Chapter 5: Scaling a Supply Limited Sediment System: Grand Canyon Sediment Sources, Processes, and Management

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INTRODUCTION

Dams affect fluvial sediment transport in dramatic but complicated ways. They cut off the main stem sediment supply and flatten the flow regime; trading seasonal extreme high and low flows for a pulsing flow regime dominated by moderate magnitude flows (See Burley this volume). River morphology, recreation, and ecology in the Grand Canyon are all directly connected to the sediment response to the Glen Canyon Dam. Sediment retention in the Canyon is also the primary first-order goal of recent controversial (and costly) management experiments (See Burley in this Volume). In order to understand sediment dynamics in this system and how these processes affect the other physical and biological processes represented in this volume it will be helpful to address three big sediment questions:

1. Where does the sediment come from? (the load question)
2. How does sediment move through the system? (the capacity and process question) and
3. How do these considerations affect management decisions and HFEs? (the management question)

1. WHERE DOES THE SEDIMENT COME FROM?

The first step in building a conceptual model of a sediment system is to carefully estimate the mass balance (mass inflows, outflows, and internal sinks). Computing a 'sediment budget' begins with identifying and quantifying sources (Figure 1). Before the dam approximately 77-82% of the sediment (60-66 MT/y) came from the Colorado River watershed upstream of the dam site and 14 to 16% came from the two major tributaries (about 2.6 MT/y from the Paria[1] and ~9.3 T/y from the Little Colorado). There is much more uncertainty, however, surrounding the contributions from the 768 ungaged tributaries ('Other Tribs' in Figure 1). Early estimates put the ungaged contribution at 6% (4.4 MT/yr)[2], but more recent analyses have (Randel and Pemberton, 1987 and Toping et al., 2000b, from Schmidt and Grams, 2011) estimated much smaller distributed contributions (<1MT/y or <1% of pre-dam loads). This may seem like a minor contribution to be the focus of sustained debate, but the magnitude of these uncertain loads is important for two reasons. First, ungaged tributaries inflows are the only source of coarse material (i.e. gravel and cobbles) in the canyon. Second, some (Web and Schmidt, 2001) argue that the sediment budget is sensitive enough that the difference between an overall sediment surplus or deficit falls within the margin of error of the tributary contributions. Large, historic, estimates of tributary loads pointed to a depositional system while the more recent, lower estimates push the sediment budget computations into deficit.

