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Key Points:
- Sand transport has declined because of reductions in discharge in the Green River and reductions in sand supply in the Colorado River
- Sediment depletion occurs during annual floods and is determined by flood duration and magnitude, depending on the river
- Despite channel narrowing, periods of bed sand coarsening and sediment depletion do not indicate conditions of sediment surplus

Supporting Information:
- Supporting Information S1

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Does Channel Narrowing by Floodplain Growth Necessarily Indicate Sediment Surplus? Lessons From Sediment Transport Analyses in the Green and Colorado Rivers, Canyonlands, Utah

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Abstract Analyses of suspended sediment transport provide valuable insight into the role that sediment supply plays in causing geomorphic change. The sediment supply within a river system evolves depending on the discharge, flood frequency and duration, changes in sediment input, and ecohydraulic conditions that modify sediment transport processes. Changes in supply can be evaluated through analyses of coupled changes in suspended sediment concentration and grain size. The concentration of sand in transport in the Green and Colorado Rivers is most strongly controlled by discharge and the bed sand grain size distribution. Since the 1950s, sand loads have decreased in response to declines in peak discharge in the Green River and coarsening of the bed sand in the Colorado River. However, changes in the bed sand grain size distribution are associated with large changes in suspended sand concentration in both rivers; concentration varies by a factor of ~3 in the Green River and a factor of ~8 in the Colorado River, depending on the bed sand grain size distribution. Analyses of hysteresis in suspended sediment measurements show that sediment depletion during annual floods is most strongly controlled by flood duration, with peak discharge being nearly equally important in the Green River. Despite channel narrowing in both rivers, periods of bed sand coarsening and sediment depletion during annual floods indicate that these rivers are not necessarily in sediment surplus. Channel narrowing appears to be strongly controlled by short-term declines in flood magnitude and the ecohydraulic effects of vegetation and may not be indicative of the long-term sediment budget.

Plain Language Summary River channels change size and shape in response to changes in the amount of sediment transported downstream. Changes in streamflow and/or the upstream sediment supply are the cause(s) of such changes in sediment transport. The channels of the Green and Colorado Rivers near Canyonlands National Park, Utah, have both narrowed over the last century. We use measurements of suspended sediment transport to investigate how changes in the sediment supply influence sediment transport and channel change. In most cases, the transport of suspended sand is primarily controlled by the discharge of water and secondarily controlled by the bed sediment grain size distribution. Depletion of the upstream sand supply leads to bed sand coarsening and erosion, whereas enrichment of the upstream sand supply leads to bed sand fining and deposition. The sand supply is progressively depleted during annual snowmelt floods on the Green and Colorado Rivers, with greater depletion occurring during longer floods. Larger floods also cause greater depletion of the upstream sand supply in the Green River but are of less importance in the Colorado River. The size and shape of the present-day river channels may therefore be maintained, and channel narrowing may be limited, if longer-duration floods occur in the future.

1. Introduction

Effective application of fluvial geomorphic research to river management partly depends on the ability to explicitly link potential management decisions with their predicted effect on river channel form. Changes in channel form are driven by changes in the flow regime, sediment supply (Lane, 1955), and ecohydraulic processes that modify hydraulics and sediment transport. Changes in these parameters may be caused by natural processes and/or anthropogenic activities and are likely to occur with climate change and increasing demands for water. Thus, understanding how future changes in streamflow and sediment supply may affect river channels is essential for the effective management of these environments.

Channel change typically occurs in response to perturbation of the sediment mass balance into deficit or surplus (Schmidt & Wilcock, 2008), yet predicting the magnitude of channel change caused by these factors is not straightforward. Channel change may alter in-channel hydraulic environments thereby affecting sediment transport, but sediment transport can also change in response to increases and/or decreases in supply. Supply-driven changes in sediment transport may be substantial and contribute to large-scale channel change (Grams et al., 2007; Ritchie et al., 2018). Alternatively, changes in supply may manifest in changes to the bed sediment grain size distribution, resulting in large changes in sediment transport, with little overall change in channel form (Topping et al., 2018). Thus, alterations in the sediment transport regime may be caused by both changes in channel form or changes in the sediment boundary condition or a combination of both.

Many researchers have studied the relations among discharge, sediment transport, and channel form in alluvial rivers (Bridge, 1993; Church, 2006; Dade, 2000; Parker, 1979), including alluvial segments of the Green and Colorado Rivers (Allred & Schmidt, 1999; Andrews, 1986; Andrews & Nelson, 1989; Birken & Cooper, 2006; Graf, 1978; Grams et al., 2007; Grams & Schmidt, 2002, 2005; Lyons et al., 1992; Manners et al., 2014; Merritt & Cooper, 2000; Mueller et al., 2014; Pitlick & Cress, 2002; Rakowski, 1997; Van Steeter & Pitlick, 1998; Walker et al., 2020). Studies within the Green and Colorado Rivers all described channel narrowing and loss of channel complexity, although some studies disagreed as to the magnitude and timing of these changes. Both rivers are dominated by suspended sediment transport, but most of the studies focused on the effect of flow regime change on channel form, with less attention given to changes in sediment supply. Our study is focused on the role of a changing sediment supply in causing changes in sediment transport and channel form in the Green and Colorado Rivers.

Andrews (1986) and Grams and Schmidt (2005) sought to link changes in sediment transport to changes in channel form in the Green River. They analyzed changes in the flow regime and assumed that increases or decreases in sediment transport rates were caused solely by increases or decreases in flow volume or flood magnitude. Using this equilibrium sediment transport assumption, Andrews (1986) used hydraulic geometry relations (Leopold & Maddock, 1953) to predict changes in channel width (Andrews, 1986). However, this widely used approach can be inaccurate (Topping et al., 2018) because sediment transport and associated geomorphic change may be driven by changes in the upstream sediment supply and not by changes in discharge (Brummer & Montgomery, 2006; Dean et al., 2016; Dietrich & Dunne, 1978; Gran et al., 2011; Howard & Dolan, 1981; Schmidt & Wilcock, 2008; Topping et al., 2018). This is especially true in rivers with spatial and temporal discontinuities in sediment supply (Dean et al., 2016; Topping et al., 2018).

There are relatively long records of flow and sediment transport and well-understood records of channel change in the alluvial reaches of the Green and Colorado Rivers in the Canyonlands region. Channel narrowing and floodplain aggradation have occurred in both rivers, accelerating during recent decades (Head, 2020; Walker et al., 2020). This pattern of geomorphic change is generally thought to have resulted from perturbation of the sediment mass balance into surplus; however, no studies have rigorously evaluated the sediment transport records to determine whether sediment surplus conditions exist in these rivers. Herein, we analyze the sediment transport records of the Green and Colorado Rivers to determine if the mass balance of either river has been significantly perturbed and to determine the relative importance of changes in the flow regime and upstream sediment supply in causing that perturbation. Specifically, we investigate four research questions. (1) How have changes in streamflow affected changes in sediment load? (2) How have changes in the sediment supply affected sediment transport and influenced geomorphic change? (3) What are the characteristics of the sediment transport regime during the annual flood? and (4) Have the Green and Colorado Rivers been perturbed into conditions of sediment surplus? These analyses are essential for understanding how future changes in streamflow may further affect sediment transport and channel form in the Green and Colorado Rivers. Finally, we discuss how large-scale changes in riparian vegetation may also be affecting sediment transport and geomorphic change in the study area.

2. Suspended Sand Transport and Geomorphic Change

Suspended sediment is composed of two dominant grain size fractions: sand and silt and clay. The concentration of suspended silt and clay is generally controlled by the upstream supply and not by the bed sediment composition (Knighton, 1998). Silt and clay is well mixed in the water column and can be readily transported and deposited in floodplains. Suspended sand, however, has a much greater interaction with the channel bed because of its larger Rouse numbers (e.g., McLean, 1992); thus, we specifically focus most of our analyses on sand-sized sediment.

Sand transport through a reach is determined by four factors: (1) the upstream sand supply, (2) the boundary shear stress (τ_B) exerted on the bed and banks by the flow, (3) the area of sand on the bed, and (4) the grain size distribution of the bed sand. Together, (3) and (4) represent the amount of sand available for transport within a reach, that is, the local sand supply (Dean et al., 2016). The influx of sand from upstream, that is, the upstream sand supply, interacts with the hydraulics of a reach to cause changes in the local sand supply thereby affecting sand transport. We use shear velocity (u_*) to characterize the influence of flow on sand transport because shear velocity and discharge (Q) are well correlated (von Karman, 1930) and because many of the analyses herein utilize Q; $u_* = \sqrt{\tau_B/\rho}$, where ρ is the density of water.

Changes in the upstream sand supply will mainly cause changes in the bed sand grain size distribution. Changes in the bed sand grain size distribution have a strong nonlinear effect on suspended sand concentration (C_{SAND}), whereas changes in bed sand area have a quasi-linear effect on C_{SAND} (Grams & Wilcock, 2007; Topping et al., 2000, 2007, 2010). Thus, we use changes in the bed sand grain size distribution to infer changes in the upstream sand supply. For our study area, the sand supplied from upstream tributaries is typically finer than the antecedent bed sand in the mainstem. Therefore, an increase in the upstream sand supply causes bed sand fining and accumulation of sand within the bed, and a decrease in the upstream sand supply causes bed sand coarsening through winnowing of the fine tail of the grain size distribution (Rubin et al., 1998; Topping et al., 2018; Topping, Rubin, & Vierra, 2000). Here, we refer to the accumulation and fining of sand within the bed as enrichment and the winnowing and coarsening of sand within the bed as depletion.

Sand transport conditions can be characterized based on the shape, scatter, and temporal changes in the relations between Q or u_*, C_{SAND}, and the suspended sand median grain size (D_S). When the bed sand area and grain size distribution do not change in time, unique relations exist among these parameters and increases in Q cause increases in both C_{SAND} and D_S, with little variability. Changes in the upstream sand supply, manifest in bed fining or coarsening, however, can result in upward or downward shifts in the relation between Q and C_{SAND} and result in distinctive styles of hysteresis (Topping & Wright, 2016). Increases in the upstream sand supply lead to increases in sand transport resulting in counterclockwise Q-C_{SAND} hysteresis coupled to clockwise Q-D_S and counterclockwise D_S-C_{SAND} hysteresis (Dean et al., 2016; Dinehart, 1998; Heidel, 1956; Juez et al., 2018; Kleinhans et al., 2007; Topping & Wright, 2016). Decreases in the upstream sand supply lead to decreases in sand transport resulting in clockwise Q-C_{SAND} hysteresis coupled to counterclockwise Q-D_S and clockwise D_S-C_{SAND} hysteresis (Dinehart, 1998; Heidel, 1956; Kleinhans et al., 2007; Rubin et al., 1998; Topping et al., 1999, 2000; Topping, Rubin, & Vierra, 2000; Topping & Wright, 2016).

In addition to causing changes in the bed sand grain size distribution, changes in the upstream sand supply may potentially lead to changes in channel form. If the upstream sand supply exceeds the local transport capacity for long periods (i.e., years or decades), and grain size-associated increases in transport do not fully offset this increase in supply, a condition of sediment surplus will develop, and sediment deposition within the channel or on the floodplain will occur (Schmidt & Wilcock, 2008). If the transport capacity exceeds the sediment supply for long periods of time, and grain size-associated decreases in transport do not fully offset this decrease in supply, a condition of sediment deficit will develop, and progressive erosion will occur.

3. Study Area

The study area consists of ~110 km of the Green River between U.S. Geological Survey (USGS) gaging Station 0931500 (Green River at Green River, UT, hereafter GR-GR) and USGS gaging Station 09328920 (Green River at Mineral Bottom near Canyonlands National Park, hereafter GR-MB) and ~77 km of the Colorado

River between USGS gaging Station 09180500 (Colorado River near Cisco, UT, hereafter CR-Cisco) and USGS gaging Station 09185600 (Colorado River at Potash, UT, hereafter CR-POT) (Figure 1). Discharge records at GR-GR exist for water years 1895–1899 and 1905 to present. At CR-Cisco, annual mean discharge records exist for water years 1914 to present, and annual peak discharge records exist for 1884 and 1914 to present. GR-MB and CR-POT were established in water years 2014 and 2015, respectively. Thus, GR-GR and CR-Cisco have "historical" data and "modern" (i.e., post-2013) data, whereas GR-MB and CR-POT have only modern data.

The drainage-basin area of the Colorado River upstream from CR-Cisco is 46% smaller than that of the Green River upstream from GR-GR, but the modern annual mean flow at CR-Cisco is ~20% larger than at GR-GR (Wheeler et al., 2019). Most of the streamflow of the Green and the Colorado rivers comes from the distant Rocky Mountains (Iorns et al., 1965) and occurs during the long-duration annual snowmelt flood between March and early July. Fine sediment is supplied from upstream during snowmelt and locally during tributary flash floods caused by thunderstorms between July and October.

The geomorphic organization of each river includes narrow canyons that are either affected by debris fans or are incised meanders and wide valleys with restricted meanders. Incised and restricted meanders are alluvial or quasi-alluvial (Grams & Schmidt, 2005; Pitlick & Cress, 2002; Schmidt, 2007; Schmidt & Brim Box, 2004; Schmidt & Rubin, 1995). The bed sediment in both rivers fines from gravel to sand in the study area. Bed sediment at GR-GR and CR-Cisco is typically gravel (Allred & Schmidt, 1999; Pitlick & Cress, 2002), whereas bed sediment at GR-MB and CR-POT is entirely sand. Floodplains of both rivers may be discontinuous, and bedrock forms the banks at the outside of some meander bends. The locations of the gravel-sand transitions in each river are likely controlled by changes in slope and the distance downstream from gravel-supplying tributaries and/or terraces (Text S1 and Figure S1 in the supporting information). In the Green River, the San Rafael River also contributes fine sediment between GR-GR and GR-MB likely contributing to some downstream increase in sand on the bed.

The two tributaries that once were the largest local suppliers of sediment in our study area were San Rafael River, which enters the Green River 36 km downstream from GR-GR, and the Dolores River, which enters the Colorado River immediately upstream from CR-Cisco. Sediment delivery by both of these rivers has been substantially reduced because of large-scale water development and extraction (Fortney, 2015; Wheeler et al., 2019). Water development on the Duchesne and Price rivers has also likely reduced sediment delivery to the Green River.

Because the focus of our study was on understanding the conditions of flow and sediment transport that influence geomorphic change in the Canyonlands region, we relied primarily on analyses at GR-GR, GR-MB, CR-Cisco, and CR-POT (Figure 1b). However, understanding how sediment inputs from upstream tributaries affected the upstream sediment supply also required analyses of data from additional upstream gaging stations (Figure 1).

4. Previous Hydrologic and Geomorphic Studies in the Green and Colorado Rivers Near the Study Area

The flow regimes of the Green and Colorado Rivers have both changed during the last century, caused by the shift from the early twentieth century pluvial period to drier conditions that began in ~1930 (Walker et al., 2020; Woodhouse et al., 2006), a warming climate resulting in declining watershed runoff (Udall & Overpeck, 2017; Xiao et al., 2018), the construction of dams (Schmidt, 2007), and diversion of large amounts of water (Fortney, 2015; Gaeuman et al., 2005; Walker, 2017; Walker et al., 2020; Wheeler et al., 2019). Flow of the Green River within the study area is partially controlled by Flaming Gorge Dam, approximately 475 km upstream. The largest sources of water to the Green River in our study area come from releases from Flaming Gorge Dam and quasi-natural flows from the Yampa River; between 2000 and 2018, these combined sources comprised ~80% of the total annual flow measured at GR-GR (Wheeler et al., 2019).

Although the total annual flow of the Colorado River is ~20% larger than the Green River, consumptive uses and losses are also greater. Water supply and flood control operations of the Aspinall Unit reservoirs on the Gunnison River, McPhee Dam on the Dolores River, and many transbasin diversions and reservoirs impact the flow regime of the Colorado River in the study area. Between 2000 and 2018, the measured flow at

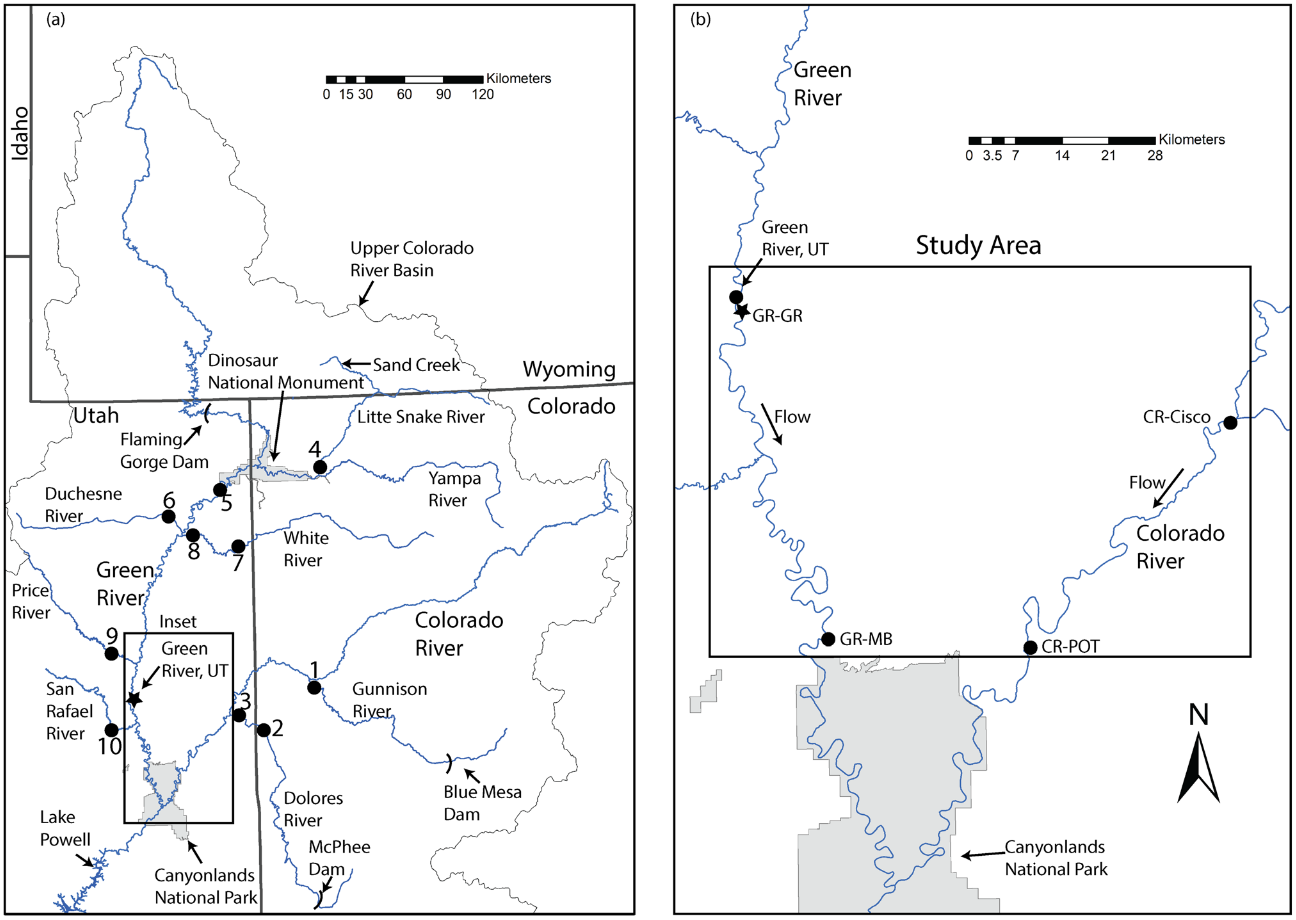

Figure 1. Map of the Green and Colorado River basins upstream from their confluence (a) and the study area (b). U.S. Geological Survey streamflow gaging stations are numbered from 1 to 10 as follows: (1) Gunnison River near Grand Junction, CO, 09152500; (2) Dolores River near Gateway, CO, 09179450; (3) Dolores River near Cisco, UT, 0918000; (4) Little Snake River near Lily, CO, 09260000 (LS-Lily); (5) Green River near Jensen, UT, 09261000; (6) Duchesne River near Randlett, UT, 09302000; (7) White River near Watson, UT, 09306500; (8) White River at mouth near Ouray, UT, 090306900; (9) Price River at Woodside, UT, 09314500; and (10) San Rafael River near Green River, UT, 09328500. The four stream gages we primarily rely on, GR-GR, GR-MB, CR-Cisco, and CR-POT, are shown in (b).

