Sediment Supply and Flow in the Colorado River Basin

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Abstract

The Colorado River Basin is one of the most regulated basins in the world, supplying water to communities in Colorado, Utah, Nevada, Arizona, California, and Mexico. Humans and climate change have increased the variability of stream flows and sediment transport within the Colorado River Basin, affecting riparian ecosystems, water resources management, and coastal environments. To assess how global changes, including the influences of humans and climate change, in the Colorado River Basin have impacted the sediment transport flow regime within the basin, concepts of fluvial geomorphology followed by a review of the Colorado River Basin, and the effects of dams and climate change within the basin are presented. Although the tributaries in the upper Colorado River Basin contribute most of the flow to the Colorado River, sediment is contributed primarily from the semi-arid tributaries of the lower basin. Due to the different sources of flow and sediment, the downstream effects of reservoirs not only depend on the size and operation schedule of the reservoir, but also the location. Alterations to the Colorado River Basin from reservoirs have changed the sediment transport regime of the Colorado River in complex longitudinal patterns. Changing climate characteristics are expected to lead to increased sediment yields as well as changes in the timing and magnitude of peak flows in the Colorado River Basin. However, due to the large storage capacity of the reservoirs within the Colorado River Basin, the flows of the Colorado River are not expected to change significantly, but an overall increase in sediment yield within the Colorado Basin from global change, having reach dependent impacts, is expected.

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1 Introduction

The Colorado River Basin is one of the most regulated basins in the world, supplying water to communities in Colorado, Utah, Nevada, Arizona, California, and Mexico. Humans and climate change have increased the variability of stream flows and sediment transport within the Colorado River Basin, affecting fluvial geomorphology, water availability, and habitat suitability (Grant, Schmidt, & Lewis, 2003; Magilligan & Nislow, 2005; Maurer & Duffy, 2005; Nijssen, O'Donnell, Hamlet, & Lettenmaier, 2001; N. LeRoy Poff, Olden, Merritt, & Pepin, 2007; Singer, 2007). To assess how global changes, including the influences of humans and climate change, in the Colorado River Basin have affected the sediment transport flow regime within the basin, concepts of fluvial geomorphology followed by a review of the Colorado River Basin, and the effects of dams as well as climate change within the basin are presented.

2 Fluvial Geomorphology

The transport, erosion, and deposition of material within the Colorado River Basin are dependent on the ability of the stream to do work, defined as the product of stream power and efficiency (Bagnold, 1966):

$$rate\ of\ work = stream\ power * efficiency$$ **Equation 1**

Stream power, Ω, is the measurable loss of potential energy per unit length of a channel from a stream doing work (Bagnold, 1966; Mount, 1995):

$$\Omega = \rho g Q S$$ **Equation 2: Stream Power**

Here, ρ is the density of the water, g is gravity, Q is the total discharge of the stream, and S is the gravity slope. Letting $\bar{u}$ denote the mean fluid velocity, τ the shear stress, and b the cross section width, the specific stream power per unit bed area, ω, is (Bagnold, 1966)

$$\omega = \frac{\Omega}{b} = \frac{\rho g Q S}{b} = \rho g S \bar{u} = \tau \bar{u}$$ **Equation 3: Specific Stream Power**

As the relative channel width decreases, the specific stream power increases, increasing the energy per unit bed area. This increase in energy per bed area increases shear stress and may increase bedload as demonstrated by the following open channel shear stress and bedload equations.

Bed shear stress, defined by Chezy denoting the bed shear stress as τ_b and the Chezy coefficient as k, is the force acting to slow a fluid (Bedient, Huber, & Vieux, 2008):

$$\tau_b = k\bar{u}^2$$ **Equation 4: Chezy Bed Shear Stress**

Chezy's equation shows that as the average channel velocity increases so will the bed shear stress. The average velocity can be found from Manning's Equation for an open channel, letting

R denote the hydraulic radius, S the energy slope, n Mannings roughness coefficient and k_m a conversion factor (1.49 for English units and 1.0 for SI units) (Bedient et al., 2008):

$$\bar{u} = \frac{k_m}{n} R^{2/3} \sqrt{S}$$

Equation 5: Mannings Equation

Here, the hydraulic radius is shown to scale with the velocity such that increases in the hydraulic radius result in increases in the average channel velocity. These increases in velocity would also increase the bed shear stress.

