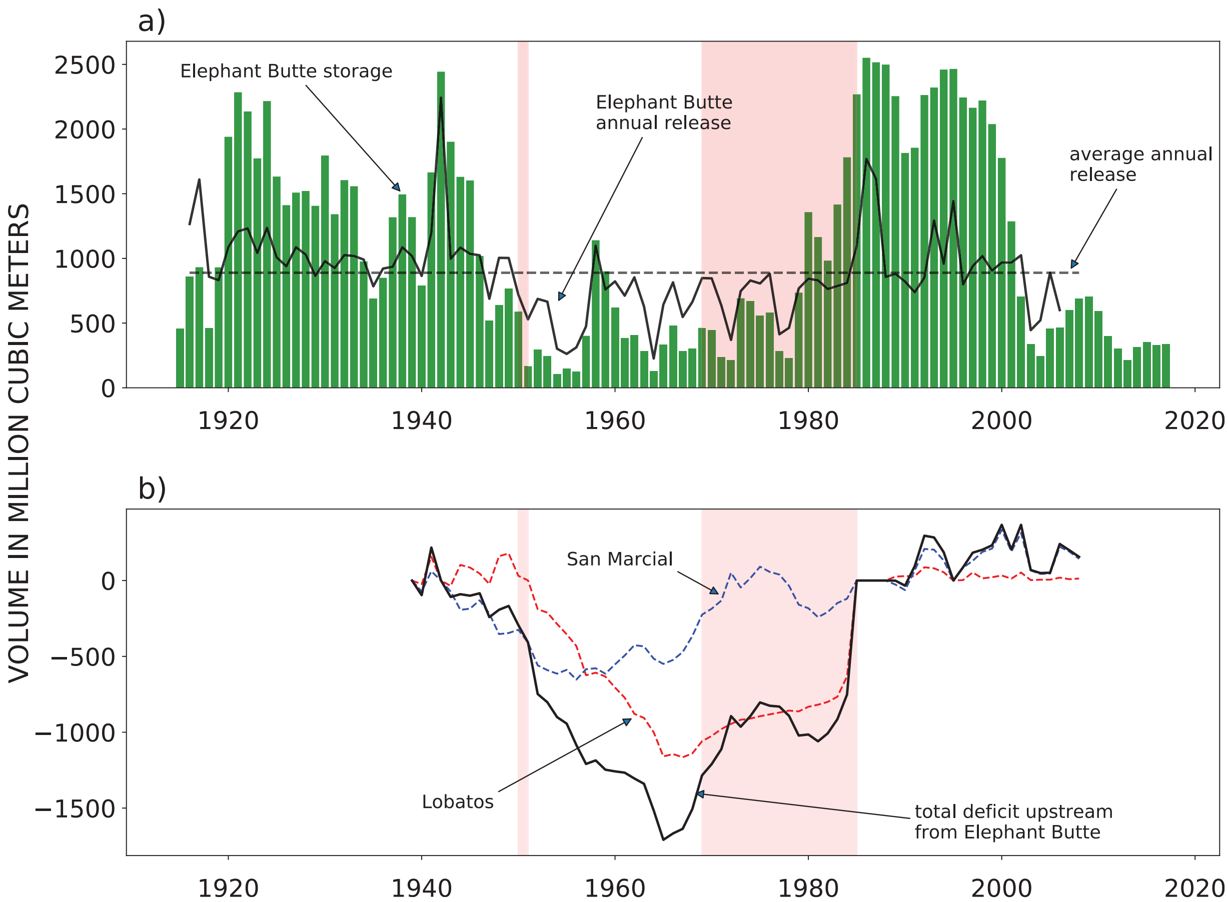

Figure 3. Graphs showing (a) mean annual storage in Elephant Butte Reservoir with annual releases since its closure; and (b) the cumulative difference between actual flow and flow required by the Rio Grande Compact at Lobatos and San Marcial. When the cumulative difference between actual and required flow is negative there is a deficit, when it is positive there is a surplus. The black line in Figure 3b shows the sum of deficits or surplus at Lobatos and San Marcial, which is the cumulative deficit or surplus in the basin upstream of Elephant Butte according to the Rio Grande Compact. The shaded red regions are the periods of flow regime change observed after 1950 near Presidio.

Butte Reservoir, when consumptive losses were continuously higher than allowed by the Rio Grande Compact, and positive numbers represent a surplus of inflows. Abrupt changes in the flow regime near Presidio coincided with transitions from surplus to deficit conditions in the 1940s and from deficit to surplus conditions in the 1980s, upstream from Elephant Butte.

5.2. Characteristics of the Measured Flow Regime

We calculated annual hydrographs describing the flow regime based on the measured data for each period defined by our change point results. These summary hydrographs depict the most frequently occurring measured flows of each period, showing the median and interquartile range of the mean daily flow for each day. We also summarized the maximum and minimum values of each day. At Lobatos, Embudo, Otowi Bridge, and San Marcial, we calculated the four metrics used to describe the annual peak flood for the early and late 20th century regimes. At El Paso and near Presidio, we calculated these metrics for the early 20th century pre-Elephant Butte regime and the late 20th century regime, for which we combined the late 20th century drought and late 20th century high flow regimes. We used data for the period between 1900 and 1914 to characterize the early 20th century pre-Elephant Butte period. Summary hydrographs, total annual flows, and flood characteristics for the seven long-term gages for all periods are provided in the supporting information Figures S8, S9, S11, S12, S14, S15, S17, S18, S20, S21, S22, S24, S25, and S26; Tables S15–S26.

The measured early 20th century regime near Lobatos, at Embudo, Otowi Bridge, and San Marcial was characterized by high flows between May and July. The spring/early summer snowmelt flood peaked in early to late May and typically lasted between 60 and 100 days. The snowmelt flood receded quickly in July, and flows between July and November were very low, except at Otowi Bridge. Base flows increased in October and remained steady from November to March. These same flow patterns existed at El Paso and near Presidio before the construction of Elephant Butte Dam. After Elephant Butte was completed, daily streamflow at El Paso was dominated by high base flows from March to October, and extreme low flows persisted year-round with occasional small, short duration flood peaks near Presidio. During the late 20th century, the magnitude of daily streamflows decreased significantly at each gage.

5.3. Characteristics of the Natural Flow Regime

We estimated the natural flow at each gage for every day of each year and summarized the typical characteristics of the natural flow regime for the same periods that we defined for the measured flows. The estimated natural flow regime of the Rio Grande near Lobatos and at Embudo was dominated by a long duration snowmelt flood between April and July. Typically, this flood peaked in May or early June and lasted between 100 and 150 days; the flood receded slowly relative to its rise. Estimated natural flows between August and September were variable and included occasional short duration floods caused by summer and fall rain. Base flows were less variable from October to March. At Otowi Bridge, San Marcial, El Paso, and near Presidio, the annual snowmelt flood was larger in magnitude, and there was a greater number of short duration, summer/fall floods. Recession of the estimated natural annual spring/early summer flood was slower, prolonged by numerous short duration floods between August and October. A comparison of the median and interquartile range for the estimated natural flows and late 20th century measured flows near Lobatos, at Otowi Bridge, San Marcial, and near Presidio are shown in Figure 4.