CR-Cisco was ~70% of the estimated natural flow at this gaging station, and 38% of that flow came from the regulated Gunnison River (Wheeler et al., 2019). Fourteen percent of the mean annual flow measured at CR-Cisco is diverted from the Colorado River basin (Wheeler et al., 2019). Relatively large flow reductions occur in tributaries that were once large natural suppliers of fine sediment. For example, more than 66% of the flow in the Dolores River headwaters are diverted to the San Juan River watershed. In the first half of the twentieth century, ~32% of the sediment load measured at CR-Cisco came from the Gunnison and Dolores rivers (Iorns et al., 1965). Sediment trapping in Gunnison and Dolores river reservoirs is relatively minor because these reservoirs are located upstream of the major sources of fine sediment in these basins (Iorns et al., 1965). Operation of these reservoirs for flood control and water extraction, however, has likely substantially reduced the sediment supply delivered to the Colorado River.

The Green and Colorado Rivers have both undergone episodes of channel narrowing and floodplain growth during the last century (Allred & Schmidt, 1999; Andrews, 1986; Birken & Cooper, 2006; Everitt, 1979; Graf, 1978; Pitlick & Cress, 2002; Van Steeter & Pitlick, 1998; Walker et al., 2020). Channel narrowing in the Green River began as early as the 1930s when peak Q declined, greatly accelerated in the late 1980s, and continued through at least 2014 (Walker et al., 2020). In the study area, most of the channel narrowing in the Green River has occurred since the late 1980s (Walker et al., 2020). Narrowing occurred through the growth of in-channel bars, stabilization of these bars by vegetation during years with small annual floods, and the subsequent conversion of these bars to floodplains. The channel of the Green River within and downstream from the study area is now ~12% narrower than in 1940, possibly indicating that sediment surplus conditions exist. The recent period of accelerated narrowing that began in the 1980s corresponded to a period of lower Q and vegetation establishment during ~13-year wet-dry cycles identified upstream by Manners et al. (2014) and Topping et al. (2018).

The timing and mechanisms of channel narrowing in the Colorado River are less well understood. In the gravel bed reach upstream from the study area, channel narrowing began in the 1950s when secondary channels filled with fine sediment and islands became attached to the nearby floodplains (Van Steeter & Pitlick, 1998). The area of islands and secondary channels decreased between 1954 and 1968 by 15% and 24%, respectively. Preliminary aerial photograph analyses show that the Colorado River downstream from CR-POT has narrowed by ~15% since 1940 (Head, 2020), suggesting that sediment surplus conditions may also exist in the Colorado River.

The ecohydraulic effects of vegetation are integral to the processes of channel narrowing and floodplain formation. Vegetation is effective at stabilizing banks, reducing channel margin flow velocities, and trapping sediment (Griffin et al., 2005; Manners et al., 2015; Pollen-Bankhead et al., 2009; Tal et al., 2004). Both native (e.g., *Salix exigua*) and nonnative species (e.g., *Tamarisk* spp.) of vegetation have greatly expanded into areas of formerly bare sediment in our study area (Mortenson & Weisberg, 2009; Walker et al., 2020). Consequently, densely vegetated floodplains now exist in areas in both rivers that once consisted of bare deposits within the active channel.

5. Methods

We analyzed flow and sediment transport records of the Green and Colorado Rivers. Statistical analyses of long-term annual streamflow data were conducted to determine changes in flow regime. We analyzed suspended sand and suspended silt-and-clay measurements to evaluate changes in the upstream sediment supply and changes in transport through the study area. We also analyzed relations between Q and C_{SAND} and D_{S} to determine whether changes in sand transport have occurred and determined the relative importance of changes in the flow regime and sand supply in causing changes in sand transport.

5.1. Hydrology

Discharge data at GR-GR and CR-Cisco were analyzed to determine the timing and magnitude of changes in the flow regime. Nonparametric Pettitt tests (Pettitt, 1979) were used to conduct change point analyses of the annual mean Q, peak Q, and annual minimum daily mean Q (i.e., minimum Q) records to determine changes in these parameters at the 95% confidence level. Pettitt tests were used to detect abrupt changes in the means of these time series, because this test is relatively insensitive to outliers. At GR-GR, we used the Pettitt test results of Walker et al. (2020), and we also conducted Pettitt tests on the flow record at CR-Cisco. We also calculated the 3-year moving averages to evaluate the existence of cycles of high and low streamflow.

Peak Q from six tributaries upstream from GR-GR and CR-Cisco (Figure 1) were also analyzed to determine how peak Q and associated sand supplied from these tributaries may have changed. Least squares linear regressions were applied to the time series of tributary peak Q data, and F tests were conducted to determine whether the slopes of these regressions were significant at the 95% confidence level.

5.2. Historical Changes in Sediment Loads

We evaluated the historical fine-sediment loads using the daily suspended sediment measurements made at GR-GR and CR-Cisco during water years 1951–1984 (Text S2). Using the intermittent grain size data associated with suspended sediment measurements at these gages between 1951 and 2000, we used the "shifting sand rating curve" method of Topping et al. (2018) to estimate the annual suspended sand loads for all years where six or more grain size-analyzed suspended sediment measurements were made. The mean and median frequency of these measurements per year were 11 at both gaging stations.

Annual silt-and-clay loads were calculated by subtracting the estimated annual suspended sand loads from the measured annual total suspended sediment loads. Uncertainty was assumed to be ±30% for the historical annual sand and annual silt-and-clay loads (Topping et al., 2018). Annual loads are provided in Text S3 and Table S1.

Because the durations of the sediment load records are much shorter than the length of the streamflow records at GR-GR and CR-Cisco, we did not use Pettitt tests to determine changes in annual sediment loads. Instead, we used Wilcoxon-Mann-Whitney (WMW) tests (Mann & Whitney, 1947) to determine if differences existed in the annual sediment loads between two periods at the 95% confidence level; these tests were used instead of *t* tests because WMW tests do not require the data to be normally distributed. For the GR-GR record, we compared sediment load data before and after a large reduction in peak Q in 1959 (Walker et al., 2020) and also compared the sediment load data between the post-1959 record at GR-GR and the modern record at GR-MB. For the record at CR-Cisco, we compared annual sediment load data before and after closure of Blue Mesa Dam on the Gunnison River in 1966 and McPhee Dam on the Dolores River in 1986 to determine if closure of those dams caused changes in sediment loads. We then used linear least squares regression for both rivers to show the long-term trends in these data; however, we did not rely on linear regression to test the significance of any apparent trends, because there are multiple periods with missing data.

5.3. Changes in Bed Sand Grain Size

Changes in bed sand grain size indicate potential changes in the upstream sand supply (Section 2) (Topping et al., 2007, 2018; Topping, Rubin, Nelson, et al., 2000). Because of a lack of historical bed sediment measurements, we used the parameter β (Rubin & Topping, 2001, 2008), a measure of the relative coarseness of the bed sand, to infer the spatially averaged bed sand grain size distribution. β is defined as follows:

$$\beta = \left(\frac{C_{\text{SAND}}}{C_{\text{SAND-REF}}}\right)^{-0.1}\left(\frac{D_{\text{S}}}{D_{\text{S-REF}}}\right) \tag{1}$$

where C_{SAND} and D_{S} are the suspended sand concentration and median grain size, respectively, in an individual suspended sand measurement. $C_{\text{SAND-REF}}$ and $D_{\text{S-REF}}$ are reference values equal to the mean C_{SAND} and D_{S} among all suspended sand measurements. β was derived using the suspended sediment theory of McLean (1992) and tested with flume and field observations (Rubin & Topping, 2001, 2008). Because β is calculated using suspended sand measurements, β includes physical suspension processes to sample the bed sand in the reach upstream from the cross section where suspended sand measurements are made. β therefore provides a more representative spatially averaged measure of bed sand grain size than do bed sediment measurements at only a single cross section. β is more sensitive to changes in the fine tail than it is to changes in the median grain size of the bed sand at the Rouse numbers common for sand in rivers (Topping et al., 2018). Thus, β is typically a better proxy for the percentage of very fine sand on the bed (B_{VF}), size classes that dominate the suspended sand. β is negatively correlated with Q in our study area (Figure S2), indicating the typical presence of finer sand on the bed at higher Q. We therefore detrended β as a function of Q so that the β time series would reflect changes in bed sand grain size mostly arising from changes in the upstream sand supply and not from changes in Q (Figure S2). We visually identified breakpoints in Q-detrended β at GR-GR and CR-Cisco to determine time periods of change in the bed sand grain size at these stations. We used least squares linear regression to determine trends in β within these time periods and used F tests to determine if the slopes of the regressions were statistically significant. Additional information on β is in Text S4.

5.4. Relative Importance of Changes in Sand Supply Versus Discharge in Regulating Suspended Sand Concentration

We used the nondimensional parameter α to determine whether changes in bed sand grain size or changes in u_*, and thus Q, exert a stronger influence on C_{SAND} (Rubin & Topping, 2001, 2008) (Text S4). Since suspended sand load is the product of C_{SAND} and Q, α analyses provide insight into the importance of changes in the upstream sand supply in controlling suspended sand loads. As with β, α was derived using the suspended sediment theory of McLean (1992) and tested using the flume data of Einstein and Chien (1953) (Rubin & Topping, 2001, 2008). The sign of α is irrelevant; hence, we use $|\alpha|$. In the formulation of α (Text S4), changes in u_* and bed sand grain size are equally important in regulating C_{SAND} when $|\alpha| = 1$. Changes in bed sand grain size are twice as important as changes in u_* in regulating C_{SAND} when $|\alpha| = 2$, and changes in u_* are twice as important as changes in bed sand grain size in regulating C_{SAND} when $|\alpha| = 0.5$. Changes in u_* completely control C_{SAND} as $|\alpha|$ approaches zero and changes in bed sand grain size completely control C_{SAND} as $|\alpha|$ approaches infinity.

α analyses can be conducted over long time periods or can be used to evaluate the effect of changes in bed sand grain size during individual floods. Larger values of $|\alpha|$ imply larger relative changes in bed sand grain size and therefore larger Q-C_{SAND}-D_S hysteresis loops and larger amounts of sand erosion or deposition during individual floods.

5.5. Changes in Discharge—Suspended Sand Concentration Relations

C_{SAND} is dependent upon the grain size distribution of the channel bed sand; thus, upward and downward shifts in Q-C_{SAND} relations would be expected to occur with changes in β. Thus, we used data associated with relatively high and low Q-detrended β to examine changes in the relations between Q and C_{SAND}. We defined high-β (i.e., coarse bed) data as those suspended sand measurements with

Q-detrended $\beta > 1.2$, and we defined low-β (i.e., fine bed) data as those suspended sand measurements with Q-detrended $\beta < 0.8$. For each of these conditions, C_{SAND} was regressed on Q, and we fit a line to these data using linear least squares regression with the y intercept forced through the origin.

5.6. Continuous Suspended Sediment Monitoring

We installed continuous sediment transport monitoring stations at GR-MB in March 2014 and at CR-POT in February 2015 (Figure 1). Each of these monitoring stations consisted of an array of 1- and 2-MHz side-looking acoustic Doppler profilers, paired with an automatic pump sampler. Acoustical data were calibrated using Equal-Width-Increment (EWI) suspended sediment measurements and calibrated automatic pump samples (Edwards & Glysson, 1999) to determine C_{SAND}, C_{SC}, and D_S (Text S5). Bed sediment measurements were made concurrently with the EWI measurements (Text S5). The 15-min continuous measurements of C_{SC}, C_{SAND}, D_S; instantaneous suspended silt-and-clay and suspended sand fluxes; and cumulative suspended silt-and-clay and suspended sand load (Porterfield, 1972) for any time period are publicly available at https://www.gcmrc.gov/discharge_qw_sediment/stations/CL (Sibley et al., 2015) and in Dean et al. (2020). Uncertainties in these loads are ±10% based on the likely maximum value of persistent biases present in the 15-min Q and suspended sediment data (Topping et al., 2018).

We analyzed the shapes of relations among Q, C_{SAND}, C_{SC}, and D_S; patterns of hysteresis; magnitude of hysteresis (i.e., H index, Langois et al., 2005); and temporal trends in C_{SAND} and C_{SC} during the annual floods. These analyses provide insight into reach-scale conditions of sediment supply and whether conditions of sediment surplus or deficit exist (Juez et al., 2018). We also analyzed the relations between α and both peak Q and annual flood duration (i.e., duration of the rising limb) to evaluate whether either of these variables exert strong control on C_{SAND} and thus cause sediment enrichment or depletion. In both rivers, the annual floods are asymmetrical, with typically a much longer rising limb than recession; thus, "longer flood duration" is synonymous with "longer rising limb". Here, we define the duration of the rising limb as the point at which the first large Q pulse begins to rise, through the peak of the last large Q pulse before complete recession of the flood. Multiple pulses in Q are common during the snowmelt floods in these rivers, and thus, all pulses of Q that may be driving sediment enrichment or depletion are included in the analysis.

Modern total annual loads, annual sand loads, and annual silt-and-clay loads from GR-MB and CR-POT were combined with historical annual sediment load data from GR-GR and CR-Cisco, respectively, so that the historical suspended sediment load data could be compared to the present day. On the Green River, the San Rafael River is the only major tributary between the two gaging stations. Peak Q in the San Rafael has decline by more than 50% since the 1950s; therefore, sediment delivery from the San Rafael has also likely been substantially reduced (Fortney, 2015). We subtracted estimates of the San Rafael annual sand and annual silt-and-clay loads from the GR-MB loads to approximate the loads at GR-GR (Text S6). On the Colorado River, there are no major tributaries that contribute water or sediment between CR-Cisco and CR-POT.

Bedform migration measurements were made at GR-MB and CR-POT to measure the sand bedload flux (Q_B) over a range of flows to determine the proportion of the total sand load transported as bedload. Continuous

Table 1
Pettitt Test Results of 2-Year Peak Q, Mean Q, and Average Annual Minimum Q at GR-GR and CR-Cisco

Period	Years	Value (m^3/s)	p value of peak flow break point
GR-GR			
2-year peak *Q*			
1895–1923	23	1,170	
1924–1958	35	807	0.026
1959–2018	58	618	5.27E−03
Mean *Q*			
1895–1929	29	215	
1930–2018	89	154	5.42E−03
1930–1986	57	164	4.15E−03
1987–2018	32	136	0.065
Average annual minimum *Q*			
1895–1929	29	30	
1930–1964	34	23	0.013
1965–1988	24	51	6.76E−09
1989–2018	30	39	3.95E−03
CR-Cisco			
2-year peak *Q*			
1914–1953	36	1,354	
1954–2017	64	739	2.59E−05
Mean *Q*			
1914–1929	11	279	
1930–1952	23	208	0.020
1953–2018	66	184	0.041
Average annual minimum *Q*			
1914–1967	49	42	
1968–2018	51	67	7.06E−09

Note. Divisions between time periods based on results of Pettitt Tests shown in Figure 1.

sand bedload was calculated using discharge-dependent relations developed between the measured ratio of Q_B to the EWI-measured suspended sand flux (Q_{SAND}) (Text S7 and Figure S3).

6. Results

6.1. Historical Changes in Hydrology

Substantial reductions in mean and peak *Q* occurred during the twentieth century (Walker et al., 2020). Annual mean *Q* decreased by ~30% at GR-GR in 1930 (Table 1 and Figure 2a), and has not changed since, despite large year-to-year variations in flow and cycles of wetter and drier conditions that began in the 1980s. Peak *Q* declined by ~31% at GR-GR in 1924, similar to the reduction in mean *Q* in 1930. These 1920s/30s declines in mean and peak *Q* occurred at the end of the twentieth century pluvial period (Woodhouse et al., 2005) of high runoff. Peak *Q* declined again in ~1959 during the onset of a few years of lower *Q* prior to the 1962 closure of Flaming Gorge Dam (Walker et al., 2020) (Table 1 and Figure 2b). Flood control operations at Flaming Gorge Dam were the primary cause of the sustained reduction in peak *Q*. There have also been statistically significant reductions in peak *Q* on many Green River tributaries that have also affected streamflow in the Green River (Figure S4). Operations of Flaming Gorge Dam have also increased the annual minimum *Q* since the 1960s (Table 1 and Figure 2c) (Andrews, 1986). In each of the mean, peak, and minimum *Q* records at GR-GR, ~13-year cycles of alternating wet and dry years are apparent starting in the 1980s, shown by the 3-year moving averages in Figures 2a–2c. These cycles are similar to those observed in the Little Snake, Yampa, and middle Green rivers by Manners et al. (2014) and Topping et al. (2018).