Assuming steady state and uniform depth, the bed shear stress of a channel can also be approximated over a channel reach of slope S and depth h by conservation of momentum (Chanson, 2004):

$$\tau_b = \rho g h \sin(S)$$

Equation 6: Bed Shear Stress for a Wide Channel

$$\tau_b = \rho g h S$$

Equation 7: Bed Shear Stress for a shallow Sloped Channel

The maximum particle size that can be transported by a stream for a given flow, known as the competence, is a measure of stream power and can be determined from evaluating the bed shear stress (Mount, 1995). For a particle of diameter d at rest on the bed surface, the fluid must exceed a critical shear stress, τ_c, to initiate motion of the grain. The critical shear stress is a function of the Reynolds number of the particle and can be determined empirically by evaluating a Shields diagram (Figure 1).

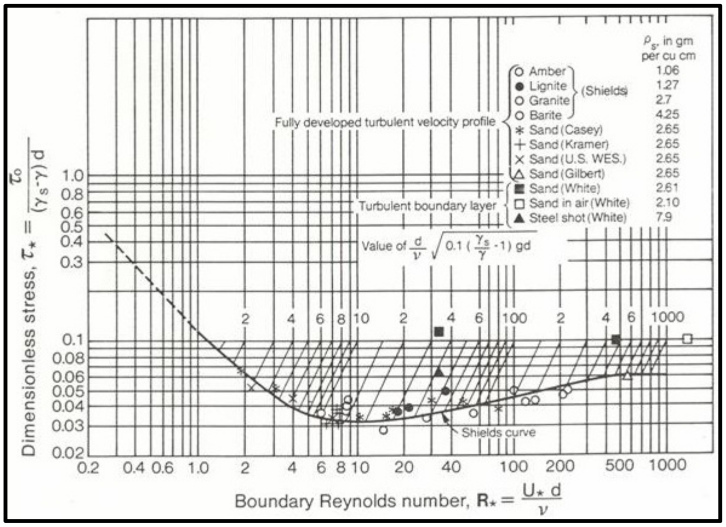

Figure 1. Shields diagram(U.S. Army Corps of Engineers, 1994).

Here, Υ denotes specific weight, ν denotes kinematic viscosity of the fluid, and U* denotes the shear velocity where k is the von Karman constant (U.S. Army Corps of Engineers, 1994):

$$u_* = \sqrt{\frac{\tau_b}{\rho_w}} = kz\frac{\partial u}{\partial z}$$

Equation 8: Shear Velocity

The critical velocity to entrain, or transport, particles for a given particle diameter on a relatively flat bed can also be related through the use of a Hjulstrom diagram (Figure 2)(Mount, 1995).

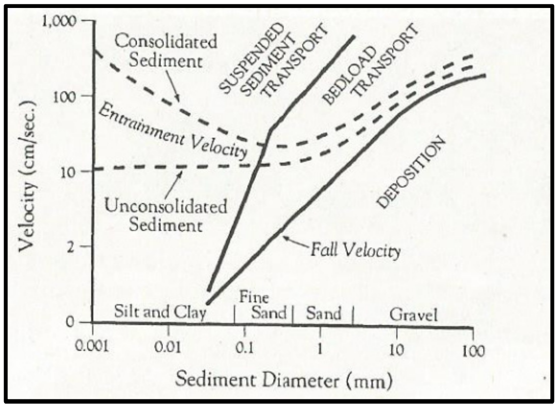

Figure 2. Modified Hjulstrom diagram of sediment transport and entrainment thresholds for given sediment diameters(Mount, 1995).