Comparison of the measured flows and the estimated natural flows demonstrates that the modern flow regime of the entire northern branch of the Rio Grande has been extensively perturbed. The magnitude of these changes is obvious when comparing total annual flows (Figure 5). Approximately 68% of the natural flow is consumed between Del Norte and Lobatos in the San Luis Valley. There is some recovery of the natural flows between Lobatos and Otowi Bridge such that the measured total annual flow is 42% less than the

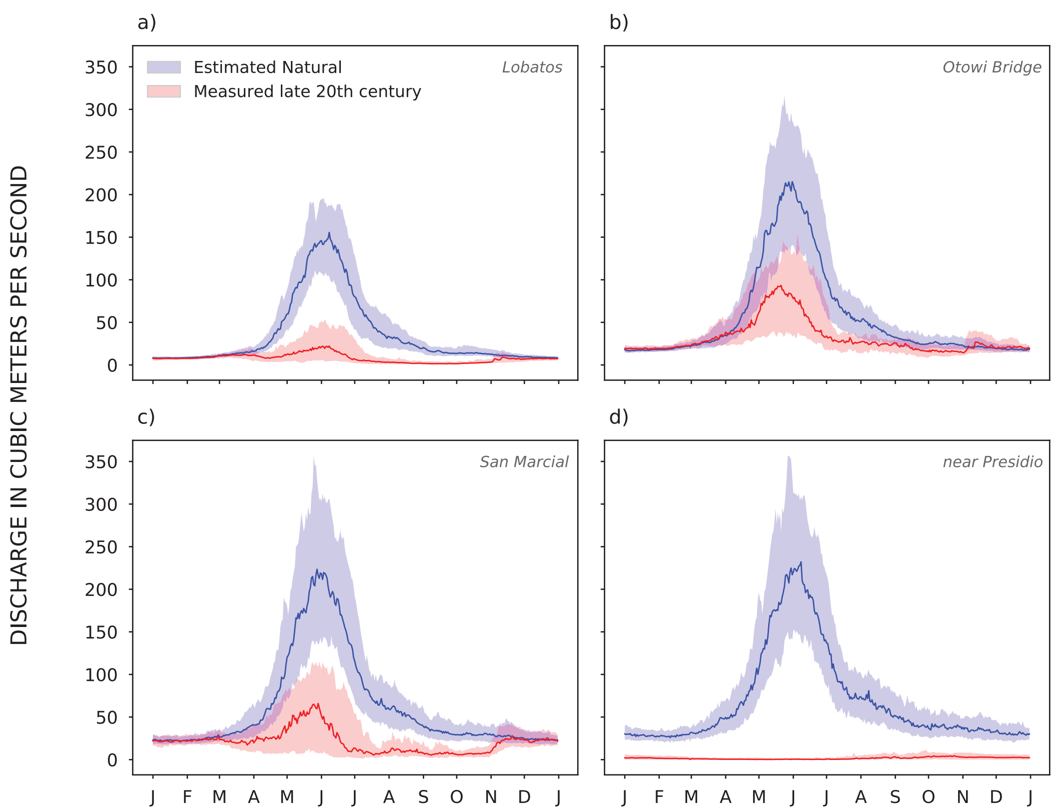

Figure 4. Graphs showing summary annual hydrographs for estimated natural flows in blue and measured late 20th century flows at (a) Lobatos, (b) Otowi Bridge, (c) San Marcial, and (d) near Presidio. The bold line is shows the median ($Q_{0.5}$) daily discharges and the shaded region is the interquartile range of daily discharges ($Q_{0.25}$ to $Q_{0.75}$).

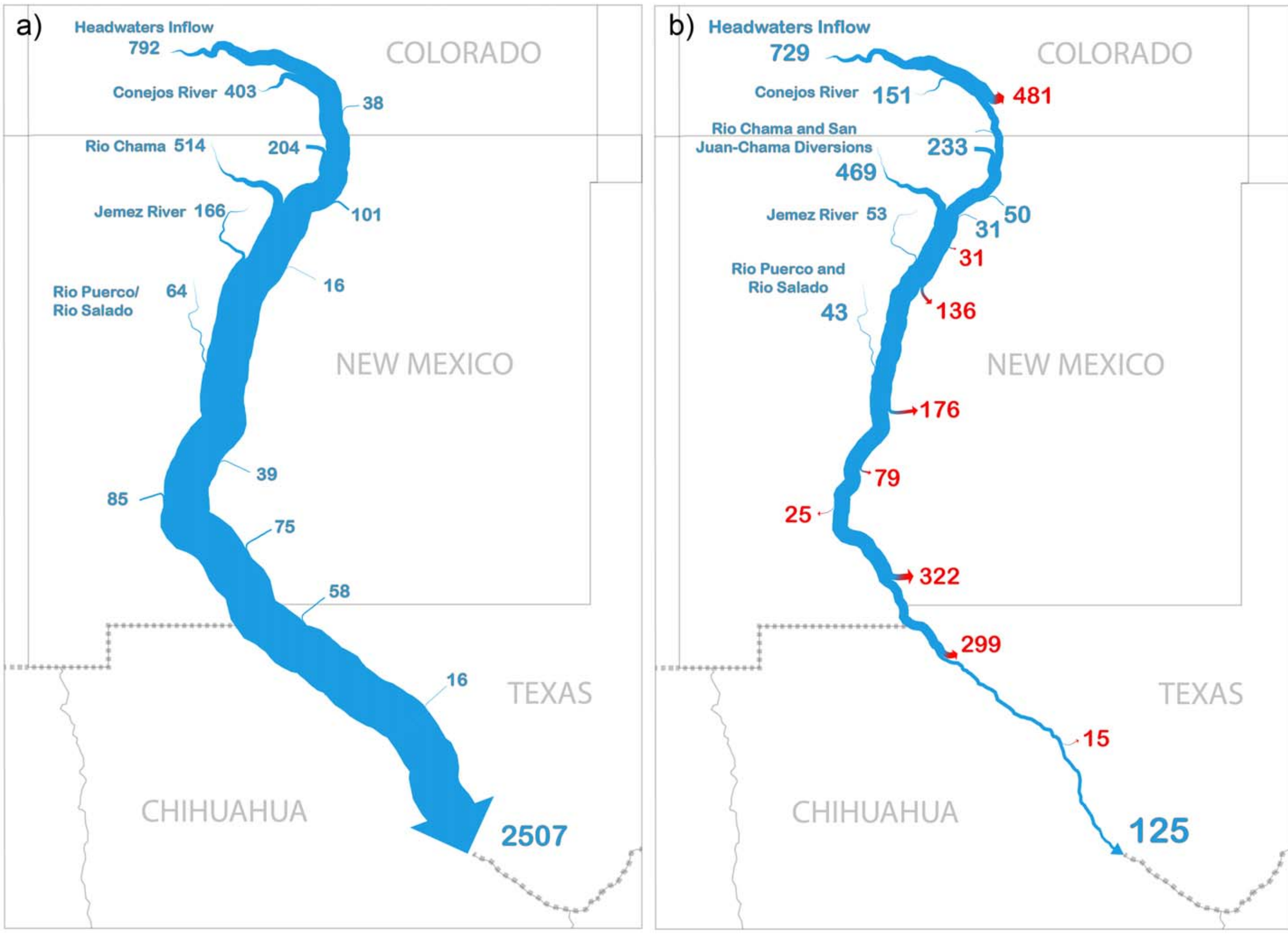

Figure 5. Scaled line diagram showing average annual inflows (blue lines) and consumptive losses (red arrows) of the northern branch in million cubic meters for (a) estimated natural conditions between 1900 and 2010; and (b) modern conditions during the latter half of the 20th century (1950–2010).

estimated natural flows at Otowi Bridge. Consumptive losses continue downstream at San Marcial and the flow regime at El Paso and near Presidio is considerably reduced due to irrigation demands and RGP operations. Today, measured streamflow near Presidio is 95% less than the estimated natural flow.