Changes in Colorado River hydrology were similar to those in the Green River. Annual mean *Q* declined by ~25% in 1930 at CR-Cisco at the end of the twentieth century pluvial period. An additional decline in annual mean *Q* of ~12% occurred in the early 1950s (Table 1 and Figure 2d). An early twentieth century decline in peak *Q* was not detected, possibly because of the short period of record prior to hydrologic change. Peak *Q* did decline by ~55%, however, at CR-Cisco in 1954 (Table 1 and Figure 2e). These mean and peak *Q* reductions were caused by transbasin diversions, flood control operations, and management of many headwater dams (Van Steeter & Pitlick, 1998). As in the Green River, operation of upstream reservoirs increased the minimum *Q* by ~60% in the late 1960s (Table 1 and Figure 2f) (Van Steeter & Pitlick, 1998). Approximately 13-year wet-dry cycles also developed in the Colorado River in the 1980s (Figure 2).

6.2. Historical Changes in Annual Sediment Loads

Annual sediment loads have declined in the Green River since at least 1951. WMW tests indicate that both annual suspended sand and silt-and-clay loads were significantly lower after the 1959 reduction in peak *Q* compared to between 1951 and 1958. This 1959 peak-*Q* reduction is associated with a factor of ~2 decrease in mean annual suspended sand load at GR-GR (Table S1). Since 1959, no statistically significant change in annual suspended sand loads has occurred (Table 2, red line Figure 3), even after removing the estimated San Rafael sand loads from the GR-MB data (Text S6 and Table S2). Changes in suspended sand loads at GR-GR can be used to infer changes in total sand load at either GR-GR or GR-MB, because annual sand bedload is equivalent to ~8% of the annual suspended sand load at GR-MB (Figure S5) and is likely an even smaller fraction at the steeper gravel-bedded GR-GR. Although no significant net decline in suspended sand loads have occurred since 1959, suspended silt-and-clay loads continued to decline; WMW tests indicate that silt-and-clay loads at GR-MB between 2014 and 2018 were significantly smaller than at GR-GR between 1959 and 1984.

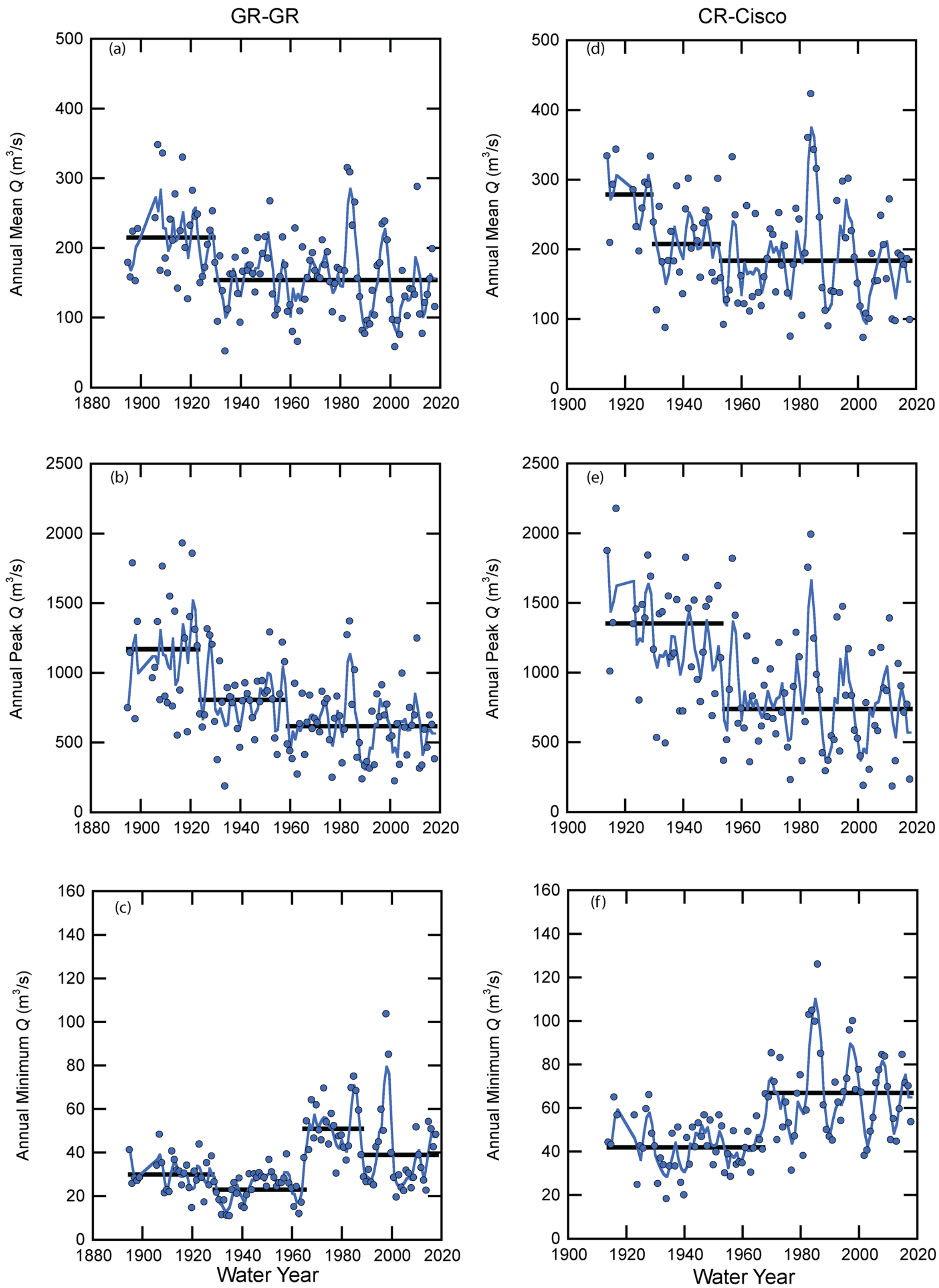

Figure 2. Annual mean Q, peak Q, and minimum Q at GR-GR and CR-Cisco. Annual mean Q is shown in (a) and (d), annual peak Q is shown in (b) and (e), and annual minimum Q is shown in (c) and (f) for GR-GR and CR-Cisco, respectively. Horizontal black lines in (a) and (d) represent the 2-year flood, that is, mean annual, for each period. Horizontal black lines in (a) through (f) are the mean values for each respective period determined to be different by the Pettitt tests. Blue line in each panel is 3-year moving average; note the presence of the wet-dry cycles in both rivers post-1980.

Table 2
Annual Sediment Load Wilcoxon-Mann-Whitney Tests

	Period 1	Period 2	Median period 1 (metric tons)	Median period (metric tons)	Difference between median values (metric tons)	*p* value
GR-GR and GR-MB						
Total sand	1951–1958 (8)	1959–2018 (37)	3.50E + 06	1.30E + 06	2.20E + 06	0.020
Total sand minus estimated San Rafael suspended sand load[a]	1951–1958 (8)	1959–2018 (37)	3.50E + 06	1.30E + 06	2.20E + 06	0.016
Total sand (GR-GR suspended sand vs. GR-MB total sand)	1959–2000 (33)	2014–2018 (5)	1.36E + 06	1.13E + 06	2.27E + 05	0.557
Total sand minus estimated San Rafael suspended Sand load (GR-GR suspended sand vs. GR-MB)[a]	1959–2000 (33)	2014–2018 (5)	1.36E + 06	9.95E + 05	3.66E + 05	0.271
Silt and clay	1951–1958 (8)	1959–2018 (29)	9.95E + 06	5.70E + 06	4.25E + 06	0.029
Silt and clay minus estimated San Rafael loads[a]	1951–1958 (8)	1959–2018 (29)	9.95E + 06	5.70E + 06	4.25E + 06	0.027
Silt and clay (GR-GR vs. GR-MB)	1959–1984 (24)	2014–2018 (5)	6.35E + 06	3.66E + 06	2.70E + 06	0.00857
Silt and Clay minus estimated San Rafael loads (GR-GR vs. GR-MB)[a]	1959–1984 (24)	2014–2018 (5)	6.35E + 06	3.35E + 06	3.01E + 06	0.007
CR-Cisco and CR-POT						
Sand[b]	1951–1985 (33)	1986–2018 (12)	1.30E + 06	690,000	610,000	0.043
Sand (CR-cisco suspended sand vs. CR-POT total sand)	1951–2000 (41)	2015–2018 (4)	1.20E + 06	674,500	525,500	0.115
Silt and clay[c]	1951–1985 (32)	1986–2018 (4)	5.80E + 06	2.30E + 06	3.50E + 06	0.015

Note. Note that the numbers in parentheses are the number of years of data included in the analysis. Gray shading indicates that data sets are statistically different.
[a]Estimated San Rafael loads were subtracted from those at GR-MB. [b]In this case, sand refers to suspended sand through water year 2000, whereas it refers to total sand during the modern, post-2015 period. [c]The silt-and-clay load data for the 1951–1985 and 2015–2018 periods are the same as the silt-and-clay load data for the historical versus modern periods.

Annual sediment loads have also declined in the Colorado River since at least 1951. In contrast to the Green River, this decline has been more gradual and was caused by a reduction in both the sand and silt-and-clay loads. Sand-load reductions appear to be progressive and therefore likely reflect the reduced sand delivery to the Colorado River caused by the cumulative effect of transbasin diversions in sand-supplying tributaries. WMW tests do not indicate a significant decline in annual sand loads after the closure of Blue Mesa Dam on the Gunnison River in 1966 but do show a significant factor of ~2 decline following the closure of McPhee Dam on the Dolores River in 1986 (Tables S1 and Table 2 and Figure 3). The five largest sand load years all occurred after the 1954 decline in peak Q, and before 1986, and correspond to water years with relatively large Dolores River floods (1957, 1958, 1965, and 1973, Figure 3c) indicating the importance of the Dolores River as a former large supplier of sand to the Colorado. For the same reasons as in the Green River, changes in suspended sand loads at the upstream gaging station (CR-Cisco) can be used to infer changes in total sand load at CR-Cisco and CR-POT. Although annual sand bedload is equivalent to ~18% of the annual suspended sand load at CR-POT (Figure S6), bedload is nevertheless a small fraction of the annual suspended sand load in the steeper, gravel-bedded reach at CR-Cisco. Colorado River annual silt-and-clay loads have also significantly declined in our study area; silt-and-clay loads were less for the 2015–2018 period at CR-POT compared to the 1951–1984 period upstream at CR-Cisco (Figure 3, Table 2).

6.3. Effects of Sand Supply and Bed Sand Grain Size on Suspended Sand Transport

Changes in the upstream sand supply have had a large effect on sand transport in both rivers since ~1960. In the Green River, rare large tributary floods have caused abrupt, short-lived increases in the amount of sand supplied to the mainstem channel, causing significant bed fining throughout the Green River downstream from the Yampa River confluence. These periods of bed sand fining and associated increases in C_{SAND} have been followed by longer periods of bed sand coarsening and associated decreases in C_{SAND}. In response, the total annual load of the Green River has increased during times when the bed was relatively fine and decreased over longer periods when the bed was relatively coarse. This supply-driven variation in sand load has caused large episodic changes, but no net change, in Green River sand load since the decrease in peak Q

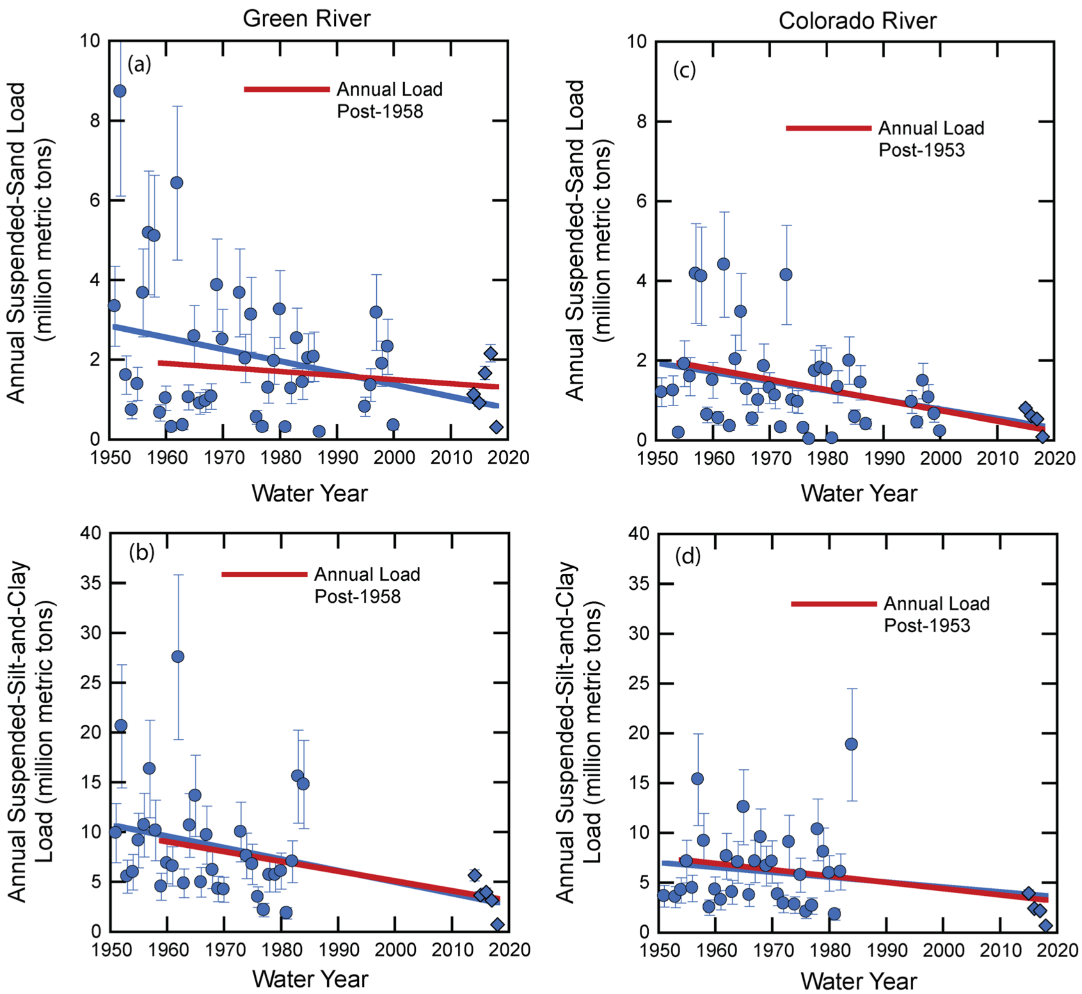

Figure 3. Temporal trends in annual suspended sand load (a) and suspended silt-and-clay load (b) at GR-GR and GR-MB and annual suspended sand load (c) and suspended silt-and-clay load (d) at CR-Cisco and CR-POT. Least squares linear regressions for the entire data sets are shown with a blue line and linear least squares regressions for the data following the reduction in peak flow in 1959 at GR-GR and 1954 at CR-Cisco shown by a red line. GR-MB and CR-POT data shown as diamonds. Error bars indicate ±30% uncertainty for historical loads and ±10% uncertainty for modern loads.

in 1959. In the Colorado River, the upstream sand supply has decreased because of flood control and transbasin diversions in the Dolores River, causing gradual bed sand coarsening and associated decreases in C_{SAND}, and a gradual decrease in sand load.

Analyses of Q at upstream gaging stations in the Green River indicate that there have been two periods of large floods on tributaries that greatly affected the upstream sand supply in the Green River. These two periods were (1) three large floods on the Little Snake River in March 1956, 1962, and 1966 (Topping et al., 2018) and (2) moderate regional tributary flooding on 24–26 July 1977, detected at gaging stations on the Little Snake, Duchesne, and White rivers (Figure 1). The largest sand supplying event during these two periods was likely the 28 March 1962, Little Snake River flood, which mostly emanated from Sand Creek, a key sand-supplying tributary. This flood had a peak Q of 290 m^3/s at LS-Lily (Figure 1), was one of the largest floods on record on the Little Snake, and generated a sand wave with an ~50-year sand transport legacy (Topping et al., 2018; USGS, 2020).

The effects of these large upstream sand inputs during the 1956–1966 and 1977 periods are evident in the ratio of annual sand loads between the GR-Jensen (upstream, Figure 1) and GR-GR or GR-MB (downstream) gaging stations. Suspended sand loads were much larger at GR-Jensen compared to those at either GR-GR or GR-MB in 1960, 1961, 1964, and 1967, and 1977 (Figures 4 and S7), the years following the large Little Snake River floods and other regional floods.

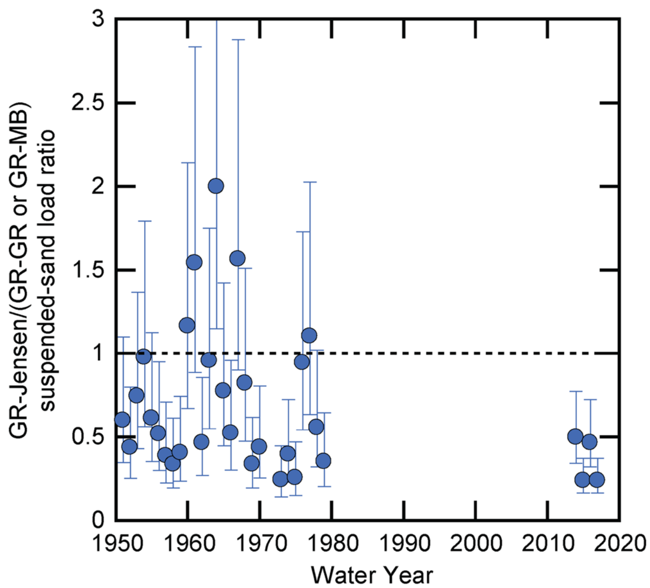

Figure 4. Ratio of the annual suspended sand load at GR-Jensen to the suspended sand load at GR-GR or GR-MB. Error bars indicate the propagated uncertainties defined in the methods; horizontal dashed line indicates ratio of one where the annual suspended sand loads at the two gages are equal. Loads at both GR-Jensen and GR-GR or GR-MB are shown in Figure S7.