Another measure of stream power is the maximum amount of sediment transported by a given flow, known as the flow capacity. However, the flow capacity of a stream is rarely reached due to supply limitations. The actual amount of sediment transported is referred to as sediment load and is dependent upon shear stress, often described by the following power function (Mount, 1995; Wolman & Miller, 1960):

$$q = k(\tau - \tau_c)^n$$ **Equation 9: Sediment Transport Rate**

Here, q denotes the rate of transport and k is an empirical rate constant dependent on the characteristics of the sediment. Considering the difference in shear stress as a variable, this equation may be simplified (Wolman & Miller, 1960):

$$q = x^n$$ **Equation 10: Sediment Transport Power Function**

Assuming that the rate of sediment transported is related to a power of the stress, a maximum sediment transport rate can be attained from the product of the flow frequency and sediment transport power function (Figure 3). Stream flow rates and the associated stresses applied by the flows are often log-normally distributed (Chow, 1954; Wolman & Miller, 1960). The flow responsible for the most transport is the effective discharge and can be derived mathematically by making assumptions about the discharge frequency and the relationship between sediment transport and flow (Nash, 1994).

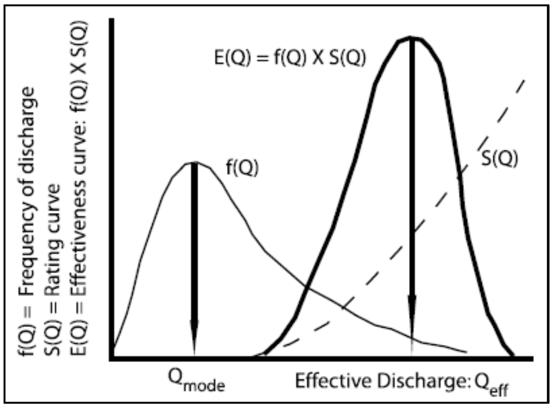

Figure 3. Effective discharge and frequency plots (Doyle, Stanley, Strayer, Jacobson, & Schmidt, 2005).

Naturally, geomorphic features of streams adjust to attain equilibrium between supply and sediment transport capacity at given flows through channel bed aggradation or incision, lateral adjustments including channel width expansion or contraction, and textural changes such as coarsening or fining of surface grain-size distributions. When a sediment deficit exits, the transport capacity exceeds supply, streams often attempt to attain more supply by eroding bed and/or bank material. Such a case is referred to as “hungry water,” in which the water becomes prone to erode channel bed and banks producing channel incision, coarsening of bed material, and loss of spawning gravels for salmon and trout (Kondolf, 1997).Whereas, if the transport capacity is less than the available sediment supply, streams are more likely to aggrade (Grant et al., 2003).

3 The Colorado River Basin

Consisting of large parts of Wyoming, Colorado, Utah, Nevada, and Arizona, the Colorado River Basin is one of the most regulated basins in the world, with six major reservoirs storing water for agricultural and urban use (Table 1). The total usable reservoir storage capacity is approximately four times the mean annual flow, exceeding 70 billion m^3 (Andrews, 1991). In addition to providing water for anthropogenic uses, the Colorado River Basin serves as source for recreation and provides habitat for many threatened and endangered species.

Table 1. Reservoirs with more than 0.5 billion m3 of usable storage capacity upstream of Boulder Dam in the Colorado River Basin (Andrews, 1991)

Reservoir	Usable Storage Capacity (billion m^3)
Flaming Gorge Reservoir	4.3
Strawberry Reservoir	1.4
Blue Mesa	1.0
Navaho reservoir	2.1
Lake Powell	31.0
Lake Mead	32.0
Total	71.8

Water and sediment are not contributed evenly to the Colorado River by tributaries within the basin (Table 2) (Howard, 1947; Iorns, Hembree, & Oakland, 1965). The upper Colorado River Basin, near the crest of the Rocky Mountains, contributes the largest proportion of water to the Colorado River, while the semiarid lower basin in southeastern Utah, northeastern Arizona, and northwestern New Mexico, near the Colorado Plateau, contribute the largest proportions of sediment to the river (Figure 4) (Andrews, 1991).