Consumptive losses were less, but still significant, in the early 20th century; total annual measured flow near Lobatos was 53% less than the estimated natural flow and only 22% less than the estimated natural flow at Otowi Bridge. Total consumptive use in the downstream part of the watershed was also long-standing. Even before Elephant Butte Dam was completed, the total annual flow near Presidio was 57% less than the estimated natural flow.

The magnitude, timing, and duration of measured floods decreased during the 20th century (Figure 6). The greatest decreases occurred during the late 20th century. The magnitude of floods today was more than 60% less than the magnitude of the estimated natural floods. The duration of today's floods was typically 20% shorter, and flood timing was more variable with the annual peak occurring later in the year. Near Lobatos, the magnitude of the measured 2 year flood was approximately 78% less than the estimated natural 2 year flood, was 33% shorter in duration, and receded much faster. More natural floods still occur at Otowi Bridge, but the magnitude of frequent, common floods was 60% less than the floods we estimated for natural conditions. Floods have been nearly eliminated at El Paso and near Presidio. Here high flows are now rare, have very short duration, and occur months later than the estimated natural floods. These changes to the natural flood regime were already underway during the early 20th century, but the magnitude of the perturbation was much less. Before the completion of Elephant Butte, there were

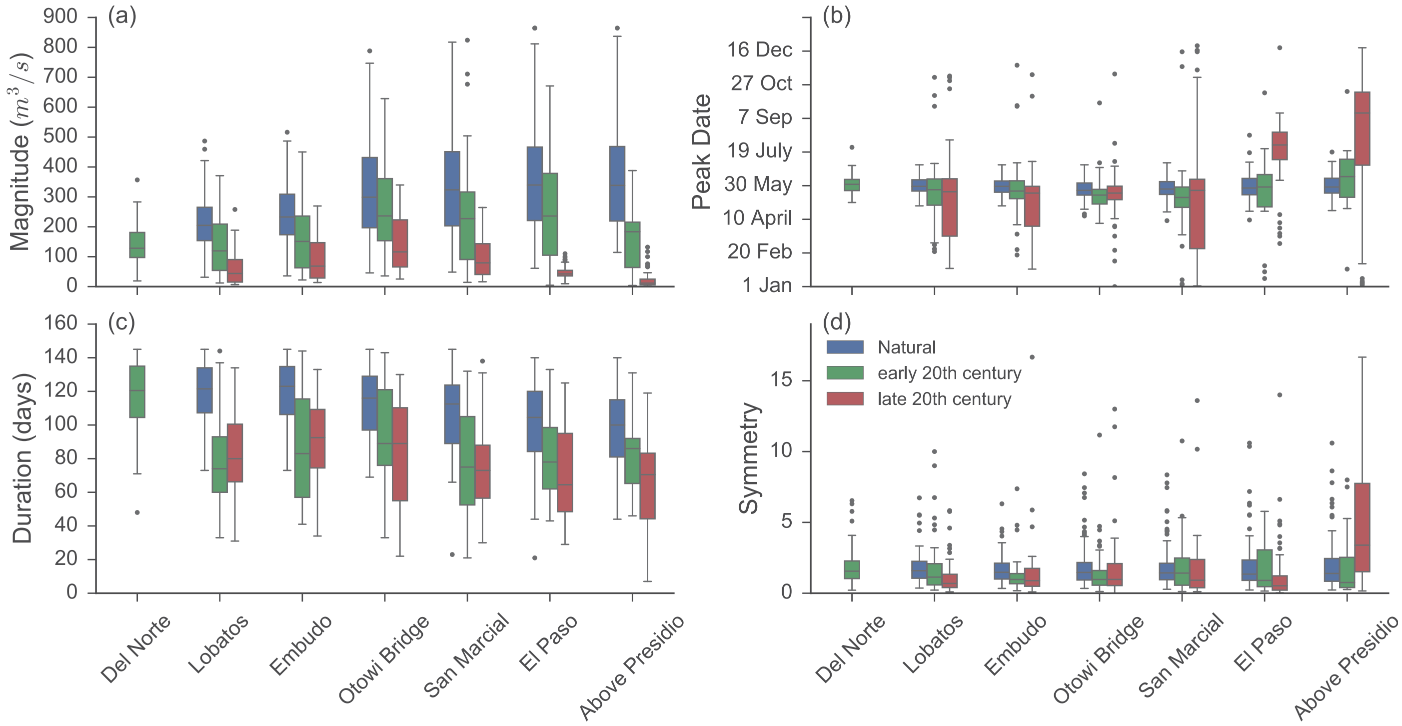

Figure 6. Boxplots of estimated natural and measured flood characteristics including (a) magnitude of the annual flood peak; (b) timing of the annual flood peak; (c) duration of the annual flood in days; and (d) the symmetry of the annual flood peak, or the ratio of rate of rise to rate of fall. Boxplot structure is standard with the interquartile range within the shaded region, the median is the line inside the shaded region, and whiskers are extreme values excluding outliers, which are shown as dots (calculated as 1.5 $\times$ IQR). Blue boxplots represent estimated, natural conditions; green boxplots represent measured conditions during the early 20th century; and red boxplots represent measured late 20th century conditions that exist today.

distinguishable annual flood peaks at El Paso and near Presidio. Near Presidio, the magnitude of the measured 2 year flood was 42% less than the estimated natural 2 year flood. Overall, the small floods of the estimated natural flow regime are now common floods, common floods of the estimated natural flow regime are now 20–50 year floods, and today, no floods occur during drought years.

Measured base flows also decreased compared to estimated natural flows. Between August and March, base flows were much lower than those of the estimated natural flow regime. During the late 20th century, the highest measured base flows were within the interquartile range of the estimated natural base flows; thus, today's rare high base flows were once the common base flows estimated in the natural flow regime. Measured base flows were the least perturbed at Otowi Bridge and most perturbed near Presidio. Today's base flows at San Marcial, El Paso, and near Presidio are zero occasionally during summer months.