In the Green River, the bed sand alternately fines and coarsens depending on the amount of sand recently contributed from upstream tributary watersheds. The large amounts of sand supplied to the Green River during the 1956–1966 and 1977 periods are evident in temporal patterns in β-inferred bed sand grain size at GR-GR. Analyses of Q-detrended β show that there have been four distinct periods at GR-GR where the bed sand fined (decreased β) and/or coarsened (increased β) (Figure 5a). The bed sand at GR-GR significantly fined between 1959 and 1965 (green +'s, Figure 5a), largely coincident with the early 1960s period of large Little Snake River floods and elevated GR-Jensen sand load (Figure 4). Thus, during years where large amounts of sand were supplied to upstream segments of the Green River, bed sand fining rapidly propagated downstream throughout most of the Green River; GR-GR is ~450 km downstream from the Little Snake River and ~285 km downstream from GR-Jensen. After the early 1960s period of bed sand fining, significant coarsening occurred until 1977 (orange x's) (Figure 5a), when β abruptly decreased in likely response to the regional tributary flooding in that year. Following this last documented large tributary sand-supplying event, the bed sand at GR-GR significantly coarsened up to 1984, and the bed sand at GR-MB also significantly coarsened from 2014 to 2018. Because of gaps in the data record, trends in bed sand grain size between 1984 and 2014 are unknown.

Unlike in the Green River, β analyses indicate that there have been no significant bed sand fining events in the Colorado River. The bed sand began to significantly coarsen at CR-Cisco in 1968 after the closure of Blue Mesa Dam on the Gunnison River and after the large Dolores River floods between 1957 and 1965. This coarsening trend continued until at least 1984 (when a data gap occurred) and is ongoing at CR-POT.

In both the Green and Colorado Rivers, the observed changes in bed sand grain size have had a substantial effect on suspended sand transport. For large values of β (i.e., >1.2), C_{SAND} is approximately a factor of 3 times less than that of C_{SAND} for small values of β (i.e., < 0.8) at GR-GR for any given Q (Figure 6a). In the Colorado River at CR-Cisco, this effect is even larger; for large β, C_{SAND} is roughly a factor of 8 times smaller than that of C_{SAND} for small β at any given Q (Figure 6b). In 1962, following the elevated GR-Jensen loads in 1960 and 1961, the GR-GR sand load was a factor of ~5 larger than the sand load in 1984 at the end of the period of bed sand coarsening; this occurred even though the mean and peak Q in 1984 was larger than that of 1962 (Table S1). Similarly, the 1965 GR-GR sand load was approximately the same as in 1983, even though the mean and peak Q in 1965 were ~2/3 of the mean and peak Q in 1965 (Table S1). These examples illustrate how changes in bed sand grain size can have large effects on sand load.

Although the observed changes in bed sand grain size exert a strong control on C_{SAND}, the changes in Q (or u_*) exerted a stronger control on C_{SAND}, as indicated by $|\alpha| < 1$ at all stations over all periods (Figures 5b and 5d), with grain size exerting a stronger control at GR-MB than at GR-GR. This result arises because the annual range in Q was large enough to offset the control of bed sand grain size on C_{SAND} (i.e., $|\alpha| < 1$).

6.4. Systematic Changes in Suspended Sediment Concentration and Grain Size During the Annual Flood

In addition to changes in sand transport driven by decadal periods of fining and coarsening of the bed sand (Figure 5), changes in sand transport in both rivers also occur over the duration of the annual flood. Changes in sand transport during the annual flood are generally indicative of supply limitation, characterized by coupled clockwise Q-C_{SAND} and counterclockwise Q-D_S hysteresis. The degree of supply limitation appears to be strongly controlled by the duration of these floods. Here, we describe the generalized coupled sediment concentration and grain size patterns during the annual flood. The largest difference in these patterns between GR-MB and CR-POT arises from local differences in the grain size architecture of the bed; the

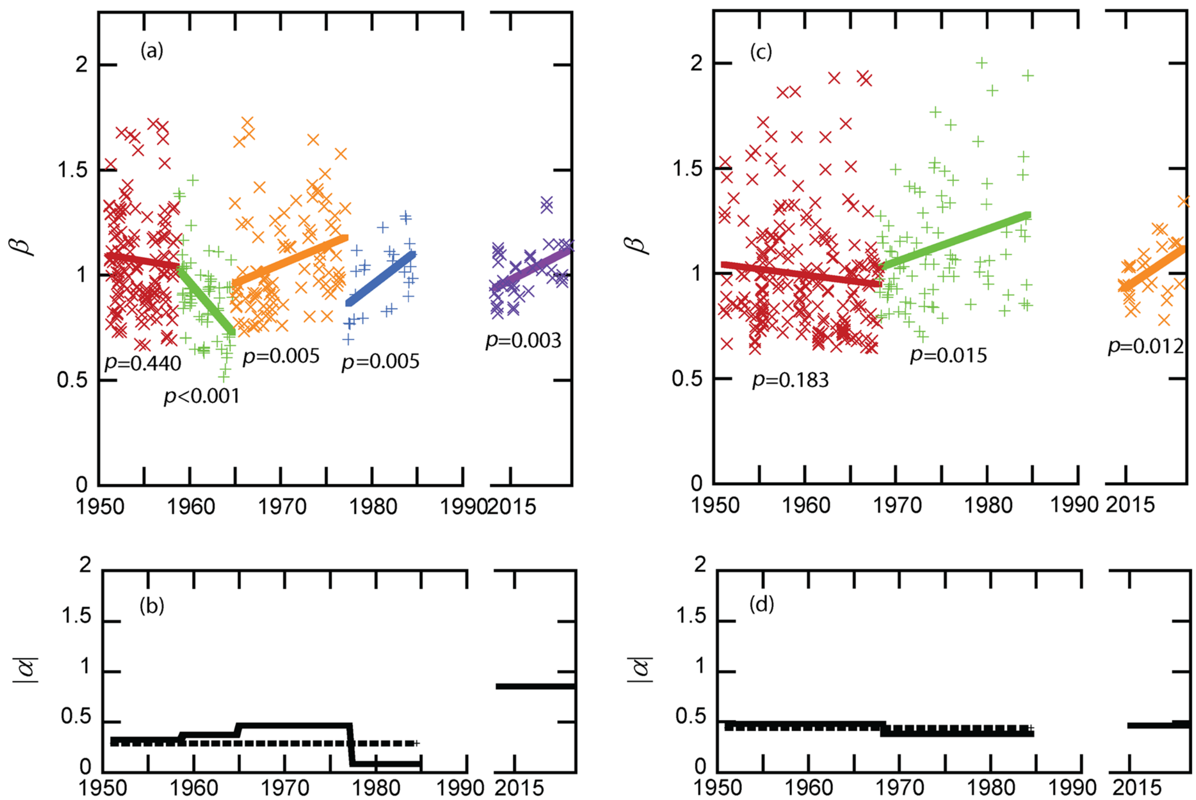

Figure 5. Temporal trends in (a) Q-detrended β and (b) $|\alpha|$ at GR-GR and GR-MB and temporal trends in (c) Q-detrended β and (d) $|\alpha|$ at CR-Cisco and CR-POT. Values of β and $|\alpha|$ calculated using the grain size analyzed EWI measurements. Solid lines in (a) and (c) are linear regressions for individual time periods and p values for each regression are stated. Solid lines in (b) and (d) are $|\alpha|$ values for individual time periods, and dashed lines are $|\alpha|$ values for the entire grain size-analyzed suspended sediment measurement record at GR-GR and CR-Cisco. Values of Q-detrended β at the GR-MB and CR-POT cannot be directly compared to those at GR-GR and CR-Cisco, respectively, owing to the differences in river geometry and hydraulics. Thus, the values of Q-detrended β at GR-MB and CR-POT may be on average higher or lower than those at GR-GR and CR-Cisco.

bed sand tends to be strongly inversely graded, that is, armored, at GR-MB, whereas inverse grading of the bed is not apparent at CR-POT.

6.4.1. Green River at GR-MB

Scour and fill of the bed exerts a strong influence on sand transport during the annual flood at GR-MB. Scour and fill at the GR-MB measurement cross section largely mirror Q during the annual flood (Figure S8); the bed scours during the rising limb of the flood, with maximum scour occurring near peak Q. An average of ~1–2 m and maximum of >6 m of bed scour occurs at GR-MB. Bed scour exposes finer sand at greater depth in the bed, as indicated by β and direct bed sediment measurements (Text S8 and Figures S8–S11). Scour of the bed is associated with a progressive large increase in B_{VF} and small decrease in D_B indicating that the bed is inversely graded. As Q increases and the bed scours, C_{SAND} increases but D_S decreases (Text S8 and Figures S8–S11); theory (e.g., McLean, 1992) dictates that increasing Q will result in increasing D_S in the absence of a large decrease in bed sand grain size. It is the large amount of bed sand fining as the bed scours that gives rise to the larger values of $|\alpha|$ at GR-MB than at GR-GR (Figure 5b). During recession, the bed fills, with bed sand coarsening (i.e., armoring) occurring quickly after recession of the annual flood (Figure S8). Other periods of increasing C_{SAND} coupled to decreasing D_S occur following flash floods on tributaries that supply finer sand. Although bed scour at GR-MB exerts a strong influence on sand transport, this bed scour is likely local and not indicative of all areas in the Green River (Colby, 1964).

Sediment supply limitation is evident in hysteresis patterns for both suspended silt-and-clay and sand at GR-MB (Figures 7 and 8). Q-C_{SAND} hysteresis is typically clockwise and associated with counterclockwise Q-D_S and clockwise D_S-C_{SAND} hysteresis, which is diagnostic of sand supply limitation (Figure 7) (Topping et al., 2000, b; Topping & Wright, 2016). Moreover, the magnitude of the clockwise Q-C_{SC} hysteresis during the annual flood is greater than that for Q-C_{SAND} (Figure 8), indicating greater limitation in the

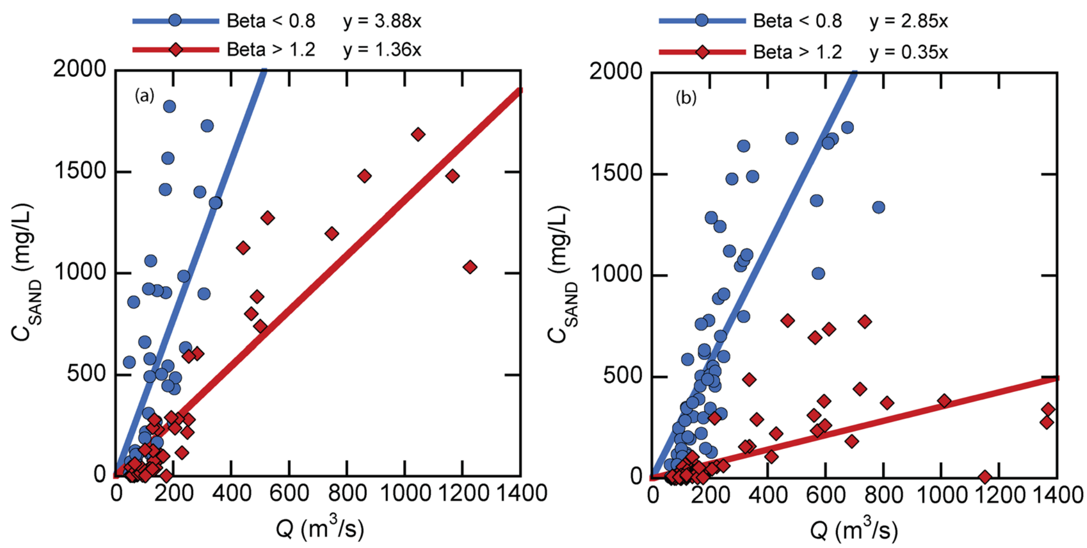

Figure 6. Relations between Q and C_{SAND} for small and large values of Q-detrended β at GR-GR (a) and CR-Cisco (b), respectively. Solid lines are best fit least squares regressions, with y intercept forced through the origin.

upstream supply for silt and clay. Although the magnitude of Q-C_{SAND} hysteresis during any 1 year is small, there is substantial interannual variability in the Q-C_{SAND} and Q-D_S relations arising from the interannual variability in sand supply (Figures 7a and 7b).

The 15-min acoustical measurements fully illustrate the complexity of the hysteresis loops at GR-MB. This complexity arises because sediment depletion occurs in a stepwise manner between different Q pulses during the annual flood. Instead of the broad open loops encompassing the entire annual flood suggested by the sparse EWI measurements in Figure 7, the 15-min measurements indicate that relatively tight clockwise Q-C_{SAND} and Q-C_{SC} hysteresis loops exist during each Q pulse, with larger downward shifts between these loops occurring between each of the pulses, as shown during the 2016 flood (Figure 8). This flood consisted of two small initial rises, followed by three larger Q pulses between mid-May and mid-July. Of these three larger pulses, each successive pulse increased in Q (Figures 8a and 8b). The largest C_{SAND} and C_{SC} occurred during the first and smallest of these pulses (Figures 8a and 8b). Despite the increasing Q with each successive pulse, C_{SAND} did not increase, and C_{SC} decreased, thus indicating depletion of the upstream sediment supply. H indices indicate that most of the depletion occurred between the Q pulses. The H indices associated with the downward steps in C_{SAND} and C_{SC} between the pulses are typically as large or larger than those associated with the Q-C_{SAND} and Q-C_{SC} loops during each pulse (Figures 8c and 8d).

6.4.2. Colorado River at CR-POT

Sand transport at CR-POT differs from that at GR-MB owing to the lack of an inversely graded bed. In addition, there is a much greater lag in bed elevation response during the annual flood at the CR-POT measurement cross section than at GR-MB. Although the bed at the CR-POT cross section scours during the rising limb, the magnitude of bed scour there is much smaller than at GR-MB (i.e., ≤1 m), and the bed at CR-POT fills slowly until the rise of the annual flood the following year. During the rising limb of the annual flood, the bed scours, the bed sand coarsens, C_{SAND} increases, and D_S coarsens slightly (Text S8 and Figures S12–S15). As the annual flood recedes, C_{SAND} decreases and D_S fines. Although the bed sand and D_S coarsen during the rising limb, β decreases; the only plausible explanation for decreases in β as the bed sand coarsens at the measurement cross section is that the flow interacts with finer bed sand in the reach upstream at higher Q. As at GR-MB, there are short periods of elevated C_{SAND} coupled to lowered D_S following sand-supplying flash floods on upstream tributaries during the summer thunderstorm season. Bed scour and fill at CR-POT is also likely local and not indicative of scour and fill patterns in all areas of the Colorado River.

Although some similarities in sediment transport exist at GR-MB and CR-POT, there are also key differences. Similar to GR-MB, the style of suspended sand hysteresis present at CR-POT is diagnostic of sand supply limitation; clockwise Q-C_{SAND} hysteresis occurs and is coupled to counterclockwise Q-D_S and clockwise

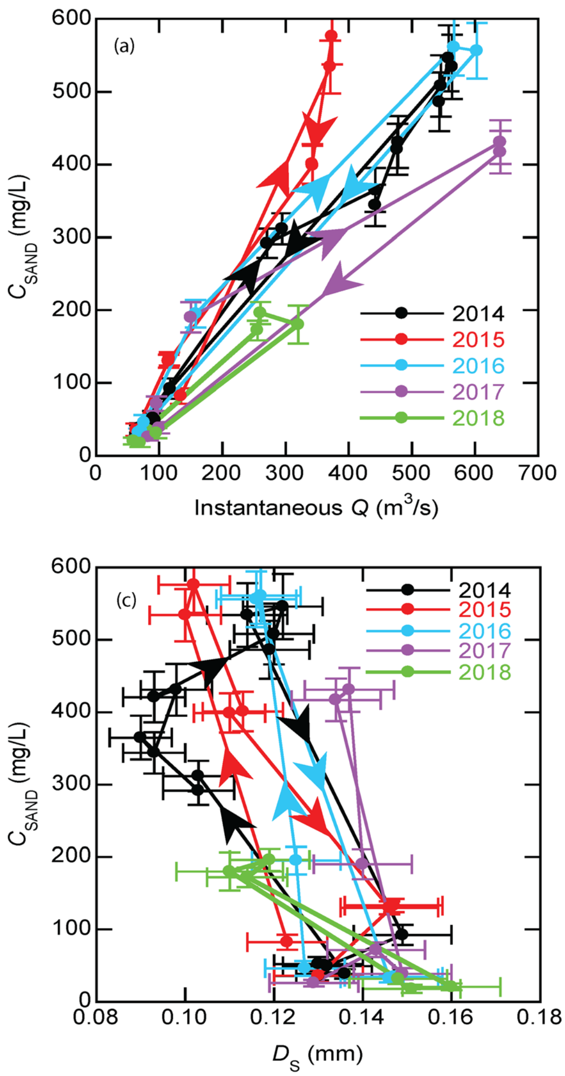

Figure 7. Plots showing the coupled (a) clockwise Q-C_{SAND} hysteresis, (b) counterclockwise Q-D_S hysteresis, and (c) clockwise D_S-C_{SAND} hysteresis evident in the EWI measurements at GR-MB. Data segregated by calendar year; error bars indicate 95% confidence level combined field and laboratory errors in the EWI measurements (Topping et al., 2010; Topping et al., 2011). Color-coded arrows indicate direction of each hysteresis loop. Arrows are not shown for 2018 because only negligible hysteresis is evident in data for that year. Only the most accurate, that is, the EWI, measurements are plotted in this figure and in Figure 9. Because these measurements are not continuous, the magnitudes of the hysteresis loops would be larger, but more confusing/complex, if the acoustical and calibrated-pump measurements were included, as in the example in Figures 8 and 10.

D_S-C_{SAND} hysteresis (Figure 9). However, there is less interannual variability in the relations among these variables at CR-POT, because there is less interannual variability in the sand supply. The degree of upstream supply limitation of silt and clay is less than at GR-MB and is similar to the magnitude of limitation for sand, as shown by the H indices during the 2016 flood (Figure 10). The rising limb of the annual flood at CR-POT tends to consist of a series of pulses of increasing Q (Figure 10). Relatively tight clockwise Q-C_{SAND} and Q-C_{SC} hysteresis loops exist during each Q pulse, with downward shifts in C_{SAND} and C_{SC} between each of the pulses. Unlike at GR-MB, however, the hysteresis associated with the downward shifts in C_{SAND} and C_{SC} between pulses is no larger than the magnitude of the hysteresis during the pulses, as indicated by the H indices (Figure 10). H index evaluation of the other years of data suggests that these similarities and differences at GR-MB and CR-POT are common.