Table 2. Colorado River Basin annual average flow contribution and sediment yield by basin area from 1941 to 1957 studies, reflecting natural conditions.

Basin	Area (%)	Flow Contribution (%)	Sediment Yield (%)
Upper	40	85	31
Lower	37	15	69

3.1 Effects of Reservoirs within the Colorado River Basin

The reservoirs within the Colorado River Basin are an integral part of human growth and technological innovation—reducing flood hazards; allowing humans to develop and farm on historic river floodplains; producing power for society and industry; and serving as a water supply source (N. Leroy Poff & Hart, 2002). However the sediment inflow and outflow to the Colorado River has been changed in complex longitudinal patterns by altering of flow and sediment transport by these reservoirs. The downstream effects of a reservoir depend on the size, operating schedule of the reservoir, and relative location of the reservoir with respect to flow and sediment contributing areas within the basin as demonstrated by the case studies of the impacts of Flaming Gorge Reservoir and Lake Powell (Andrews, 1991).

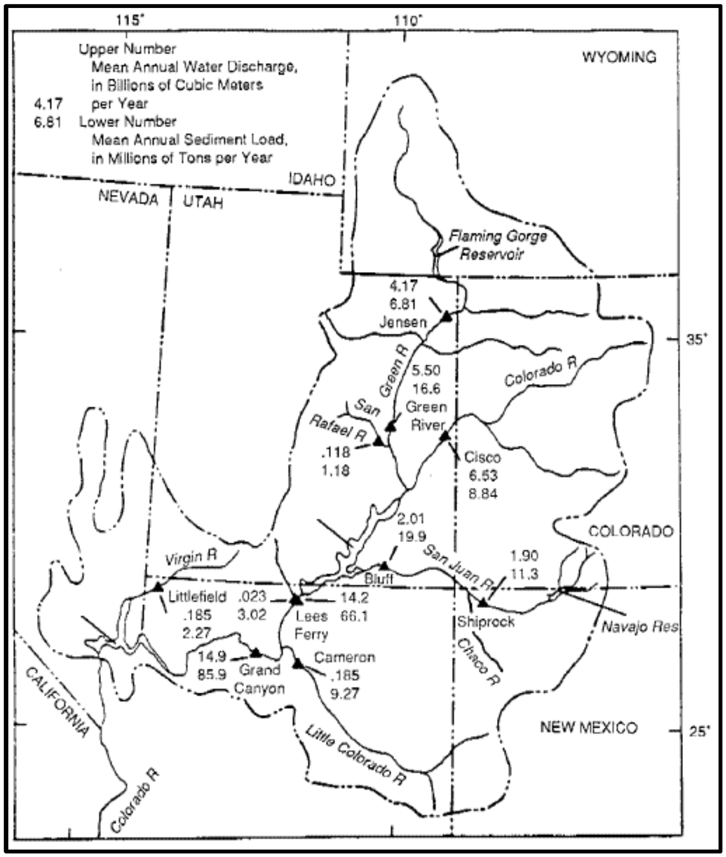

Figure 4. 1941-1957, mean annual runoff and sediment load in the Colorado River basin, indicative of natural conditions (Andrews, 1991).