We applied the same analytical change point method to the estimated natural mean annual flow, annual maximum flow, and annual minimum flow, and found no strong evidence for large-scale shifts in natural runoff. We identified one abrupt change in the time series of mean annual flow at San Marcial. Elsewhere, the estimated natural flows have slowly decreased, with no abrupt changes during the 20th century. This is the case near Lobatos, at Embudo, Otowi Bridge, El Paso, and near Presidio. Mean annual flows changed abruptly around 1978 at San Marcial, which was the time of the highest estimated natural flows of the 20th century. There were statistically significant, gradual decreases in mean annual, annual maximum, and annual minimum flows near Lobatos, and in mean annual and annual minimum flows at Embudo. We estimate that the natural base flows gradually increased downstream from Otowi Bridge throughout the 20th century.

5.4. Mass Balance Validation

Other mass balance methods used to calculate natural flows rely on uncertain estimates of evaporation, conveyance losses, and other processes. Our method eliminated uncertainty involved with estimating the many unknown parameters of a water budget, because we primarily relied on measured streamflow data and estimates of reservoir storage. Thus, the only measurement uncertainty in our method is associated with the accuracy of discharge measurements. In cases where data were missing, we made no attempt to interpolate or extrapolate data; instead, we extendeded the segment to the next upstream gage. This strategy decreased the accuracy of ungaged flow calculations and explicitly underestimated the natural streamflow of those days. Our method likely overestimated flows in regions with significant irrigation, because we assumed that inflow equals outflow during the majority of the irrigation season, thus eliminating any natural depletions for part of the year.

We compared our results with other mass balance and flood magnitude estimates for the region to determine how our assumptions affected the model. There are several water supply studies, or data sets, for the northern branch that can be used to estimate natural flows or inflows. We acquired provisional, unregulated daily streamflow estimates from the USACE Albuquerque District for long-term gages between Del Norte and El Paso, based on the Upper Rio Grande Water Operations Model (URGWOM). URGWOM is a comprehensive accounting model developed for the northern branch that uses traditional water budget methods (USACE, 2013a, 2013b). The unregulated URGWOM flows remove most human influences by accounting for diversions, other human inputs, and routing flow through reservoirs. However, output of the URGWOM is not considered a true estimate of natural conditions, because the output does not account for natural depletions, groundwater influence, or other difficult-to-measure hydrologic interactions (P. E. Marc Sidlow, U.S. Army Corps of Engineers Albuquerque District, personal communication, 13 December 2017). The Natural Resources Conservation Service (NRCS) also reports monthly natural streamflow estimates for gages between Del Norte and San Marcial (https://wcc.sc.egov.usda.gov/reportGenerator/). There is little information on the NRCS methodology, but the data are described as being adjusted for human regulation and use upstream from each gage (NRCS, 2011). Several other local water budgets have been calculated for the river segment between Otowi Bridge and San Marcial (MRGWA, 1999; SSPA, 2000, 2004), but these water supply studies do not account for upstream regulation or depletions. Downstream from El Paso, the IBWC estimated annual average natural yield that was used to inform treaty negotiations for equitable distribution of water. Natural, unregulated peak flows have been estimated at eight gages on the northern branch using a linear regression modeling approach that relied on correlations among reservoir storage, peak inflows, and peak outflows to adjust downstream discharges (Bullard & Lane, 1993).

We used three common metrics to evaluate the agreement between our estimated daily natural flows and the URGWOM unregulated daily flows: Nash-Sutcliffe Efficiency (NSE), percentage bias (PBIAS), and the ratio between the RMSE of our estimates and the standard deviation of the URGWOM flows (Moriasi et al., 2007). NSE measures how well the plot of simulated versus observed data fits the 1:1 line, based on the variance of the residuals and the variance of the data. NSE values range from $-\infty$ to 1.0 with values between 0.0 and 1.0 considered acceptable performance. PBIAS measures the tendency of simulated data to be greater than or less than observations as a percentage; values close to 0.0 are considered optimal. A positive PBIAS is indicative of overestimation while a negative PBIAS is indicative of underestimation. A ratio of RMSE and standard deviation of the observed data $\leq$0.5 is considered optimal. Our estimated natural flows at Lobatos had the best agreement with the URGWOM unregulated flows (Figure 7a). The ratio of the RMSE and the standard deviation of URGWOM values was 0.32, and the NSE coefficient was 0.9. Our estimates tended to be higher than URGWOM values with a PBIAS = 13.5. The agreement between our estimates and the URGWOM unregulated flows at Otowi Bridge were excellent (Figure 7b). Here the ratio of the RMSE and the URGWOM standard deviation was 0.47, the NSE coefficient was 0.78, and our estimates tended to be higher with a PBIAS of 25. At San Marcial, the ratio of the RMSE and the URGWOM standard deviation was 0.91, the NSE coefficient was 0.17, and our estimates were higher with a PBIAS of 91 (Figure 7c). We did not compute any metrics of fit with NRCS flows, because they did not differ substantially from measured flows at each gage (Figure 7). We cannot conclude that the NRCS estimates are comparable to our estimates without additional information on the NRCS flow adjustment methods. There is a noticeable difference between URGWOM data and NRCS estimates that suggests either a difference in methods or of input data. .

Downstream from Otowi Bridge, tributary inflows, and precipitation are more variable than in the northernmost part of the watershed. The agreement between our estimated natural flows and URGWOM unregulated flow estimates at gages downstream from Otowi Bridge were unsatisfactory. The URGWOM estimates do not consider ungaged inflows downstream of Otowi Bridge, which leads to underestimation of natural flows for portions of the year (P. E. Marc Sidlow, U.S. Army Corps of Engineers Albuquerque District, personal communication, 13 December 2017). However, the difference between our estimates and those of