6.5. Effects of Flood Duration on Sand Depletion

Larger $|\alpha|$ during annual floods requires larger amounts of sand depletion at GR-MB and CR-POT because of the type of Q-C_{SAND}-D_S hysteresis diagnostic of sand supply limitation. α analyses indicate that longer-

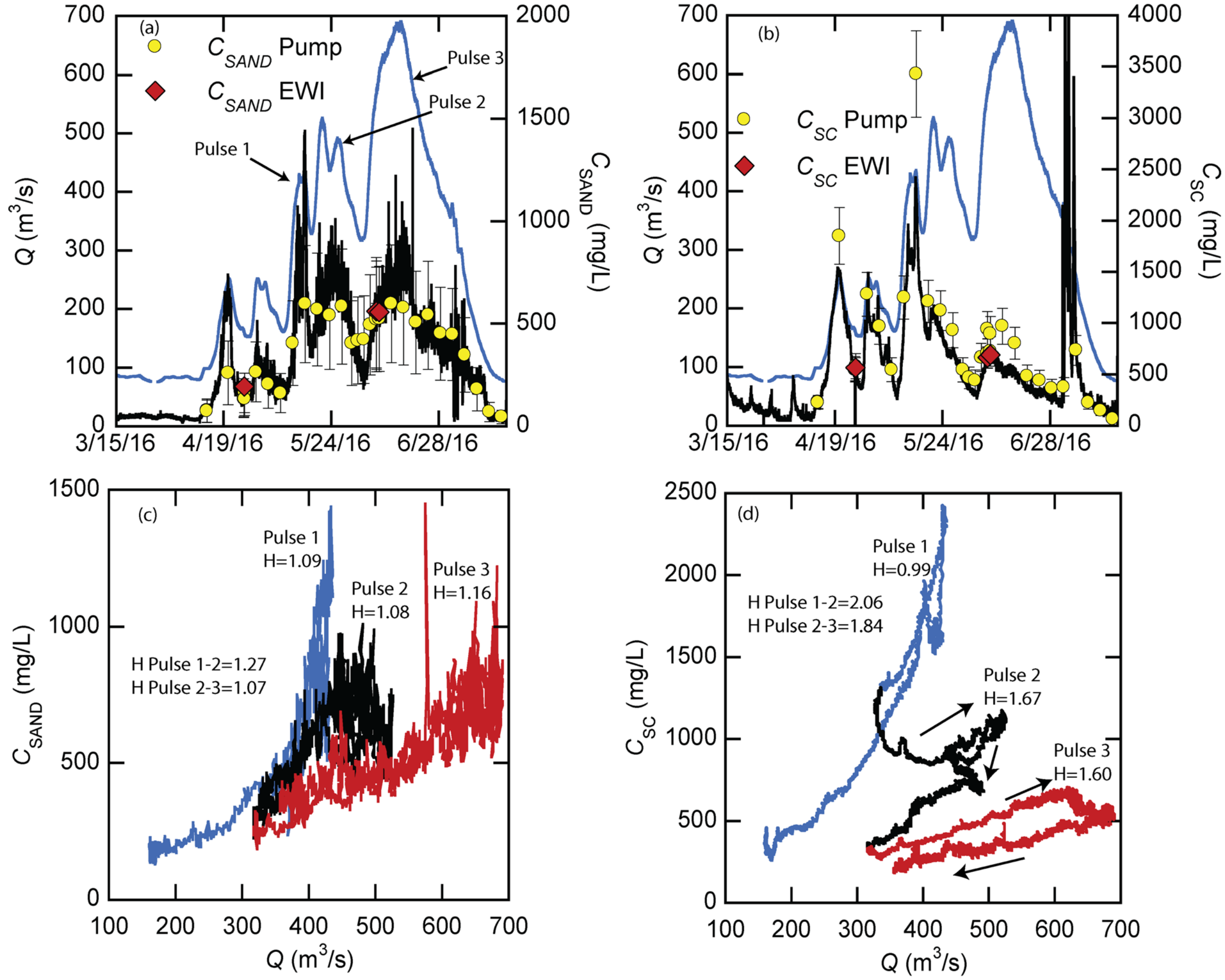

Figure 8. Discharge and sediment-concentration characteristics during the 2016 snowmelt flood at GR-MB. Time series of Q and C_{SAND} and Q and C_{SC} are shown in (a) and (b), respectively. Relations between Q and acoustical measurements of C_{SAND} and Q and acoustical measurements of C_{SC} are shown in (c) and (d), respectively. In (a) and (b), Q is shown by blue line, acoustical suspended sediment concentrations are shown by black line, calibrated-pump concentrations are shown by yellow circles, and EWI concentrations are shown by red diamonds. Error bars on samples indicate 95% confidence level combined field and laboratory error (Topping et al., 2010, 2011). In (c) and (d), each pulse is represented by a different color, and the H index is indicated for each pulse and between pulses, based on average concentrations over the same Q range. The large C_{SC} spikes in (b) near the end of the flood were caused by local tributary floods; the effects of these spikes have been removed from (d).

duration annual floods, specifically longer-duration rising limbs, cause sand depletion in both rivers. In the Green River, α analyses indicate that peak Q is also important in driving sand depletion. The value of $|\alpha|$ calculated during the rising limb of the annual flood in the Green River is very strongly correlated with peak Q ($r = 0.8$) and the duration of the rising limb ($r = 0.9$) (Figures 11a, 11b, and S16). Additionally, substantial grain size regulation of C_{SAND} occurs during almost all floods at GR-MB, because most of the $|\alpha|$ values exceed 1. At CR-POT, however, rising limb $|\alpha|$ is uncorrelated with peak Q ($r = 0.05$) but strongly correlated with the duration of the rising limb ($r = 0.7$) (Figures 11c, 11d, and S17). At CR-POT, where there is less variability in D_S, and thus lower $|\alpha|$, grain size regulation of C_{SAND} does not occur until the rising limb duration exceeds ~90 days. Substantial sand depletion thus requires floods of very long duration in the Colorado River.

7. Discussion

7.1. Linkages Between Changes in Hydrology, Sediment Transport, and Geomorphology

Potentially offsetting processes of sediment deposition on the channel margins (channel narrowing) and sediment depletion within the channel (bed sand coarsening) have been occurring in the Green and

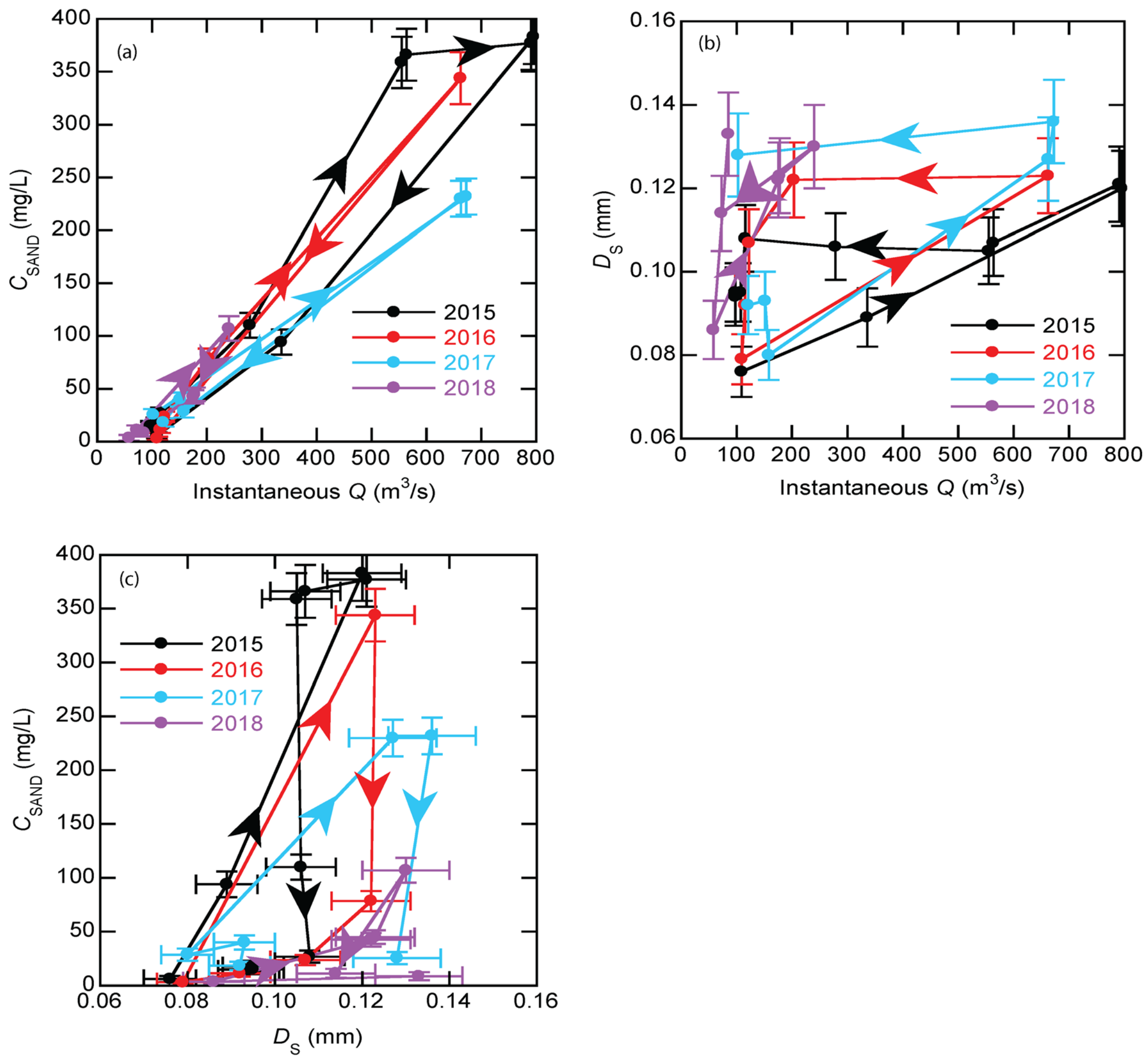

Figure 9. Plots showing the coupled (a) clockwise Q-C_{SAND} hysteresis, (b) counterclockwise Q-D_S hysteresis, and (c) clockwise D_S-C_{SAND} hysteresis evident in the EWI measurements at CR-POT. Data segregated by calendar year; error bars indicate 95% confidence level combined field and laboratory errors in the EWI measurements (Topping et al., 2010, 2011). Color-coded arrows indicate direction of each hysteresis loop.

Colorado Rivers simultaneously. Both rivers narrowed over most of the last century, and narrowing accelerated in the 1980s (Head, 2020; Walker et al., 2020). During the same period, suspended sand loads decreased (Figure 3), there were long periods of bed sand coarsening (increases in β, Figure 5), downward shifts in relations between Q and C_{SAND} (Figure 6), and hysteresis patterns indicative of sediment depletion during long-duration floods in both rivers (Figures 7–10). Bed sand coarsening appears to be associated with decreases in the tributary sediment supply from the Yampa River, which appear to be largely natural (Topping et al., 2018), and from other rivers with large declines in peak Q caused by water development (Duchesne, Price, San Rafael, Gunnison, Dolores). These results raise the questions, how do the geomorphic observations that imply sediment surplus relate to the sediment transport observations that imply sediment deficit? Does the volume of sediment eroded from the channel bed during periods of bed sand coarsening offset the volume of sediment involved in channel narrowing? Are these rivers in sediment surplus or sediment deficit?

Andrews (1986) argued that the magnitude of channel narrowing in the Green River could be predicted using hydraulic-geometry relations based on the changes in Q caused by flood control operations at Flaming Gorge Dam. Andrews (1986) supported this claim by finding no change in the relations between Q and sediment load after the closure of Flaming Gorge Dam; however, sediment load variation of 1 to 3

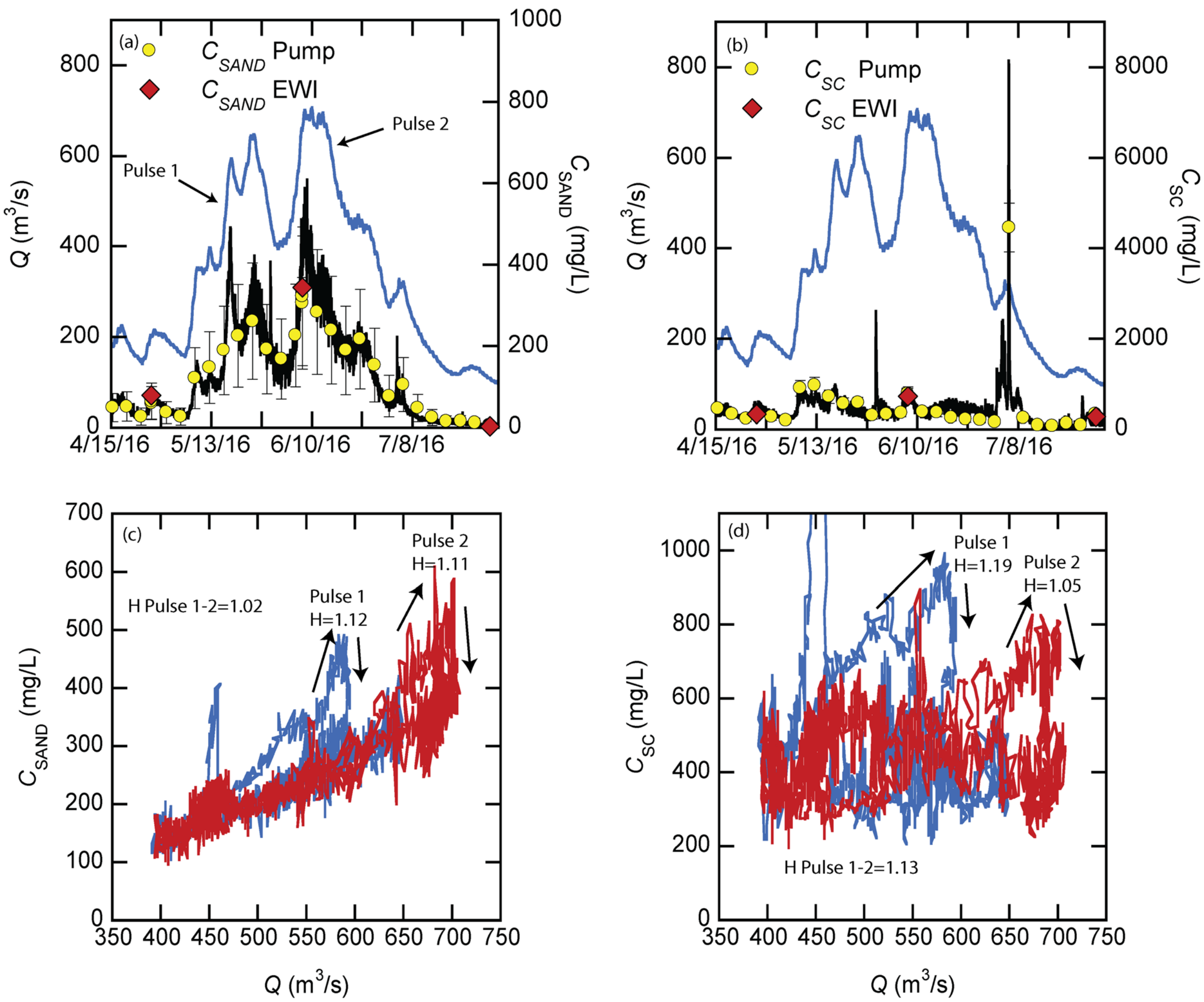

Figure 10. Discharge and sediment-concentration characteristics during the 2016 snowmelt flood at CR-POT. Time series of Q and C_{SAND} and Q and C_{SC} are shown in (a) and (b), respectively. Relations between Q and acoustical measurements of C_{SAND} and C_{SC} are shown in (c) and (d), respectively. In (a) and (b), Q is shown by blue line, acoustical suspended sediment concentrations are shown by black lines, pump sample concentrations are shown by yellow circles, and EWI concentrations are shown by red diamonds. Error bars represent 95% confidence intervals as in Figure 8. In (c) and (d), each pulse is represented by a different color, and the H index is indicated for each pulse and between pulses, based on average concentrations over the same Q range. The effects of the large C_{SC} spikes in (b) caused by local tributary floods have been removed from (d).

orders of magnitude for any given Q were not addressed. He concluded that following closure of Flaming Gorge Dam, the Green River was perturbed into a condition of sediment surplus (aggradation) in our study area, whereby the river was not able to convey the imposed upstream sediment supply. The reduction in Q, combined with an assumption that the tributary sediment supply was unchanged, was the cause of this sediment surplus.

Here, we show that much of the variation in sediment transport relations (e.g., Q-C_{SAND}) in the Green River is caused by systematic changes in the upstream sediment supply, manifest in changes to the bed sand grain size distribution. Large upstream tributary inputs of sand can cause the bed sand to fine and C_{SAND} to increase. This is generally followed by bed sand coarsening and decreases in C_{SAND} over years to decades during periods of relative tributary quiescence. Smaller changes in sediment supply also occur during long-duration annual floods when the local sediment supply is depleted as shown by declines in C_{SAND} and increases in D_S during these floods. Thus, even though sand loads decreased following the 1959 reduction in peak Q made permanent by Flaming Gorge Dam operations, changes in sand supply have caused similar magnitudes of change in sand transport. Systematic changes in bed sand grain size caused by the early 1960s and 1977 tributary floods (Figure 5) are associated with changes in sand load of a factor of ~2

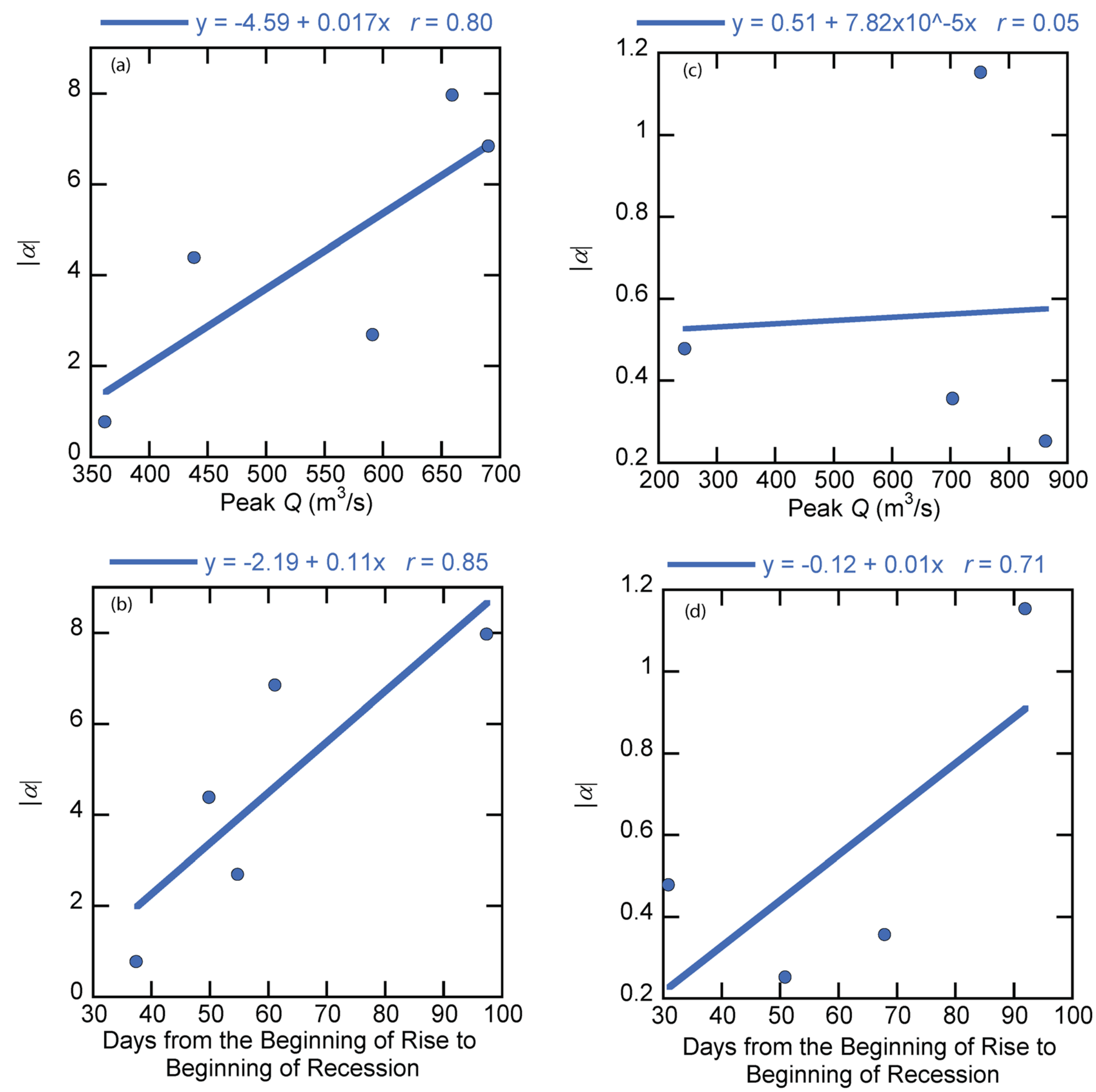

Figure 11. Relations between (a, c) rising limb $|\alpha|$ and peak Q and (b, d) rising limb $|\alpha|$ and the duration of the rising limb of the annual flood. Relations for GR-MB are in (a) and (b), relations for CR-POT are in (c) and (d). $|\alpha|$ values were calculated using the 15-min acoustical suspended sand measurements made during the rising limb, defined in section 5.6.

or more (Figures 3 and 6, Table S1), although there are large uncertainties in the historical sand loads. This is similar to the factor of ~2 decrease in sand load caused by the 1959 decline in peak *Q* (Table S1).