A quasi-equilibrium condition, where the supply of sediment into the reach equaled the rate of sediment transported out of the reach, existed in the Green River prior to the construction of the Flaming Gorge Dam. The construction of the dam in 1962 reduced the mean annual sediment discharge downstream of the dam, attributed primarily to a more uniform hydrograph rather than a reduction in the annual runoff, resulting in three distinct longitudinal zones involving channel degradation, quasi equilibrium, and aggradation (Table 3) (Andrews, 1986). Directly downstream of the reservoir, degradation exits from the stream capacity exceeding the sediment supply. However, the stream capacity is quickly met by sediment supplied from tributaries such that from river km 110 to 269 a quasi-equilibrium state exists with no net accumulation or depletion of bed material and from river km 269 to the mouth of the Green River the river is aggrading (Andrews, 1986). The increase in sediment supply relative to stream capacity in the lower reach of the Green River has resulted measurable morphologic adjustments, occurring primarily in valley reaches where alluvial characteristics are more easily altered than in bedrock reaches (Grant et al., 2003).

Table 3. Pre- and post-dam sediment transport (Andrews, 1986)

Gauging Station	Pre-Dam Sediment Transport (million tons)	Post-Dam Sediment Transport (million tons)	Change (%)
Jensen	6.29	2.92	54
Ouray	11.6	6.02	48
Green River, Utah	15.5	8.03	48

Prior to the construction of the Glen Canyon Dam and Lake Powell, the Colorado River in Marble and Grand Canyons was annually supply limited of fine sediment. However, this supply limitation did not exist for all seasons (Figure 5). July through March, 0.0625-0.25 mm sand accumulated and was stored within these reaches until eroded during large flow events, typically snowmelt driven flows April through June. These effects were observed in Glen Canyon to a lesser degree than in the Grand Canyon suggesting that the exceedance of the capacity over sediment supply increased with the changing canyon geometry from Glen Canyon to Marble and the upper Grand Canyons, where the channel narrows and steepens (Topping, Rubin, & Vierra, 2000). The seasonal pre-dam variations are not observed post-dam in the Marble and Grand Canyons.

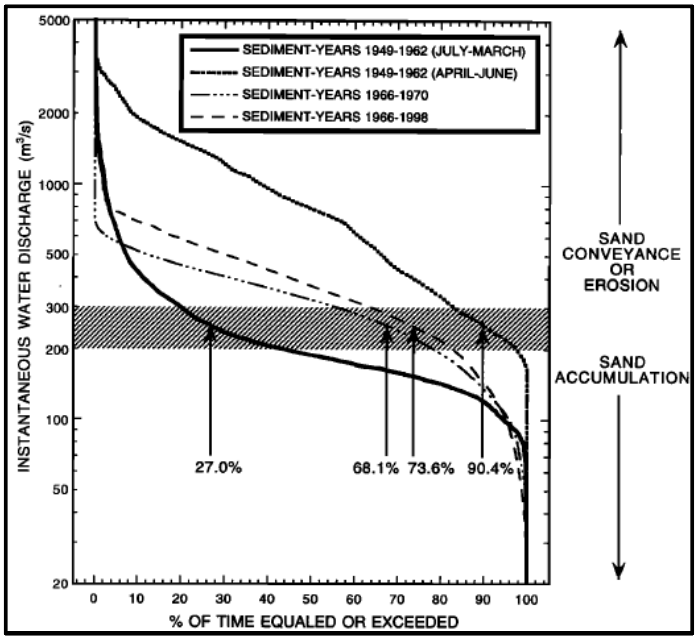

Figure 5. Flow duration curves from instantaneous discharge records of the Colorado River from the Lees Ferry gage(Topping et al., 2000).

The construction of Lake Powell has not only reduced the sediment load entering Marble and Grand Canyons, but also altered the flow patterns below the lake to be more similar to pre-dam flows when sand would have been eroded than to the flows during the periods of sand accumulation and storage (Topping et al., 2000). Although tributaries may have contributed as little as 10-15% of the pre-dam sediment supply, the local geologic controls, such as the morphology and orientation of debris fans from the tributaries, influence the locations of erosion and deposition due to a lack of competence from flow regulation to move debris fans (Grant et al., 2003).