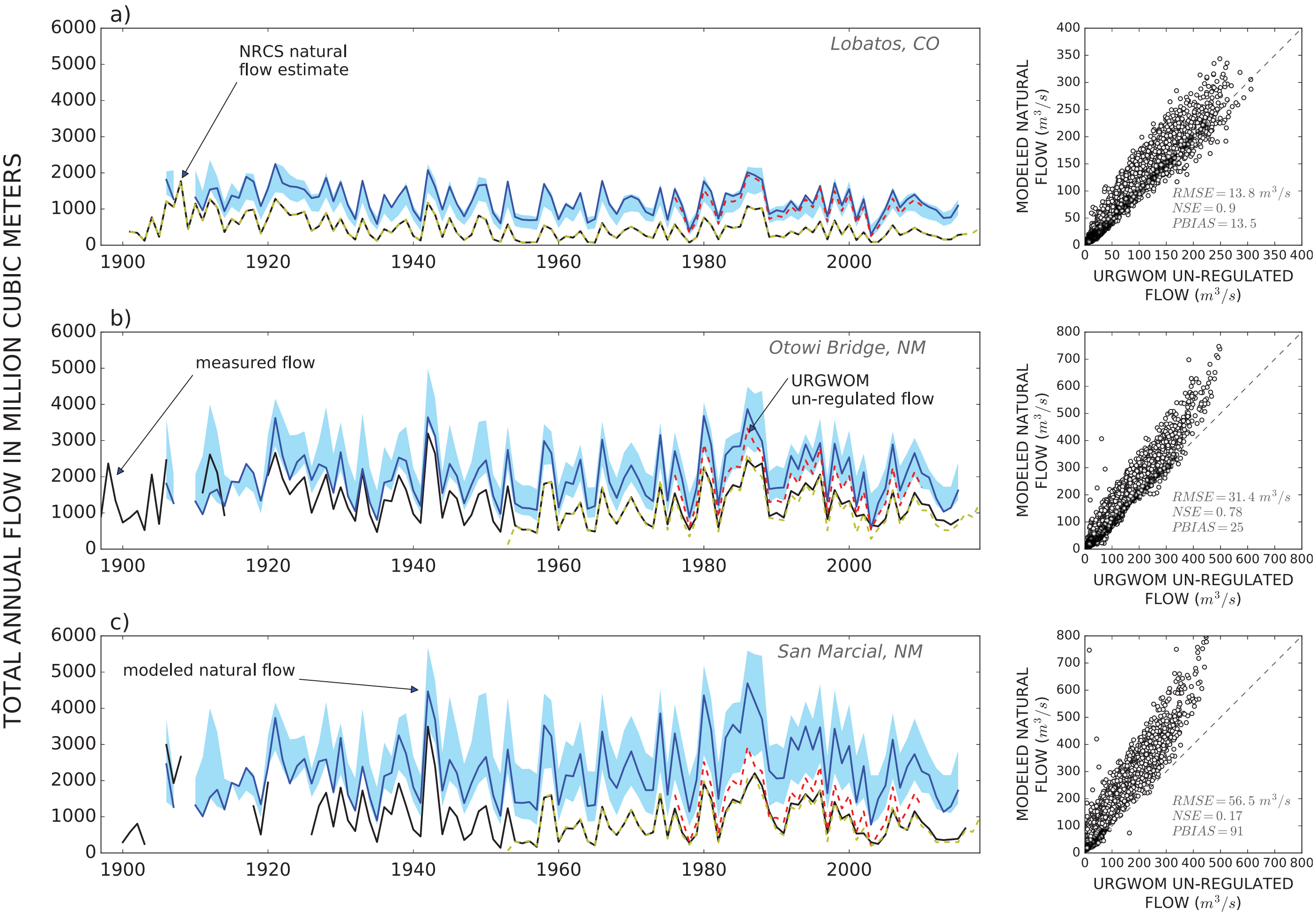

Figure 7. Graphs showing the estimated natural total annual flow in blue with shaded error band, measured total annual flow in black, URGWOM estimated unregulated total annual flow in dashed red, and NRCS adjusted total annual flow in dashed yellow for (a) Lobatos; (b) Otowi Bridge; and (c) San Marcial. To the right of each time series is an *x-y* comparison plot of our estimated daily natural flows on the *y* axis and URGWOM unregulated flows on the *x* axis at that gage, the dashed line represents the 1:1 line of the two data sets.

URGWOM also likely arises due to the fact that our method underestimates the natural depletions for this region, which are substantial in the downstream part of the watershed. A probabilistic water budget for the region between Otowi Bridge and San Marcial calculated a natural inflow of approximately 489 $\times$ 10^6 m^3 with natural depletions from riparian evapotranspiration and open water evaporation of approximately 382 $\times$ 10^6 m^3. Accounting for these losses, this equates to a total increase in flow of 107 $\times$ 10^6 m^3 with a standard deviation of 208 $\times$ 10^6 m^3 (SSPA 2004). Our natural flow method estimates an increase of flow between 13 and 536 $\times$ 10^6 m^3 with a central value of 285 $\times$ 10^6 m^3. The error between the two estimates is less than one standard deviation of the SSPA water supply study; however, our error band is large enough to encompass the variability of estimated natural depletions.

The IBWC estimated that the annual average, natural supply of the Rio Grande delivered to the Gulf of Mexico was between 10 and 12 km^3 (Enriquez-Coyro, 1976). The estimated annual supply between Ft. Quitman and the Gulf of Mexico was approximately 8.9 km^3. The difference between annual supply of the entire river and annual runoff downstream from Ft. Quitman provides an estimated range of average annual natural runoff for the northern branch of 1.1–3.1 km^3. Our method yields an estimate of the average annual natural runoff during the 20th century between 1.4 and 3.7 km^3 with a central value of approximately 2.51 km^3, which is within the range of the IBWC estimates.

Bullard and Lane (1993) estimated instantaneous flood peak magnitudes at gages between Embudo and El Paso for unregulated flow conditions. We estimated peak flood magnitudes based on maximum mean daily flows. Bullard and Lane (1993) did not incorporate irrigation losses or the effects of flow regulation from small reservoirs in Colorado. Based on these exclusions, despite their estimation of instantaneous data, we expected Bullard and Lane's (1993) estimates to be lower than ours. We did not compute standard metrics of fit for this comparison, because we compared four different recurrence intervals with one observation each, for the three gages. Visually the fit was very close to the 1:1 line, suggesting that our method produced reasonable flood magnitudes when compared to a very different statistical approach for reconstructing peak discharges. Our estimates tended to be greater than those of Bullard and Lane (1993). Our estimates of the magnitude of the 2 year recurrence flood tended to be slightly higher for all three locations (Figure 8). We found better agreement with our estimates of the magnitude of the 5 and 10 year recurrence floods. Our estimated 50 year recurrence flood magnitudes had the worst fit, which tended to be much lower than those of Bullard and Lane (1993) except at Otowi Bridge.

6. Discussion

6.1. Limitations and Additional Uncertainties

Our model is based on several assumptions. These assumptions were inspired by the intended purpose of our method as well as the nature of data for the Rio Grande. The treatment of missing data and our method of identifying human consumptive losses affected model accuracy. We ignored gages when data were missing and adjusted the control volume to the next upstream gage, because such a strategy had minimal effect on our estimates in a river with such abundant data. Additionally, we depict the daily natural flow regime using the interquartile range of daily flows for all years, which minimizes the significance of missing data or estimation uncertainty resulting from our assumptions.

The uncertainty associated with our method is dependent on the number of gages used to estimate ungaged flows and is represented by our calculated error bands. This uncertainty mainly affects estimated magnitudes and does not affect estimates of other components of the flow regime such as timing, duration, and frequency of flow events. An alternative approach would be to keep the number of control volumes fixed and estimate the missing data using techniques such as linear regression. For certain rivers, this might be a better approach, but the uncertainty from whichever method is used to fill missing data would accumulate in our model. Most methods for filling missing data also do not accurately maintain the timing, duration, and frequency of flow events except in basins where flows are spatially correlated. The ungaged flows term in our model contains information on natural inflows, diversions, returns, evapotranspiration, open water evaporation, and ground-surface water interactions. Our method of identifying human-caused depletions has the greatest effect on our results, because it does not accurately capture all natural consumptive losses. We assume zero depletions for periods when ungaged flows are negative for 30 or more consecutive days, such that we assumed the outflow of a segment equals inflow. This threshold for adjusting flows undoubtedly overestimated flows where natural depletions are high and underestimated where natural inflows are greater. This is the major limitation of the model presented in this study; however, we sought to present our method in its simplest form. One alternative would be to adjust negative ungaged flows by drainage area or apply a discharge-dependent function for transmission losses. Ultimately, the method used to identify and adjust ungaged flows for depletions is user-defined to meet specific objectives.