In the Colorado River, the channel has also narrowed (Head, 2020; Van Steeter & Pitlick, 1998), while progressive reductions in sediment supply and loads have occurred since the 1960s (Figures 3 and 5). Progressive bed sand coarsening associated with the reduction in sand supply has resulted in a factor of ~2–3 decrease in sand load (Figures 3, 5, and 6 and Table S1). Like Andrews (1986), Pitlick and Cress (2002) and Pitlick and Van Steeter (1998) used hydraulic geometry relations to demonstrate that the Colorado River, despite recent narrowing, was in quasi-equilibrium, whereby downstream changes in width and depth were maintained by flows slightly greater than those required to mobilize the bed. However, these studies were conducted in the largely gravel-bedded segments upstream that partially overlap our roughly half sand-bedded study area; this difference thus precludes direct comparison between our study and theirs. The results from our study indicate that the sediment transport regime continues to adjust to a reduction in the upstream sand supply.

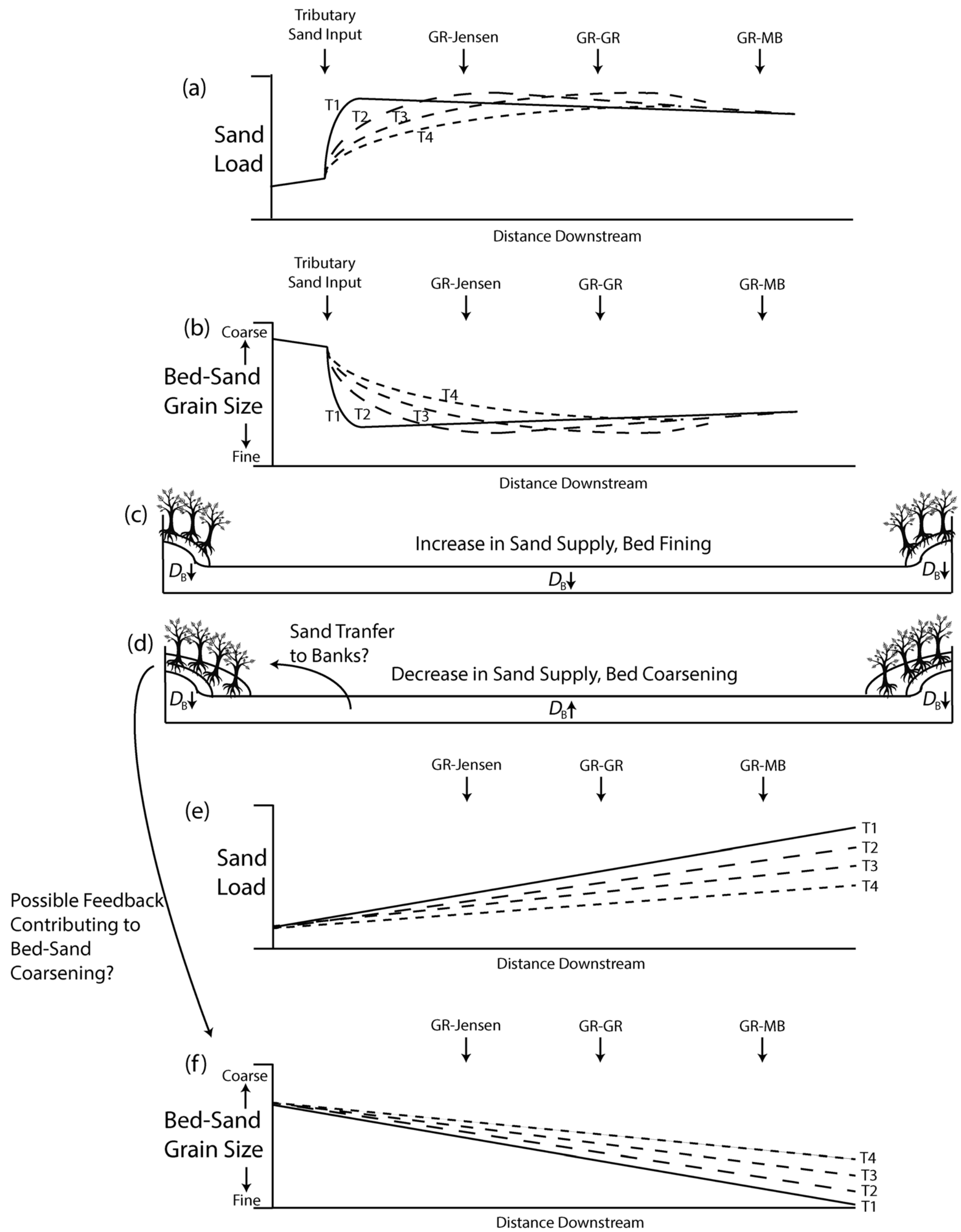

Figure 12. Conceptual model describing changes in sand load, bed sand grain size, and geomorphic change. Longitudinal changes in sand load and bed sand grain size following large sand-supplying floods from upstream tributaries are shown in (a) and (b), respectively. In this case, tributary inputs of sand cause abrupt increases in sand load and decreases in bed sand grain size that propagates through the river network relatively fast, shown by times T1–T4. The relatively fine bed is depicted in the channel cross section (c). When there are long periods between tributary supplying floods, or no upstream tributaries that supply large amounts of sand, the bed sand coarsens (d). Erosion of the finest grain size fractions from the channel bed can be a source for deposition along the vegetated channel margins. When the sand supply is not replenished by tributaries, progressive declines in sand load and bed sand coarsening can occur as shown in (e) and (f). Vegetation can promote channel narrowing by establishing within the channel during multiple low flow years, reducing the channel margin flow velocities, and trapping sediment (d). For the case of the Green River, the relative longitudinal positions within the watershed of the GR-Jensen, GR-GR, and GR-MB gages are shown in (a) and (b) and (e) and (f). However, trends in sand load and bed sand grain size also apply to the Colorado River.

A summary of how changes in sand supply affect sand load and bed sand grain size is presented in a conceptual model (Figure 12). Following large sand-supplying floods from upstream tributaries, the sand load increases, and the bed fines (Figures 12a and 12b). This represents the Green River in the late 1950s and 1960s when a phase of channel narrowing began with reductions in peak Q in 1959 (Allred & Schmidt, 1999) and when there were large tributary sand inputs (Figure 12c). However, during relative tributary quiescence, when there are no upstream sand inputs, the sand supply becomes progressively depleted, through winnowing of the fine tail of the bed sand grain size distribution, resulting in declines in sand load (Figures 12d–12f). This is what appears to have occurred in the Green River between 1966 and the bed sand fining event in 1977 and from 1977 to 1984. This is also what appears to have occurred in the Colorado River between 1968 and 1984, which has likely continued until present day.

Our analyses of sediment transport allow further evaluation of the previous estimates of sediment surplus conditions in the Green River and possible surplus or deficit conditions in the Colorado River. In the Green River, Allred and Schmidt (1999) showed that channel narrowing by ~17 m occurred at the upper end of our study area between 1962 and 1985 by vertical aggradation of ~1.1 m of sediment on top of bars within the active channel; aggradation occurred in 12 of the years in this period. Walker et al. (2020) showed that the Green River within and below the study area narrowed by ~12 m between the mid-1980s and 2014 by the vertical aggradation of ~1.5 m of sediment also on top of active channel bars. These numbers indicate that ~1.5 and ~2 million metric tons of sand accumulated along the ~110-km river segment in our study area (GR-GR to GR-MB) between 1962 and 1985 and the mid-1980s and 2014, respectively. These quantities are equivalent to ~3% and ~4% of the average annual sand load over these respectively time periods or ~1% of the sand load prior to 1959. Thus, channel margin and floodplain deposition of only a small amount of the annual load is required to achieve the observed channel narrowing (Walker et al., 2020). This is consistent with the findings of Grams and Schmidt (2005) that floodplain accretion in Dinosaur National Monument was ~1% of the annual sand load.

Furthermore, the approximate amount of sand deposited along the channel margins and on the floodplain could be entirely accommodated by only ~10 cm of erosion of bed sand throughout the ~110-km segment between GR-GR and GR-MB from 1962 to 2014, equivalent to ~2–3 mm of bed erosion per year. Depending on the thickness of the active layer, substantial changes in bed sand grain size can occur with relatively little geomorphic change. Walker (2017) and Allred and Schmidt (1999) detected no change in the bed elevation; 10 cm of bed elevation is difficult to detect given that scour and fill of a couple meters occur annually (Walker, 2017). However, Grams et al. (2020) showed that ~10 cm of reach averaged erosion does occur during some annual floods. Thus, even though both the Green and Colorado Rivers have progressively narrowed, the amount of sand within the deposits responsible for the narrowing in the Green River could entirely be sourced from sand on the channel bed, accommodated through a relatively small amount of bed erosion. In addition, the bed sand coarsening associated with the decrease in the upstream sand supply in both rivers could be caused by some sequestration of the finer sand along the channel margins and on the floodplain; increases in vegetation could exacerbate this process (Figures 12d–12f), as discussed further in section 7.2. Only a small amount of the annual load would need to be sequestered, and the accompanying decrease in load would be much smaller than the load decrease observed during periods of bed sand coarsening. Therefore, bed sand coarsening may not indicate that depletion of the upstream sand supply is occurring by transport of all sand downstream but rather by partial sequestration of sand in the channel banks and floodplains. These approximations therefore do not support Andrews' (1986) finding that the Green River within our study area is in sediment surplus. Our data suggest that the sediment mass balance in the Green River is likely indeterminate, as indicated by Schmidt and Wilcock (2008).

Unlike in the Green River, there are no undeveloped large tributaries that supply sand to the Colorado River upstream from or in our study area to offset the sand supply depletion indicated by the progressive bed sand coarsening. Thus, even though channel narrowing has occurred in the Colorado River as in the Green River, it may be possible that the Colorado River has been perturbed into a state of sediment deficit given the reduction in fine sediment from upstream tributaries; reduction in floods and fine sediment from the Gunnison and Dolores rivers are likely the largest drivers contributing to potential sediment-deficit conditions. A possible condition of sediment deficit is also apparent in the long time (i.e., 1 year) that it takes for the Colorado River at CR-POT to fill following channel bed scour during the annual floods (Figure S13). Greater lags in bed elevation response during floods indicate greater sediment supply depletion (Topping, Rubin, Nelson, et al., 2000). At cross sections that scour during a flood, a bed elevation response where bed scour and fill mirror Q indicates negligible sediment supply depletion. Thus, the much greater lag in fill during recession at the CR-POT cross section compared to at GR-MB suggests that the Colorado River is in greater sediment deficit than the Green River.

These findings indicate that channel narrowing in sand-bedded rivers does not necessarily mean that they are in sediment surplus (c.f., Grams & Schmidt, 2005; Schmidt & Wilcock, 2008). Patterns of hysteresis indicative of sediment depletion and systematic reductions in C_{SAND} driven by bed sand coarsening indicate that large sand-bedded rivers can at times be supply limited, even if they are narrowing. Thus, caution should be used when applying hydraulic-geometry relations to predict changes in channel geometry.

Regardless of the findings concerning the sediment mass balance, channel narrowing has been shown to negatively impact instream aquatic habitat because sand bars, secondary channels, and other low-velocity habitats, which are important for the rearing and growth of native juvenile fish, fill with sediment and become abandoned (Bestgen et al., 2012; Valdez & Nelson, 2004). This begs the question, what flow and sediment transport conditions are necessary to prevent or reverse the progressive channel narrowing that is underway? Reversal of channel-narrowing processes necessarily implies that net erosion must occur. In terms of sand transport, the amount of erosion will depend on the magnitude of the coupled clockwise Q-C_{SAND} and counterclockwise Q-D_S hysteresis during annual floods. As demonstrated in Figures 7 and 9, all five of the 2014–2018 annual floods at GR-MB and all four of the 2015–2018 annual floods at CR-POT exhibit this style of coupled Q-C_{SAND}-D_S hysteresis indicative of sediment depletion. Rising limb values of $|\alpha|$ calculated for the individual annual floods (Figure 11) indicate that long-duration floods, specifically floods with longer rising limbs, are the most effective mechanism for driving sediment depletion in both rivers, with larger floods having similar importance in the Green River.

Thus, any river management action that results in additional reductions in peak Q or flood duration, including changes in dam management or increased water extraction from upstream tributaries, will likely reduce the magnitude of the coupled Q-C_{SAND}-D_S hysteresis loops and cause additional sediment accumulation and narrowing in the Green and Colorado Rivers. These findings corroborate findings in other sand- or gravel-bedded rivers that demonstrate that flood duration may be equally, if not more important, in exhausting the upstream sediment supply and causing erosion (Costa & O'Connor, 1995; Draut & Rubin, 2013; Dean et al., 2016; Hickin & Sichingabula, 1988;).

7.2. Ecohydraulic Effects of Vegetation on Geomorphic Processes

It is well established that riparian vegetation can substantially modify fluvial processes (Dean & Schmidt, 2011; Dean & Topping, 2019; Diehl et al., 2017; Griffin et al., 2005; Manners et al., 2015; Perignon et al., 2013; Tal et al., 2004; Vincent et al., 2009). Vegetation reduces channel margin flow velocities (Griffin et al., 2005; Manners et al., 2015), roots bind fluvial deposits thereby increasing the threshold required for erosion (Abernethy & Rutherford, 2001; Gran et al., 2015; Pollen, 2007), plant stems increase the form drag on fluvial deposits thereby reducing the boundary shear stress (Manners et al., 2015; Nepf, 1999) and promoting deposition (Butterfield et al., 2020; Diehl et al., 2017; Le Bouteiller & Venditti, 2014; Zong & Nepf, 2010), and sufficient vegetative roughness can disrupt flood conveyance (Burkham, 1976a, 1976b; Dean & Topping, 2019; Gellis et al., 2017; Juez et al., 2019).

Historically, the Green and Colorado Rivers contained numerous large, bare sand bars. Channel narrowing in the Green River occurs during multiyear periods of reduced peak Q, when riparian vegetation can establish within the channel on bare surfaces and not get subsequently scoured (Graf, 1978; Walker et al., 2020). Vegetation encroachment associated with reduced hydrologic disturbance has been shown to drive channel narrowing in other field and numerical studies (Eke et al., 2014; Manners et al., 2014). In this sense, the dominant mechanism that may drive channel narrowing in the Green and Colorado Rivers is a reduction in peak Q that persists long enough for new vegetation to successfully establish, withstand erosion, and trap sediment (Walker et al., 2020). This process may be exacerbated by the dam-induced increases in the annual minimum flows since the 1960s (Figure 2), which potentially provide artificial water availability to plants during naturally dry times of the year. The Green River downstream from the study area is now ~12–15% narrower than in 1940, and the river corridor is densely vegetated. The greatest amount of narrowing has occurred since the 1980s, beginning during a low-flow period of a wet-dry cycle. Such cycles were documented throughout the upper Green River and Yampa River watersheds by Manners et al. (2014) and Topping et al. (2018) and are similar to those detected in the Colorado and Snake river basins by White et al. (2005).

Channel narrowing by floodplain growth is coupled to sediment transport because sediment deposition is required for narrowing to occur. Given that most depositional environments (e.g., floodplains) are elevated above the channel bed, deposition in these environments occurs through the deposition of the finest sediment in suspension (fine sand, silt, and clay) from the upper part of the water column. Walker (2017) showed that the sediment along the channel margins and on the floodplain is substantially finer than that on the bed of the active channel. Thus, as channel narrowing occurs by deposition of the finest part of the upstream sediment supply on the vegetated channel margins, this sequestration of part of the finer sand may result in bed sand coarsening within the channel (Figure 12d). The documented reductions in the upstream sand supply are the dominant drivers of bed sand coarsening in both rivers, as shown by bed sand coarsening during periods of relative tributary quiescence. However, the sediment trapping ability of vegetation could play an important secondary role in bed sand coarsening.