3.2 Climate Change

Climate trends suggest that the western US is undergoing drying of the regional climate and warming leading to more frequent weather disturbances such as summer droughts and intense storms, further impacting the Colorado River Basin (Luce & Holden, 2009; Mote, Hamlet, Clark, & Lettenmaier, 2005; Overpeck, Rind, & Goldberg, 1990). As shown by equations 2 and 3, stream power is directly related to flow whereas the sediment load is a function of basins sediment yield and availability. Sediment yield is controlled by precipitation and weathering (driving forces) as well as vegetation type and density (resistive forces), forces controlled by climate (Figure 6).

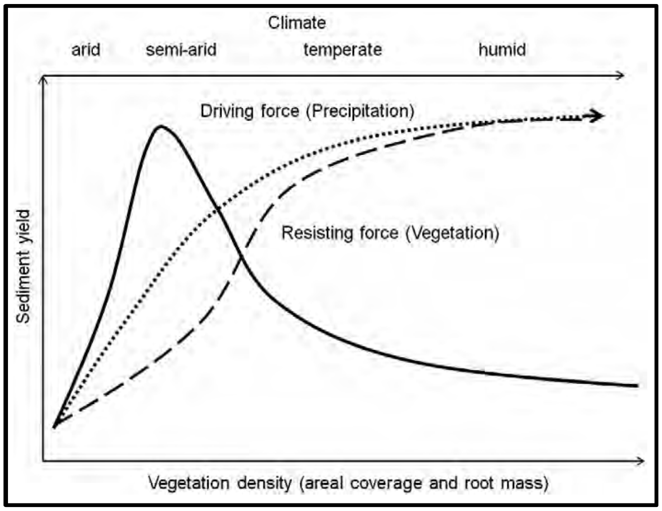

Figure 6. Sediment yield (solid line) with respect to driving and resisting forces(Langbein & Schumm, 1958).

Sediment yields tend to be largest in semi-arid climates, where the lack of precipitation limits the growth of vegetation but is sufficient to generate soils and cause erosion (Goode, Luce, & Buffington, 2012). Because of the relationship of sediment yield to resistive forces, landscape disturbances can significantly affect sediment yields (Collins & Bras, 2008). Promoting hillslope instability and large-scale erosion by reducing vegetation and creating water repellent soils, wildfires are one of the most significant sources of landscape disturbance in western North America (Moody & Martin, 2009; Swanson, 1981). The reduction in erosion resistive forces from the removal of vegetation in combination with increased runoff from the water repellent soils often leads to large sediment transport events in the form of landslides and debris flows (Goode et al., 2012)

Climate-driven variations in either landscape disturbances or the local hydroclimate are likely to produce changes in sediment yield (Goode et al., 2012). The western US is expected to continue to undergo drying of the regional climate and warming leading to more frequent weather disturbances, such as summer droughts and intense storms, as well as an increased extent and frequency of wildfires (Luce & Holden, 2009; Mote et al., 2005; Overpeck et al., 1990). Each of these changing climate characteristics are expected to increase sediment yields as well as the timing and magnitude of peak flows into the Colorado River (Goode et al., 2012).

4 Conclusions

The Colorado River Basin is one of the most regulated basins in the world, with over 70 billion m^3 of usable storage. Due to the variation of flow and sediment sources within the Basin, the construction of reservoirs has changed the sediment inflow and outflow to the Colorado River in complex longitudinal patterns. A drying of the regional climate leading to more frequent weather disturbances, such as summer droughts and intense storms, as well as increased frequency and intensity of wildfires, are expected to lead to increased sediment yields as well as changes in the timing and magnitude of peak flows in the Colorado River Basin. The large storage capacities of reservoirs within the Basin are expected to mute the impacts of the changing flow regimes of the tributaries into the Colorado River such that the Colorado Rivers flows will not change significantly. However, an overall increase in sediment yield within the Colorado Basin from global change is expected, having reach dependent impacts.

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