The specific objective of applying our mass balance method to the Rio Grande was to quantify the 20th century changes in streamflow and provide an ecologically relevant quantification of the natural flow regime. Because we were focused on all components of the flow regime, we made assumptions that placed less importance on volume of flow. Thus, using our method for water supply studies would require a more accurate representation of flow volume. For example, we excluded wastewater discharge, transbasin diversions upstream of Del Norte, and inflows from the Closed Basin Project located at the northern end of the San Luis Valley. Although wastewater inputs can be large relative to measured flows in New Mexico and in Ciudad Juarez-El Paso, these inputs are less than 3% of the estimated natural flow volume. Also, because these inflows are relatively constant through time, they have a very small effect on daily streamflow magnitudes. This is similarly true for the minor trans-basin inflows upstream from Del Norte. The Closed Basin Project in Colorado imports water from a topographically isolated region that is within the Rio Grande watershed. This project has only been operated since 2000 with an average annual inflow of 20×10^6 m^3, which is 3% of

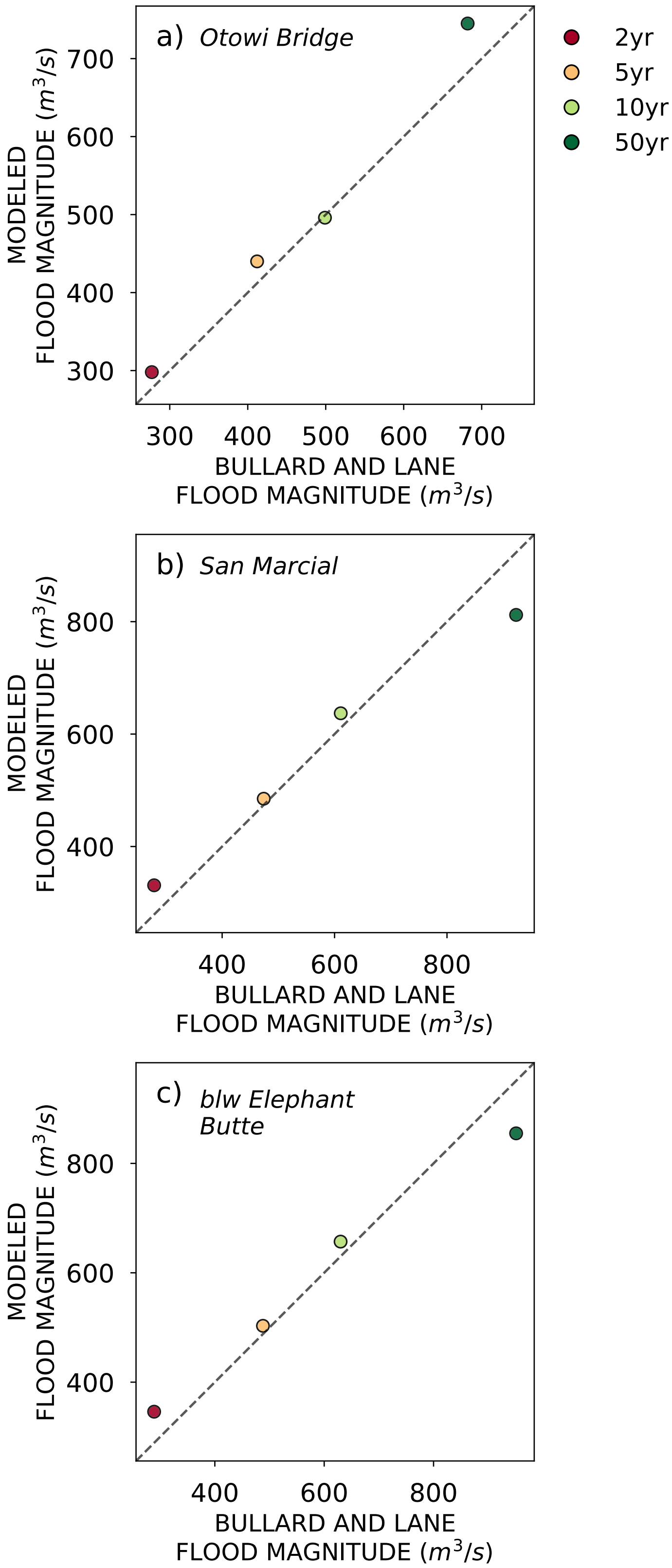

Figure 8. X-Y plots showing the comparison of estimated natural peak flood magnitudes with estimated unregulated peak flood magnitudes calculated by Bullard and Lane (1993) for (a) Otowi Bridge; (b) San Marcial; and (c) below Elephant Butte Dam. Modeled, natural flood magnitudes for the 2, 5, 10, and 50 year recurrence interval (colored points), using mean daily discharge, are on the *y* axis. Bullard and Lane estimates using annual peak discharge data are on the *x* axis. The dotted line shows the 1:1 line which represents an exact fit. Points above this line are overestimated by our model, while points below are underestimated.

the estimated natural flow volume at Lobatos. Despite the treatment of missing data and various assumptions, our method provides comparable results with more comprehensive models that use traditional mass balance methods, and estimate all the terms of a water budget.

There is also an additional component of unquantifiable uncertainty associated with natural versus contemporary channel conditions. We acknowledge that our estimates are a representation of current conditions including riparian vegetation and channel modifications that effect our estimated travel times and transmission losses. The channel morphology and riparian vegetation that would exist under natural conditions is unknown, and further research would be needed to describe the effects of these changes on daily natural flows. However, this assumption may not apply to river basins with less channel modifications.

6.2. Effects of Development on the Modern Flow Regime of the Rio Grande

The natural flow of the northern branch gradually decreased during the 20th century, likely driven by large-scale changes in climate or land use. We observed only one abrupt shift in the natural flow regime, which coincided with the onset of above average mean annual flows in the late 20th century. In contrast, actual flows decreased abruptly, and these coincided with changes in infrastructure and reservoir operations. The existence of many more change points in the time series of measured flows demonstrates that the magnitude and spatial pattern of consumptive losses from irrigation exerts a significant influence on the flow regime. Also, main stem and tributary reservoirs exert a secondary control on the flow regime by providing flood control and steady base flows that facilitate irrigation diversions. At El Paso and near Presidio, the influence of irrigation and reservoirs increases, as demonstrated by the greater number of change points relative to the upstream portion of the watershed. Here, the flow regime is completely regulated by releases from Elephant Butte and Caballo Reservoirs to meet consumptive demands of the RGP and obligations of the 1906 Convention. Our results suggest that the effect of irrigation and infrastructure operations in this region is to amplify climate fluctuations.