Given the detailed analyses of changes in sediment transport and sediment supply, and the refined understanding of channel change mechanisms in the Green River (Walker et al., 2020), determination of long-term sediment surplus/deficit conditions may be irrelevant when trying to predict channel change. Channel change in the Green River occurs during discrete periods of consecutive years of small floods, paired with the establishment of vegetation within the channel. Generalizations of possible surplus/deficit conditions, such as those made by Andrews (1986) and Schmidt and Wilcock (2008), may be too imprecise to be used to predict channel change, especially when there is conflicting evidence of surplus and deficit conditions (e.g., channel narrowing indicating possible surplus, and bed-coarsening implying possible deficit). Instead, the ecohydraulic conditions that exist during the discrete periods of channel change are important, not whether the long-term sediment budget is in surplus or deficit.

Given that the channel banks of the Green and Colorado Rivers are densely vegetated, and thus, stable, it is likely that substantial increases in Q, potentially paired with vegetation management/removal, may be the only mechanism by which increases in channel width may occur. Increases in Q alone may be insufficient to cause channel widening because dense stands of riparian vegetation increase bank strength and substantially reduce flow velocities along the channel banks, thereby potentially offsetting the increases in τ_B on the banks that may occur with larger Q. Large-scale removal of nonnative tamarisk is currently occurring along the Dolores River, and biocontrol of tamarisk throughout both the Green and Colorado Rivers (Bedford et al., 2018) is ongoing using a beetle (*Diorhabda* spp.) that feeds on that plant. In a few circumstances, vegetation removal has resulted in bank erosion and channel widening (Vincent et al., 2009); however, those effects are usually local and not widespread (Jaeger & Wohl, 2011; Keller et al., 2014). Thus, even if large, long-duration snowmelt floods occur, and sufficient sediment depletion occurs, channel widening is likely to be limited because of the ecohydraulic effects of vegetation.

The maintenance of existing bare in-channel bars, however, is possible if no further reductions in Q occur. Given that these environments are free of vegetation, the maintenance of these features will depend upon the magnitude and duration of the annual flood. Bare surfaces will only be maintained if these floods contain a sufficiently long period of elevated Q to scour seedlings and deplete the available sediment supply such that deposition within these environments is limited. Our results indicate that annual floods with longer durations may be more successful in maintaining current channel geometries in the Green and Colorado Rivers than shorter-duration floods with larger peaks. In addition, longer-duration floods that do not inundate floodplains, and thereby cause additional floodplain deposition, may be the most successful at maintaining current channel geometries.

8. Conclusions

Comprehensive analyses of suspended sediment transport provide valuable insight into fluvial geomorphic change driven by changes in sediment supply. The sediment supply within a river system evolves depending on the discharge, duration, and frequency of floods, changes in sediment contributions from tributaries or other sources, and the ecohydraulic conditions that modify sediment transport processes. Geomorphic change is caused by spatial changes in the sediment flux, which can be caused by changes flow, sediment supply, or both. Therefore, analyses of sediment transport, such as those herein, provide insight regarding geomorphic processes that may be driven by changes in sediment supply.

The concentration of sand in suspension is controlled by both flow conditions and the bed sand grain size distribution within the channel. Reductions in peak discharge combined with periods of bed sand coarsening have occurred in both the Green and Colorado Rivers. In the Green River, bed sand fining driven by large upstream tributary inputs of sand between 1956 and 1966, and in 1977, has offset longer periods of bed sand coarsening, resulting in no net change in sand loads since 1959. The bed sand fining caused by these sand-supplying events propagates many hundreds of kilometers downstream within one to a few years in the Green River. Subsequent bed sand coarsening then occurs for decades. In the Colorado River, water development in key sand-supplying tributaries appears to have caused declines in the upstream sand supply, manifested in progressive bed sand coarsening, and declines in sand loads since the late 1960s. Changes in bed sand grain size have caused changes in suspended sand concentration by factors of ~3 and ~8 in the Green and Colorado Rivers, respectively.

Hysteresis patterns among discharge and silt-and-clay concentration, sand concentration, and the suspended sand median grain size show that large, long-duration floods result in sediment depletion in both the Green and Colorado Rivers. Even though sediment depletion occurs, processes of channel narrowing are ongoing, which is likely governed by reductions in peak discharge and aided by the ecohydraulic reductions in the boundary shear stress along the channel margin caused by the establishment and expansion of dense vegetation. Patterns of hysteresis diagnostic of sand depletion indicate that the maintenance of present-day channel conditions and potential channel widening can only occur if large, long-duration annual floods occur and deplete the upstream supply of sand. The duration of the rising limb of these floods appears to be generally most important in driving sediment depletion. Patterns of sediment enrichment or depletion during floods cannot be understood without continuous sediment monitoring.

In both rivers, offsetting processes of sediment deposition (channel narrowing) and sediment depletion (bed sand coarsening) are occurring. Because of these offsetting processes, channel narrowing and floodplain growth therefore do not necessarily indicate conditions of sediment surplus. The sediment budget for the Green River is most likely indeterminate, whereas the sediment budget for the Colorado River is either indeterminate or possibly in deficit. Sediment deficit in the Colorado River is more likely than in the Green River because of the persistent post-1960s bed sand coarsening and the greater lag in bed elevation response during floods. However, the determination of surplus/deficit conditions may be irrelevant when trying to predict channel changes, because channel changes in the Green and Colorado Rivers occur during discrete periods of unique hydrological, sediment transport, and vegetative conditions (Walker et al., 2020). This irrelevancy may be especially true when there is conflicting evidence regarding relative surplus (channel narrowing) and deficit (bed sand coarsening) conditions.

Data Availability Statement

Streamflow data were downloaded from the USGS website (https://waterdata.usgs.gov/nwis). Historical sediment load data are listed in the supporting information; data collected during the 2014–2018 period are available at https://www.gcmrc.gov/discharge_qw_sediment/? and through a USGS data release (Dean et al., 2020).

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References

Abernethy, B., & Rutherford, I. (2001). The distribution and strength of Riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes*, *15*, 63–79. https://doi.org/10.1002/hyp.152

Allred, T. M., & Schmidt, J. C. (1999). Channel narrowing by vertical accretion along the Green River near Green River, Utah. *Geological Society of America Bulletin*, *111*(12), 1757–1772. https://doi.org/10.1130/0016-7606(1999)111<1757:cnbvaa>2.3.co;2

Andrews, E., & Nelson, J. (1989). Topographic response of a bar in the Green River, Utah to variation in discharge. In S. Ikeda & G. Parker (Eds.), *River meandering*, *Water Resources Monograph* (Vol. 12, pp. 463–485). Washington, DC: American Geophysical Union.

Andrews, E. D. (1986). Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin*, *97*(8), 1012–1023. https://doi.org/10.1130/0016-7606(1986)97<1012:deofgr>2.0.co;2

Bedford, A., Sankey, T. T., Sankey, J. B., Durning, L., & Ralston, B. E. (2018). Remote sensing of tamarisk beetle (*Diorhabda carinulata*) impacts along 412 km of the Colorado River in the Grand Canyon, Arizona, USA. *Ecological Indicators*, *89*, 365–375. https://doi.org/10.1016/j.ecolind.2018.02.026

Bestgen, K., Zelasko, K., & White, G. (2012). Monitoring reproduction, recruitment, and population status of razorback suckers in the Upper Colorado River Basin, Final Report. In *Upper Colorado river endangered fish recovery program, US fish and wildlife service* (Vol. 170, pp. 1–75). Denver, CO: Larval Fish Laboratory Contribution.

Birken, A. S., & Cooper, D. J. (2006). Processes of tamarix invasion and floodplain development along the Lower Green River, Utah. *Ecological Applications*, *16*(3), 1103–1120. https://doi.org/10.1890/1051-0761(2006)016[1103:potiaf]2.0.co;2

Bridge, J. S. (1993). The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. *Geological Society, London, Special Publications*, *75*(1), 13–71. https://doi.org/10.1144/gsl.sp.1993.075.01.02

Brummer, C. J., & Montgomery, D. R. (2006). Influence of coarse lag formation on the mechanics of sediment pulse dispersion in a mountain stream, Squire Creek, North Cascades, Washington, United States. *Water Resources Research*, *42*, W07412. https://doi.org/10.1029/2005WR004776

Burkham, D. E. (1976a). Effects of changes in an alluvial channel on the timing, magnitude, and transformation of flood waves, southeastern Arizona. In *U S. Geological Survey Professional Paper 655* (pp. K1–K25). Washington, DC: U.S. Government Printing Office.

Burkham, D. E. (1976b). Hydraulic effects of changes in bottom-land vegetation on three major floods, Gila River in southeastern Arizona. In *U.S. geological survey professional paper 655* (pp. J1–J14). Washington, DC: U.S. Government Printing Office.

Butterfield, B. J., Grams, P. E., Durning, L. E., Hazel, J., Palmquist, E. C., Ralston, B. E., & Sankey, J. B. (2020). Associations between riparian plant morphological guilds and fluvial sediment dynamics along the regulated Colorado River in Grand Canyon. *River Research and Applications*, *36*, 410–421. https://doi.org/10.1002/rra.3589

Church, M. (2006). Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Sciences*, *34*, 325–354. https://doi.org/10.1146/annurev.earth.33.092203.122721

Colby, B. R. (1964). *Scour and fill in sand-bed streams* (Vol. 462). Washington, DC: U.S. Government Printing Office.

Costa, J. E., & O'Connor, J. E. (1995). In J. E. Costa, A. J. Miller, K. W. Potter, & P. R. Wilcock (Eds.), *Geomorphically effective floods, in natural and anthropogenic influences in fluvial geomorphology* (Volume, pp. 89–104). Washington, DC: American Geophysical Union.

Dade, W. B. (2000). Grain size, sediment transport and alluvial channel pattern. *Geomorphology*, *35*(1), 119–126. https://doi.org/10.1016/S0169-555X(00)00030-1

Dean, D. J., & Schmidt, J. C. (2011). The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. *Geomorphology*, *126*, 333–349. https://doi.org/10.1016/j.geomorph.2010.03.009

Dean, D. J., & Topping, D. J. (2019). Geomorphic change and biogeomorphic feedbacks in a dryland river: The Little Colorado River, Arizona, USA. *Geological Society of America Bulletin*, 1920–1942. https://doi.org/10.1130/B35047.1

Dean, D. J., Topping, D. J., Grams, P. E., Sabol, T. A., & Tusso, R. B. (2020). *Suspended-sediment, bed-sediment, and in-channel topographical data at the Green River at Mineral Bottom near Canyonlands National Park, and Colorado River at Potash, UT stream gages: U.S. Geological Survey data release*. U.S. Geological Survey. https://doi.org/10.5066/P9KT3GOS

Dean, D. J., Topping, D. J., Schmidt, J. C., Griffiths, R. E., & Sabol, T. A. (2016). Sediment supply versus local hydraulic controls on sediment transport and storage in a river with large sediment loads. *Journal of Geophysical Research: Earth Surface*, *121*, 82–110. https://doi.org/10.1002/2015JF003436

Diehl, R. M., Wilcox, A. C., Stella, J. C., Kui, L., Sklar, L. S., & Lightbody, A. (2017). Fluvial sediment supply and pioneer woody seedlings as a control on bar-surface topography. *Earth Surface Processes and Landforms*, *42*(5), 724–734. https://doi.org/10.1002/esp.4017

Dietrich, W., & Dunne, T. (1978). Sediment budget for a small catchment in a mountainous terrain. In *Zeitschrift für geomorphologie* (Vol. 29, pp. 191–206). New York, NY: Routledge.

Dinehart, R. L. (1998). Sediment transport at gaging stations near Mount St. Helens, Washington, 1980-90: Data collection and analysis. In *U.S. Geological Survey Professional Paper 1,573* (pp. 1–105). Denver, CO: U.S. Geological Survey. Retrieved from https://pubs.usgs.gov/pp/1573/

Draut, A. E., & Rubin, D. M. (2013). Assessing grain-size correspondence between flow and deposits of controlled floods in the Colorado River, U.S.A. *Journal of Sedimentary Research*, *83*(11), 963–974. https://doi.org/10.2110/jsr.2013.79

Edwards, T. K., & Glysson, G. D. (1999). *Field methods for measurement of fluvial sediment: Techniques of water-resources investigations of the U.S. Geological Survey, in book 3, chapter C2* (p. 89). Denver, CO: U.S. Geological Survey.

Einstein, H. A., & Chien, N. (1953). Transport of sediment mixtures with large ranges of grain size. In *Missouri river district sediment series* (Vol. 2, pp. 1–49). Berkeley: University of California.

Eke, E., Parker, G., & Shimizu, Y. (2014). Numerical modeling of erosional and depositional bank processes in migrating river bends with self-formed width: Morphodynamics of bar push and bank pull. *Journal of Geophysical Research: Earth Surface*, *119*, 1455–1483. https://doi.org/10.1002/2013JF003020

Everitt, B. L. (1979). Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: Discussion and reply. *Geological Society of America Bulletin*, *90*, 1183. https://doi.org/10.1130/0016-7606(1979)90<1183:fattsa>2.0.co;2

Fortney, S. T. (2015). *A century of geomorphic change of the San Rafael River and implications for river rehabilitation* (pp. 1–206). Logan, UT: Utah State University. Retrieved from https://digitalcommons.usu.edu/etd/4363/

Gaeuman, D., Schmidt, J. C., & Wilcock, P. R. (2005). Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. *Geomorphology*, *64*(3–4), 185–206. https://doi.org/10.1016/j.geomorph.2004.06.007

Gellis, A. C., Elliott, J. G., & Pavich, M. (2017). Geomorphic processes responsible for decadal-scale arroyo changes, Rio Puerco, New Mexico. *Geological Society of America Bulletin*, *129*(11–12), 1660–1680. https://doi.org/10.1130/b31622.1

Graf, W. L. (1978). Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geological Society of America Bulletin*, *89*, 1491–1501. https://doi.org/10.1130/0016-7606(1978)89<1491:fattso>2.0.co;2

Grams, P. E., Dean, D. J., Walker, A. E., Kasprak, A., & Schmidt, J. C. (2020). *The roles of flood magnitude and duration in controlling channel width and complexity on the Green River in Canyonlands, Utah, USA: Geomorphology, v. 371* (Vol. 107438, pp. 1–14). https://doi.org/10.1016/j.geomorph.2020.107438

Grams, P. E., & Schmidt, J. C. (2002). Streamfow regulation and multi-level flood plain formation: channel narrowing on the aggrading Green River in the eastern Unita Mountains, Colorado and Utah. *Geomorphology*, *44*(3–4), 337–360. https://doi.org/10.1016/s0169-555x(01)00182-9

Grams, P. E., & Schmidt, J. C. (2005). Equilibrium or indeterminate? Where sediment budgets fail: Sediment mass balance and adjustment of channel form, Green River downstream from Flaming Gorge Dam, Utah and Colorado. *Geomorphology*, *71*(1–2), 156–181. https://doi.org/10.1016/j.geomorph.2004.10.012

Grams, P. E., Schmidt, J. C., & Topping, D. J. (2007). The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000. *Geological Society of America Bulletin*, *119*(5–6) 556–575. https://doi.org/10.1130/b25969.1

Grams, P. E., & Wilcock, P. R. (2007). Equilibrium entrainment of fine sediment over a coarse immobile Bed. *Water Resources Research*, *43*, W10420. https://doi.org/10.1029/2006WR005129

Gran, K. B., Montgomery, D. R., & Halbur, J. C. (2011). Long-term elevated post-eruption sedimentation at Mount Pinatubo, Philippines. *Geology*, *39*(4), 367–370. https://doi.org/10.1130/g31682.1

Gran, K. B., Tal, M., & Wartman, E. D. (2015). Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system Mount Pinatubo, Philippines. *Earth Surface Processes and Landforms*, *40*(8), 1101–1115. https://doi.org/10.1002/esp.3699

Griffin, E. R., Kean, J. W., Vincent, K. R., Smith, J. D., & Friedman, J. M. (2005). Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. *Journal of Geophysical Research*, *110*, F04023. https://doi.org/10.1029/2005JF000322

Head, E. (2020). *Channel narrowing and floodplain inundation in Meander Canyon, Colorado River, Canyonlands National Park Utah. M.S. Thesis*. Flagstaff, AZ: Northern Arizona University (p 374).

Heidel, S. (1956). The progressive lag of sediment concentration with flood waves. *Eos, Transactions of the American Geophysical Union*, *37*(1), 56–66. https://doi.org/10.1029/tr037i001p00056

Hickin, E. J., & Sichingabula, H. M. (1988). The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish River, southwestern British Columbia. *Canadian Journal of Earth Sciences*, *25*(7), 1078–1087. https://doi.org/10.1139/e88-105

Howard, A., & Dolan, R. (1981). Geomorphology of the Colorado River in the Grand Canyon. *The Journal of Geology*, *89*(3), 269–298. https://doi.org/10.1086/628592

Iorns, W. V., Hembree, C. H., & Oakland, G. L. (1965). Water resources of the upper Colorado River basin: Technical report. In *U.S. Geological Survey Professional Paper 442* (pp. 1–370). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/pp441

Jaeger, K. L., & Wohl, E. (2011). Channel response in a semiarid stream to removal of tamarisk and Russian olive. *Water Resources Research*, *47*, W02536. https://doi.org/10.1029/2009WR008741

Juez, C., Hassan, M. A., & Franca, M. J. (2018). The origin of fine sediment determines the observations of suspended sediment fluxes under unsteady flow conditions. *Water Resources Research*, *54*, 5654–5669. https://doi.org/10.1029/2018WR022982

Juez, C., Schärer, C., Jenny, H., Schleiss, A., & Franca, M. J. (2019). Floodplain land cover and flow hydrodynamic control of overbank sedimentation in compound channel flows. *Water Resources Research*, *55*, 9072–9091. https://doi.org/10.1029/2019WR024989

Keller, D. L., Laub, B. G., Birdsey, P., & Dean, D. J. (2014). Effects of flooding and tamarisk removal on habitat for sensitive fish species in the San Rafael River, Utah: Implications for fish habitat enhancement and future restoration efforts. *Environmental Management*, *54*(3), 465–478. https://doi.org/10.1007/s00267-014-0318-7

Kleinhans, M., Wilbers, A., & Ten Brinke, W. (2007). Opposite hysteresis of sand and gravel transport upstream and downstream of a bifurcation during a flood in the River Rhine, the Netherlands. *Netherlands Journal of Geosciences/Geologie en Mijnbouw*, *86*(3). https://doi.org/10.1017/s0016774600077854

Knighton, D. (1998). *Fluvial forms and processes*. London: Edward Arnold.

Lane, E. W. (1955). The importance of fluvial geomorphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers*, *81*, 1–17.