The operation of RGP reservoirs is influenced by upstream consumptive losses. The late 20th century drought and late 20th century high flow period did not exist upstream from Elephant Butte; thus, these periods were created by management actions. Although annual runoff from the northern branch headwaters was below average in the 1950s and above average in the 1980s, there were no change points in response to these dry and wet cycles upstream from Elephant Butte. The northern branch of the Rio Grande has a highly variable natural flow regime. The river has periods of drought in which available water supply does not meet the full consumptive demand. The Rio Grande Compact was designed to account for year-to-year variability in supply by mandating flows near Lobatos and at San Marcial based on flows measured near Del Norte and at Otowi Bridge, respectively. The mandated flows near Lobatos account for consumptive use downstream, because central New Mexico's water demands, combined with required inflows to Elephant Butte Reservoir, are greater than the natural runoff between Lobatos and San Marcial. Although the operating rules for Elephant Butte are not defined by the Compact, noncompliance with mandated flows at upstream gages can create a deficit of inflows to Elephant Butte Reservoir that in turn affects releases further downstream, which was the case during the late 20th century drought period. Thus, the combination of RGP operations and noncompliance with the Rio Grande Compact could make low flow conditions more severe downstream from Elephant Butte. Conversely, when substantial amounts of inflow reach Elephant Butte, reservoir releases are much larger because of surplus water. This was the case in the 1980s and resulted in the only observed floods at El Paso and near Presidio since 1945 (Everitt, 1993).

6.3. Geomorphic Implications of Natural Flows

At the onset of gaging, the decreasing streamflow of the northern branch was already causing an imbalance between flow and sediment supply that resulted in channel aggradation in New Mexico and Ciudad Juarez-El Paso (Mueller, 1975; Scurlock, 1998; Stotz, 2000). The construction of dams and conveyance infrastructure disrupted the widespread pattern of aggradation by creating segments of sediment deficit downstream from Cochiti Dam (Lagasse, 1981; Schmidt & Wilcock, 2008) and Elephant Butte Dam (Ainsworth & Brown, 1933; Schmidt & Wilcock, 2008; Stevens, 1938). The sediment deficit downstream from each dam transitioned to sediment surplus farther downstream where local sediment inputs increased, such that channel narrowing and aggradation continued in some segments of the channel network (Everitt, 1993; Swanson et al., 2011). The spatial pattern of channel aggradation and narrowing demonstrates that the

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natural sediment supply of the northern branch is large. Our estimated natural flow regime provides one estimate of flows needed to transport the natural sediment supply to the sea.

Relatively little is understood about the natural hydrologic or geomorphic connectivity between the northern branch and the lower Rio Grande. Downstream from the Rio Conchos, the lower Rio Grande has been perturbed into sediment surplus, because the flow regime has been reduced much more than the sediment supply (Dean et al., 2011; Dean & Schmidt, 2011). In this study, we estimated that the total annual flow of the northern branch near Presidio has been reduced by approximately 95%, which greatly reduced the sediment transport capacity. However, discussions about the changing sediment dynamics of the lower Rio Grande do not include estimates of the sediment supply, nor the additional transport capacity, that was delivered by the undisturbed snow melt flood.

6.4. Implications for Estimating Environmental Flows

Native ecosystems that evolved under our estimated, natural flow regime have experienced protracted degradation. Ecosystems today that evolved with the natural flow regime may not be recoverable unless those natural life history cues are restored (Gore & Shields, 1995). Today, environmental conditions and the actual flow regime are less desirable for native species on the northern branch. This is apparent with the loss of once flourishing endemic organisms (Alò & Turner, 2005; Bestgen & Platania, 1991; Cowley, 2006; Cowley et al., 2006; Edwards & Contreras-Balderas, 1991; Howe & Knopf, 1991; Medley, 2009; Medley & Shirey, 2013; Shirey et al., 2008). The predisturbance aquatic ecological structure of the lower Rio Grande is less well known, but the amount of threatened or endangered species (CEC, 2014) suggests a similar level of

Table 2
Comparison of Common Environmental Flow Metrics for San Marcial

Metric	Environmental flows using estimated natural (1900–2010)	Environmental flows using measured flow (1900–1944)	Environmental flows using measured flow (1950–2010)
Magnitude			
Base flows			
Mean annual Flow (m^3/s)	71	41	28
Median annual 7 day minimum (m^3/s)	17	0	1.4
Low flow-base flow ratio	0.26	0	0.05
Floods			
Median annual daily maximum (m^3/s)	331	268	112
High flow-base flow ratio	4.7	6.5	4
Duration			
Base flows			
Median extreme low flow duration (days)	2.5	10	7
Floods			
Flood rate of rise (% of flood magnitude/day)	3	3	2.5
Flood recession rate (% of flood magnitude/day)	2	3	3.5
Timing			
Base flows			
Median extreme low flow date	11 Dec	1 Sep	23 Aug
Floods			
Median peak flood date	28 May	12 May	27 May
Frequency			
Base flows			
Median number of zero flow days per year	0	11	0
Floods			
Median number of high pulse flows per year	5	7	5

Note. Median values are calculated per year for the specified period. Extreme low flows were calculated as less than the 90th exceedance prob ability from a flow duration curve. High pulse flows were identified as flood peaks greater than the 25th exceedance probability from a flow duration curve. Small floods were high pulse flows with a recurrence interval between 2 and 10 years; large floods were high pulse flows greater than the 10 year flood. High flow-base flow ratio is median daily max divided by mean annual flow. Low flow-base flow ratio is median 7 day minimum divided by mean annual flow.

degradation. Given the ecological response to a declining flow regime, it is reasonable to assume that the snowmelt peak was important for life history cues (Archdeacon, 2016; Junk et al., 1989).

Environmental flows are defined as the amount of streamflow needed to maintain certain ecosystem functions and are used as a tool to balance human and ecosystem water needs. Restoration of the natural flow regime of the Rio Grande is not possible, and proposals for environmental flows focus on determining the minimal amount of streamflow required to improve aquatic habitat or benefit specific organisms. Environmental flows are being considered on the northern branch and in the Big Bend region of the lower Rio Grande. The primary objective on the Rio Grande is to restore environmental conditions that are conducive to native species, particularly the federally listed endangered Rio Grande Silvery Minnow. Degraded or limited habitat was identified as a primary factor contributing to the decline of this species; therefore, environmental flows are focused on inundation of the floodplain and maintaining desirable channel morphology (CEC, 2014; Lane et al., 2014; Sandoval-Solis & McKinney, 2014; USFWS, 2010).

There are hundreds of methods used to quantify environmental flows, but the most common approach uses statistical analyses of hydrologic data in the form of naturalized streamflow (Tharme, 2003). There have been little to no analyses or recommendations of environmental flows on the northern branch. The flow regime in the Big Bend was analyzed using existing discharge records (Dean & Schmidt, 2011; Sandoval-Solis & McKinney, 2014; Schmidt et al., 2003) and initial environmental flow recommendations were made by the interdisciplinary Upper Rio Grande Basin and Bay Expert Science Team (BBEST). Recommendations were based on statistical analysis of the earliest streamflow records. Our results demonstrate that the earliest flow records of the Rio Grande describe a significantly perturbed flow regime.

To explore the effects of using early streamflow records for environmental flow recommendations on the northern branch, we calculated common environmental flow statistics (Poff & Ward, 1989; Richter et al., 1996, 1997) using our estimated natural flows and the measured early and late 20th century flows at San Marcial (Table 2). The estimated natural mean annual flow is nearly 2 times the magnitude of the early 20th

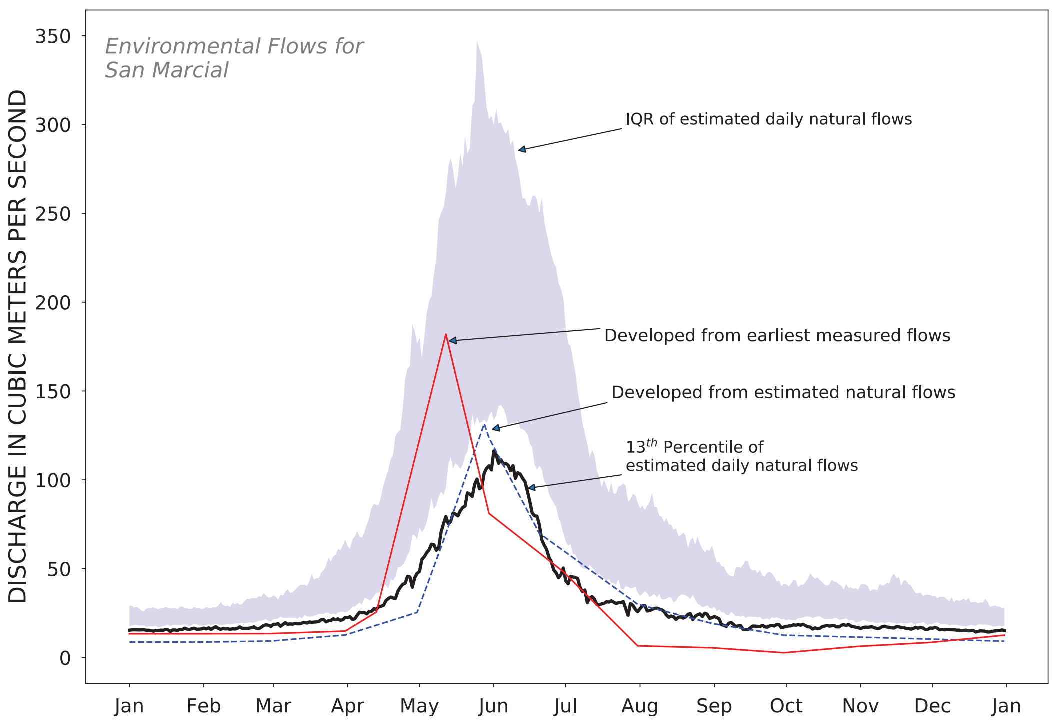

Figure 9. Graph of monthly natural hydrographs for San Marcial designed using the earliest stream gage records (red) and natural flows estimated by our mass balance model (dotted-blue), compared with the hydrograph formed by the 13th Percentile of the estimated natural flows (black) which has a total annual flow equivalent to the average total annual flow measured at San Marcial during the late 20th century. The shaded blue region is the interquartile range of the estimated natural flows that represents the actual magnitude of the natural flow regime.

century measured mean annual flow. The estimated natural weekly minimum flow of each year was much greater than zero, and there were no days when flow was zero. Extreme low flows of the estimated natural flow regime occurred in the winter, rather than the summer, and were four times shorter in duration than those measured during the early 20th century. Our estimated natural floods receded nearly 30% slower than the earliest measured floods and were 24% greater in magnitude. However, the separation between estimated natural base flows and peak flood magnitude was less than the earliest measured records. Thus, basing environmental flow recommendations on existing streamflow data for the northern branch undermines potentially important geomorphic and ecological drivers.

Although full restoration of the natural flow regime is impossible, certain components might be scaled-down to create a flow regime that mimics the variability of the natural flow regime (Jacobson & Galat, 2008). We used the statistics calculated for the early 20th century (1900–1944) data to design a scaled-down hydrograph that maintains the streamflow characteristics of the earliest gaged flows. The hydrograph was scaled using a method based on a common environmental flow technique (Tennant, 1975, 1976), where we calculated monthly flows and flood components as a proportion of the mean annual flow. We assumed that the mean annual flow measured at San Marcial during the late 20th century (1950–2010) was representative of the available water for environmental flows.

Rather than using the same approach, we took advantage of the precise daily results provided by our model to develop a hydrograph similar to that of the estimated natural flow regime. We calculated the total annual flow of the hydrographs formed by each percentile of our estimated mean daily natural flows, where each percentile was a scaled hydrograph. Using the relationship between percentile of daily flows and total annual flow, we identified the scaled-down hydrograph that maintains natural flow variability, but whose total annual flow is equivalent to the modern average total annul flow at San Marcial. This method allows managers and researchers to specify the quantity of water available for environmental flow purposes and easily determine how that volume of water should be distributed throughout the year to mimic the natural flow regime. The hydrograph developed using the early streamflow record is noticeably different than the hydrograph developed using our estimated natural flows (Figure 9). We also estimated a scaled-down hydrograph developed using the estimated natural flow statistics in Table 2 but using monthly data to illustrate that this variation is not due to the difference in methods. The main differences are between the annual floods and the summer/fall base flows. The annual flood developed using early gaging records was larger than the annual flood of the estimated natural flows, because the ratio between maximum discharge and mean annual flow was 6.5 for the early 20th century and only 4.7 for the estimated natural flows.

7. Conclusions

The availability of natural flow data and the advancement of methods used to estimate natural flows has lagged behind commonly used environmental flow estimation techniques that routinely depend on these data. Simple, and accurate, methods to estimate the natural flow regime are needed to make informed environmental flow decisions on significantly disturbed rivers.

We developed a mass balance model that can be used to estimate the daily resolution, natural flow regime of any river basin using only modern streamflow data. This method is especially useful for long-perturbed rivers or those with limited consumptive loss data. This method is advantageous over traditional mass balance methods, which require large amounts of measured or simulated data to quantify each term in a water budget and have large uncertainties in the estimates.

We tested our method on the northern branch of the Rio Grande, which has a long history of water development and large-scale depletions that alter the flow regime. We were able to estimate the daily resolution, natural flow regime characteristic of the last century, including the early 20th century before irrigation diversions were measured. We also quantified the difference between modern and natural conditions. Such estimates have not previously been made.

We determined that the total annual flow of the northern branch of the Rio Grande at its confluence with the Rio Conchos is 95% less than the estimated natural flow. Where a snowmelt flood once characterized the annual hydrograph, there are only small flash floods from summer and monsoon rains, and a large portion of the watershed, which produced approximately 23% of the annual flow, now contributes virtually no flow to the lower Rio Grande. The methods presented in this study provide accurate and high-resolution natural flows which can be used for more precise and accurate environmental flow analyses or for other ecological applications. With more basin-specific information, and some alteration to our basic assumptions, this method could also be used for accounting and streamflow forecasting. Our study provides a point of reference to understand the magnitude of present-day impacts to the flow regime and to understand the regime in which the native flora and fauna evolved.

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