Langois, J. L., Johnson, D. W., & Mehuys, G. R. (2005). Suspended sediment dynamics associated with snowmelt run-off in a small mountain stream of Lake Tahoe. *Hydrological Processes*, *19*, 3569–3580. https://doi.org/10.1002/hyp.5844

Le Bouteiller, C., & Venditti, J. G. (2014). Vegetation-driven morphodynamic adjustments of a sand Bed. *Geophysical Research Letters*, *41*, 3876–3883. https://doi.org/10.1002/2014GL060155

Leopold, L. B., & Maddock, J. R. (1953). The hydraulic geometry of stream channels and some physiographic implications. In *U.S. Geological Survey Professional Paper* (Vol. 252, pp. 1–57). Washington, DC: U.S. Government Printing Office.

Lyons, J. K., Pucherelli, M. J., & Clark, R. C. (1992). Sediment transport and channel characteristics of a sand-bed portion of the green river below flaming gorge dam, Utah, USA. *Regulated Rivers: Research & Management*, *7*(3), 219–232. https://doi.org/10.1002/rrr.3450070302

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, 50–60. https://doi.org/10.1214/aoms/1177730491

Manners, R. B., Schmidt, J. C., & Scott, M. L. (2014). Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river: Results from a natural field-scale experiment. *Geomorphology*, *211*, 100–115. https://doi.org/10.1016/j.geomorph.2013.12.033

Manners, R. B., Wilcox, A. C., Kui, L., Lightbody, A. F., Stella, J. C., & Sklar, L. S. (2015). When do plants modify fluvial processes? Plant-hydraulic interactions under variable flow and sediment supply rates. *Journal of Geophysical Research: Earth Surface*, *120*, 325–345. https://doi.org/10.1002/2014JF003265

McLean, S. (1992). On the calculation of suspended load for noncohesive sediments. *Journal of Geophysical Research*, *97*(C4), 5759–5770. https://doi.org/10.1029/91JC02933

Merritt, D. M., & Cooper, D. J. (2000). Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River Basin, USA. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, *16*(6), 543–564. https://doi.org/10.1002/1099-1646(200011/12)16:6<543::aid-rrr590>3.0.co;2-n

Mortenson, S. G., & Weisberg, P. J. (2009). *Plant community response to Tamarisk invasion and hydrologic regime in the Cataract Canyon, Canyonlands National Park: A preliminary investigation: University of Nevada, Reno* (pp. 1–36). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.728.2633&rep=rep1&type=pdf

Mueller, E. R., Grams, P. E., Schmidt, J. C., Hazel, J. E., Alexander, J. S., & Kaplinski, M. (2014). The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River basin. *Geomorphology*, *226*, 65–75. https://doi.org/10.1016/j.geomorph.2014.07.029

Nepf, H. M. (1999). Drag, turbulence, and diffusion in flow through emergent vegetation. *Water Resources Research*, *35*(2), 479–489. https://doi.org/10.1029/1998WR900069

Parker, G. (1979). Hydraulic geometry of active gravel rivers. In *ASCE J Hydraul Div* (Vol. 105). American Society of Civil Engineers (ASCE).

Perignon, M. C., Tucker, G. E., Griffin, E. R., & Friedman, J. M. (2013). Effects of riparian vegetation on topographic change during a large flood event, Rio Puerco, New Mexico, USA. *Journal of Geophysical Research: Earth Surface*, *118*, 1193–1209. https://doi.org/10.1002/jgrf.20073

Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society: Series C: Applied Statistics*, *28*(2), 126–135. https://doi.org/10.2307/2346729

Pitlick, J., & Cress, R. (2002). Downstream changes in the channel geometry of a large gravel bed river. *Water Resources Research*, *38*(10), 1216. https://doi.org/10.1029/2001WR000898

Pitlick, J., & Van Steeter, M. M. (1998). Geomorphology and endangered fish habitats of the upper Colorado River: 2. Linking sediment transport to habitat maintenance. *Water Resources Research*, *34*(2), 303–316. https://doi.org/10.1029/97WR02684

Pollen, N. (2007). Temporal and spatial variability in root reinforcement of streambanks: Accounting for soil shear strength and moisture. *Catena*, *69*(3), 197–205. https://doi.org/10.1016/j.catena.2006.05.004

Pollen-Bankhead, S., N., A., Jaeger, K., & Wohl, E. (2009). Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona. *Geomorphology*, *103*(3), 363–374. https://doi.org/10.1016/j.geomorph.2008.07.004

Porterfield, G. (1972). *Computation of fluvial sediment discharge, in United States Geological Survey. Techniques of water-resource investigations, book 3, chap. C3* 66 pp. Washington, D. C: U.S. Gov. Printing Office.

Rakowski, C. L. (1997). *The geomorphic basis of Colorado squawfish nursery habitat in the Green River near Ouray, Utah* (MS thesis). Logan, UT: Utah State University. Retrieved from https://digitalcommons.usu.edu/etd/6929/

Ritchie, A. C., Warrick, J. A., East, A. E., Magirl, C. S., Stevens, A. W., Bountry, J. A., et al. (2018). Morphodynamic evolution following sediment release from the world's largest dam removal. *Scientific Reports*, *8*, 13279. https://doi.org/10.1038/s41598-018-30817-8

Rubin, D. M., Nelson, J. M., & Topping, D. J. (1998). Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon. *Geology*, *26*(2), 99–102. https://doi.org/10.1130/0091-7613(1998)026<0099:roigdt>2.3.co;2

Rubin, D. M., & Topping, D. J. (2001). Quantifying the relative importance of flow regulation and grain size regulation of suspended sediment transport α and tracking changes in grain size of bed sediment β. *Water Resources Research*, *37*(1), 133–146. https://doi.org/10.1029/2000WR900250

Rubin, D. M., & Topping, D. J. (2008). Correction to "quantifying the relative importance of flow regulation and grain size regulation of suspended sediment transport α and tracking changes in grain size of bed sediment β". *Water Resources Research*, *44*, W09701. https://doi.org/10.1029/2008WR006819

Schmidt, J. C. (2007). The Colorado river. In A. Gupta (Ed.), *Large rivers: Geomorphology and management* (pp. 183–233). Ltd, West Sussex, England: John Wiley and Sons.

Schmidt, J. C., & Brim Box, J. (2004). Application of a dynamic model to assess controls on age-0 Colorado Pikeminnow distribution in the middle Green River, Colorado and Utah. *Annals of the Association of American Geographers*, *94*, 458–476. https://doi.org/10.1111/j.1467-8306.2004.00408.x

Schmidt, J. C., & Rubin, D. M. (1995). Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans. *Geophysical Monograph Series*, *89*, 177–195. https://doi.org/10.1029/GM089p0177

Schmidt, J. C., & Wilcock, P. R. (2008). Metrics for assessing the downstream effects of dams. *Water Resources Research*, *44*, W04404. https://doi.org/10.1029/2006WR005092

Sibley, D., Topping, D. J., Hines, M., & Garner, B. (2015). *User-interactive sediment budgets in a browser: A web application for river science and management*. Paper presented at 3rd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, Reno, Nevada, U.S. Department of the Interior, Advisory Committee on Water Information. Retrieved from http://acwi.gov/sos/pubs/3rdJFIC/Proceedings.pdf

Tal, M., Gran, K., Murray, A. B., Paola, C., & Hicks, D. M. (2004). Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. In *Riparian vegetation and fluvial geomorphology* (Vol. 8, pp. 43–58). Washington, D.C: American Geophysical Union.

Topping, D. J., Mueller, E. R., Schmidt, J. C., Griffiths, R. E., Dean, D. J., & Grams, P. E. (2018). Long-term evolution of sand transport through a river network: Relative influences of a dam versus natural changes in grain size from sand waves. *Journal of Geophysical Research: Earth Surface*, *123*, 1879–1909. https://doi.org/10.1029/2017JF004534

Topping, D. J., Rubin, D. M., Grams, P. E., Griffiths, R. E., Sabol, T. A., Voichick, N., et al. (2010). Sediment transport during three controlled-flood experiments on the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park. In *U.S. Geological Survey Open-File Report 2010–1128* (pp. 1–111). Reston, VA: U.S. Geological Survey. Retrieved from http://pubs.usgs.gov/of/2010/1128/

Topping, D. J., Rubin, D. M., Nelson, J. M., Kinzel, P. J., & Bennett, J. B. (1999). Linkage between grain-size evolution and sediment depletion during Colorado River Floods. In R. H. Webb, J. C. Schmidt, G. R. Marzolf, R. A. Valdez (Eds.), *The 1996 controlled flood in Grand Canyon*, *Geophysical monograph 110* (pp. 71–98). Washington, D.C: American Geophysical Union.

Topping, D. J., Rubin, D. M., Nelson, J. M., Kinzel, P. J., & Corson, I. C. (2000). Colorado River sediment transport: 2. Systematic bed-elevation and grain-size effects of sand supply limitation. *Water Resources Research*, *36*(2), 543–570. https://doi.org/10.1029/1999WR900286

Topping, D. J., Rubin, D. M., & Vierra, L. E. (2000). Colorado River sediment transport: 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research*, *36*(2), 515–542. https://doi.org/10.1029/1999WR900285

Topping, D. J., Rubin, D. M., Wright, S. A., & Melis, T. S. (2011). Field evaluation of the error arising from inadequate time averaging in the standard use of depth-integrating suspended-sediment samplers. In *U.S. Geological Survey Professional Paper 1774* (pp. 1–95). Reston, VA: U.S. Geological Survey. Retrieved from http://pubs.usgs.gov/pp/1774/

Topping, D. J., & Wright, S. A. (2016). Long-term continuous acoustical suspended-sediment measurements in rivers—Theory, application, bias, and error. In *U.S. Geological Survey Professional Paper 1823* (pp. 1–98). Reston, VA: U.S. Geological Survey. Retrieved from https://doi.org/10.3133/pp1823

Topping, D. J., Wright, S. A., Melis, T. S., & Rubin, D. M. (2007). *High-resolution measurements of suspended-sediment concentration and grain size in the Colorado River in Grand Canyon using a multi-frequency acoustic system* (pp. 330–339). Paper presented at Proceedings of the 10th International Symposium on River Sedimentation, Moscow State University, Moscow, Russia.

U.S. Geological Survey. (2020). *Peak streamflow for the nation*. Washington, DC: U.S. Government Printing Office. Retrieved from https://nwis.waterdata.usgs.gov/nwis/peak?search_criteria=state_cd&search_criteria=search_station_nm&submitted_form=introduction, accessed on March 17, 2020.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*, 2404–2418. https://doi.org/10.1002/2016WR019638

Valdez, R., & Nelson, P. (2004). Green River subbasin floodplain management plan. In *Upper Colorado River endangered fish recovery program, project number C-6, Denver, CO* (pp. 1-1–8-3). Retrieved from https://coloradoriverrecovery.org/documents-publications/technical-reports/hab/GreenFMP.pdf

Van Steeter, M. M., & Pitlick, J. (1998). Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology. *Water Resources Research*, *34*(2), 287–302. https://doi.org/10.1029/97WR02766

Vincent, K., Friedman, J., & Griffin, E. (2009). Erosional consequence of saltcedar control. *Environmental Management*, *44*(2), 218–227. https://doi.org/10.1007/s00267-009-9,314-8

von Karman, T. (1930). Mechanische Ähnlichkeit und Turbulenz. In *Nachr. Ges. Wiss. Goettingen, Math. Phys. Kl., Fachgruppe 1* (Vol. 5, pp. 58–76). Washington, DC: Reprinted in the Mechanical Similitude and Turbulence, Natl. Advisory Comm. for Aeronaut. (NACA).

Walker, A. E. (2017). *Twentieth century channel change of the Green River in Canyonlands National Park, Utah (MS thesis)*. Logan, UT: Utah State University. Retrieved from https://digitalcommons.usu.edu/etd/6884/

Walker, A. E., Moore, J. N., Grams, P. E., Dean, D. J., & Schmidt, J. C. (2020). Channel narrowing by inset floodplain formation of the lower Green River in the Canyonlands region, Utah. *GSA Bulletin*. https://doi.org/10.1130/B35233.1

Wheeler, K. G., Schmidt, J. C., & Rosenberg, D. E. (2019). Water resource modeling of the Colorado River: Present and future strategies rep. In *Quinney college of natural resources* (pp. 2–46). Logan, UT: Utah State University, Center for Colorado River Studies.

White, M. A., Schmidt, J. C., & Topping, D. J. (2005). Application of wavelet analysis for monitoring the hydrologic effects of dam operation: Glen Canyon Dam and the Colorado River at Lees Ferry, Arizona. *River Research and Applications*, *21*(5), 551–565. https://doi.org/10.1002/rra.827

Woodhouse, C. A., Gray, S. T., & Meko, D. M. (2006). Updated streamflow reconstructions for the Upper Colorado River basin. *Water Resources Research*, *42*, A02205. https://doi.org/10.1029/2005WR004455

Woodhouse, C. A., Kunkel, K. E., Easterling, D. R., & Cook, E. R. (2005). The twentieth-century pluvial in the western United States. *Geophysical Research Letters*, *32*, L07701. https://doi.org/10.1029/2005GL022413

Xiao, M., Udall, B., & Lettenmaier, D. P. (2018). On the causes of declining Colorado River Streamflows. *Water Resources Research*, *54*, 6739–6756. https://doi.org/10.1029/2018WR023153

Zong, L., & Nepf, H. (2010). Flow and deposition in and around a finite patch of vegetation. *Geomorphology*, *116*(3), 363–372. https://doi.org/10.1016/j.geomorph.2009.11.020

References From the Supporting Information

Allen, P. B., & Petersen, D. V. (1981). *A study of the variability of suspended sediment measurements in erosion and sediment transport measurement* (Vol. 133, pp. 203–211). Paper presented at Proceedings of the Florence Symposium, International Association of Hydrological Sciences Publication, Paris, France.

Claude, N., Rodrigues, S., Bustillo, V., Bréhéret, J.-G., Macaire, J.-J., & Jugé, P. (2012). Estimating bedload transport in a large sand–gravel bed river from direct sampling, dune tracking and empirical formulas. *Geomorphology*, *179*, 40–57. https://doi.org/10.1016/j.geomorph.2012.07.030

Dinehart, R. L. (2002). Bedform movement recorded by sequential single-beam surveys in tidal rivers. *Journal of Hydrology*, *258*(1), 25–39. https://doi.org/10.1016/S0022-1694(01)00558-3

Iorns, W. V., Hembree, C. H., Phoenix, D. A., & Oakland, G. L. (1964). Water resources of the Upper Colorado River Basin—Basic data. In *U.S. Geological Survey Professional Paper 442* (pp. 1–1036). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/pp442

Love, S. K. (1955). Quality of the surface waters of the United States 1951, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply paper 1,200* (pp. 1–258). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1200

Love, S. K. (1957). Quality of the surface waters of the United States 1952, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,253* (pp. 1–344). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1253

Love, S. K. (1958). Quality of the surface waters of the United States 1953, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,293* (pp. 1–372). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1293

Love, S. K. (1959a). Quality of the surface waters of the United States 1954, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. geological survey water-supply paper 1,353* (pp. 1–426). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1353

Love, S. K. (1959b). Quality of the surface waters of the United States 1955, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,403* (pp. 1–437). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1403

Love, S. K. (1960). Quality of the surface waters of the United States 1956, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,453* (pp. 1–447). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1453

Love, S. K. (1961). Quality of the surface waters of the United States 1957, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,523* (pp. 1–497). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1523

Love, S. K. (1964a). Quality of the surface waters of the United States 1958, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,574* (pp. 1–487). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1574

Love, S. K. (1964b). Quality of the surface waters of the United States 1962, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1945* (pp. 1–691). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1945

Love, S. K. (1966a). Quality of the surface waters of the United States 1959, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1,645* (pp. 1–24). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1645

Love, S. K. (1966b). Quality of the surface waters of the United States 1963, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1951* (pp. 1–781). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1951

Love, S. K. (1967). Quality of the surface waters of the United States 1961, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1885* (pp. 1–677). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1885

Love, S. K. (1968). Quality of the surface waters of the United States 1960, parts 9–14. Colorado river basin to Pacific slope basins in Oregon and lower Columbia river basin. In *U.S. Geological Survey Water-Supply Paper 1745* (pp. 1–607). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1745

Thorne, P. D., & Meral, R. (2008). Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport processes. *Continental Shelf Research*, *28*(2), 309–317. https://doi.org/10.1016/j.csr.2007.08.002

U.S. Geological Survey. (1969). Quality of the surface waters of the United States 1964, parts 9–11. Colorado River basin to Pacific slope basins in California. In *U.S. Geological Survey Water-Supply Paper 1958* (pp. 1–615). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1958

U.S. Geological Survey. (1970). Quality of the surface waters of the United States 1965, parts 9–11. Colorado River basin to Pacific slope basins in California. In *U.S. Geological Survey Water-Supply Paper 1965* (pp. 1–678). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1965

U.S. Geological Survey. (1971). Quality of the surface waters of the United States 1966, parts 9–11. Colorado River basin to Pacific slope basins in California. In *U.S. Geological Survey Water-Supply Paper 1995* (pp. 1–726). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp1995

U.S. Geological Survey. (1972). Quality of the surface waters of the United States 1967, parts 9–11. Colorado River basin to Pacific slope basins in California. In *U.S. Geological Survey Water-Supply Paper 2015* (pp. 1–702). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp2015

U.S. Geological Survey. (1973). Quality of the surface waters of the United States 1968, parts 9 and 10. Colorado River basin and the Great Basin. In *U.S. Geological Survey Water-Supply Paper 2098* (pp. 1–296). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp2098

U.S. Geological Survey. (1974). Quality of the surface waters of the United States 1969, parts 9 and 10. Colorado River basin and the Great Basin. In *U.S. Geological Survey Water-Supply Paper 2,148* (pp. 1–348). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp2148

U.S. Geological Survey. (1976). Quality of the surface waters of the United States 1970, parts 9 and 10. Colorado River basin and the Great Basin. In *U.S. Geological Survey Water-Supply Paper 2,158* (pp. 1–371). Washington, DC: U.S. Government Printing Office. Retrieved from https://pubs.er.usgs.gov/publication/wsp2158

U.S. Geological Survey. (2019). *Water quality samples for the nation*. Retrieved from http://nwis.waterdata.usgs.gov/usa/nwis/qwdata

Van der Mark, C., & Blom, A. (2007). *A new and widely applicable bedform tracking tool* (pp. 1–44). Twente, Netherlands: University of Twente. Retrieved from http://www.vliz.be/imisdocs/publications/217518.pdf

Van der Mark, C., Blom, A., & Hulscher, S. J. (2008). Quantification of variability in bedform geometry. *Journal of Geophysical Research*, *113*, F03020. https://doi.org/10.1029/2007JF000940