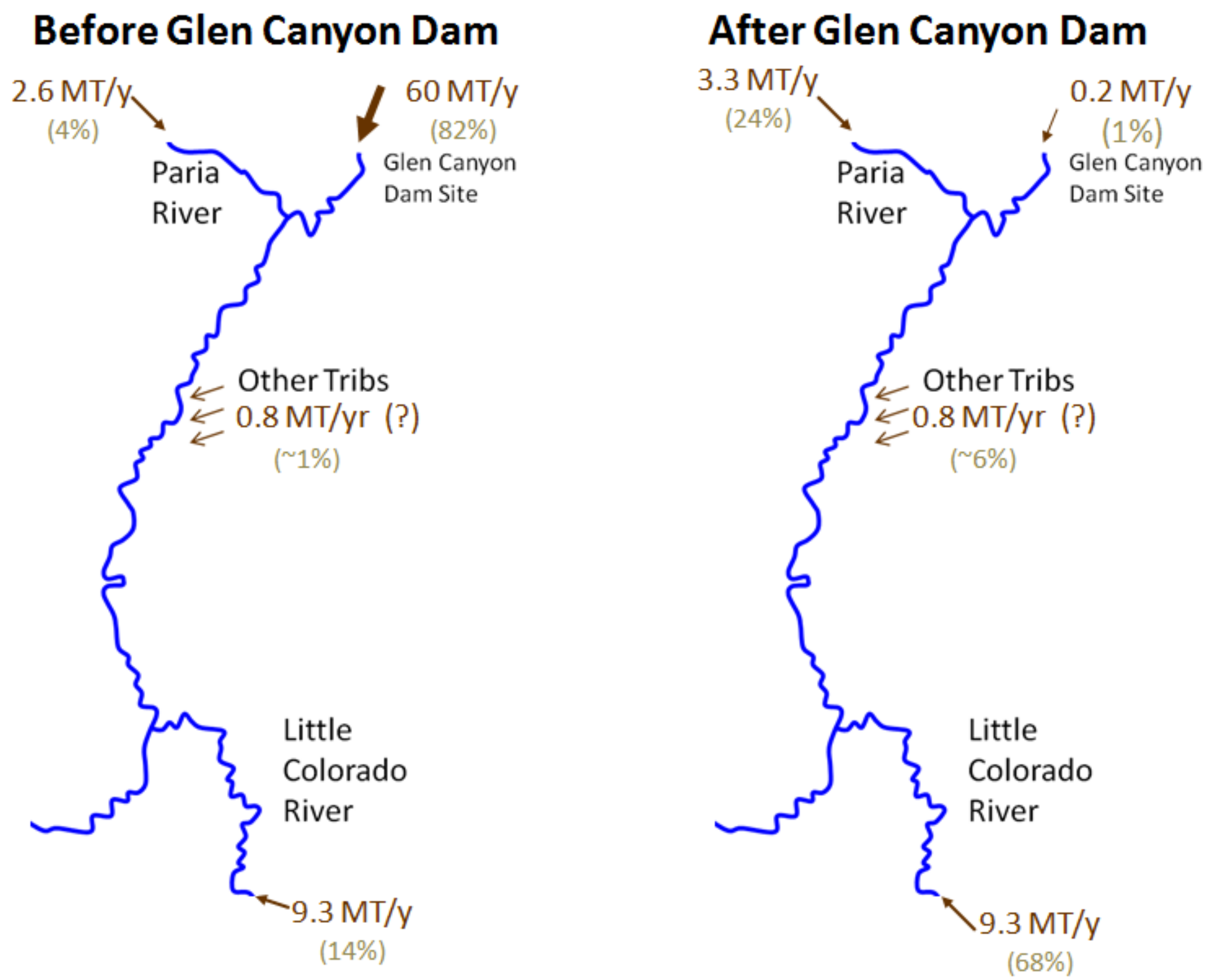

Figure 1: Pre and post-dam sediment budgets of the Colorado River through the Grand Canyon. These numbers vary depending on the source and assumptions. This figure is estimated based on the meta-analysis reported in Schmidt and Grams (2011).

Constructing a budget of total sediment loads can be a little deceiving, however, as most of the clay and silt (particles finer than 0.0625 mm) passes through the system as 'wash load', without forming persistent deposits or directly affecting river morphology. Most management questions focus on the sand component of these loads (0.0625 mm to 2 mm). According to Topping *et al.* (2000a) the Paria delivers approximately 50% sand while the Little Colorado sand component falls between 30 and 40%. Webb and Griffiths (2001) reported that the ungaged tributary loads are approximately 50% sand and generally fine downstream (Figure 2). However, somewhere between 4 and 23% of the ungaged tributary load comes from debris flows (Griffiths *et al*. 1996) which are very poorly sorted (well graded)[3] and are the only substantial source of gravel and cobble sized material.

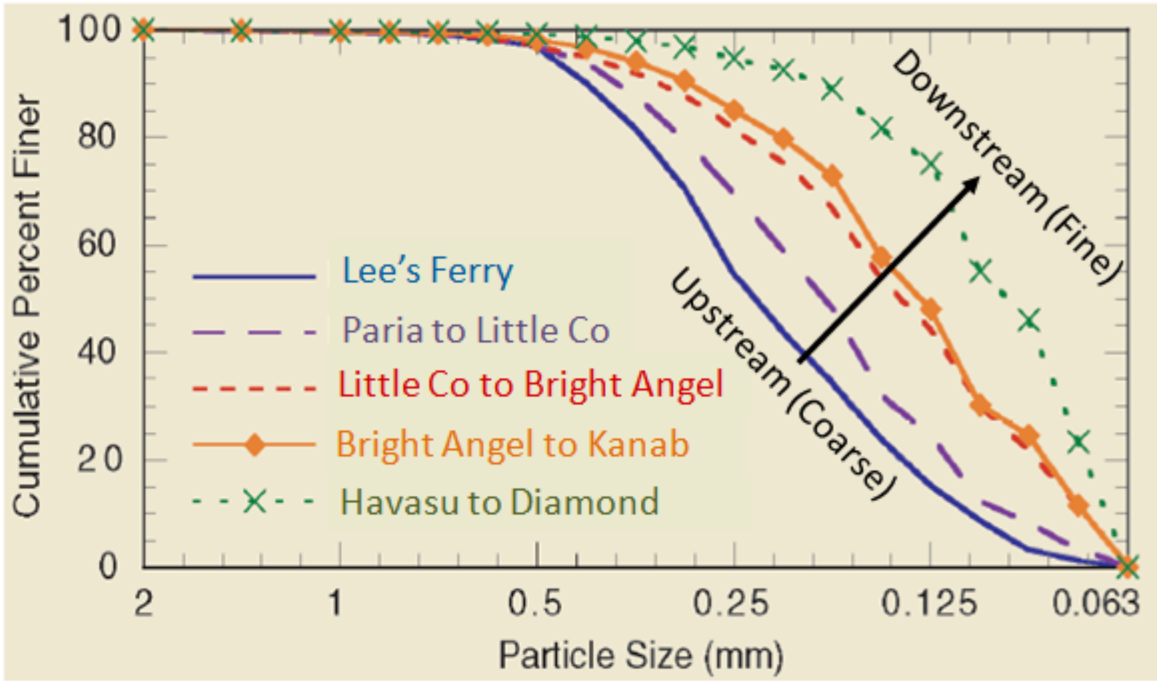

Figure 2: Gradation of sediment contributions by ungaged tributaries averaged by reach (Modified from Webb and Griffiths, 2001). Tributary contributions fine in the downstream direction.

2. HOW DOES SEDIMENT MOVE THROUGH THE SYSTEM?

Sediment Transport Capacity

Accounting for loads is only the first step in constructing a sediment budget.[4] The load has to be compared to the capacity; the amount of sediment the river can transport. The difference between the capacity and the load gives an indication of how much sediment can be stored or removed from storage. Usually, the most important process to understand about sediment transport capacity is the dramatic non-linearity of the flow-capacity relationship. Sediment transport capacity can usually be roughly estimated with a power function $G_s=aQ^b$ where G_s is capacity (tonnes/day), Q is flow (m^3/s), a is an empirical coefficient and b is a power that generally falls between 1.5 and 2.5, but appears to be greater than 3 for in the Grand Canyon. Because the relationship of flow to load is so intensely non-linear, it is common for the majority of sediment in most systems to transport in the largest 10% or even 1% of flows (Figure 3). Therefore, attenuating the highest annual flows in a reservoir reduces the total system transport capacity dramatically.

This non-linear reduction in transport capacity combines with the fact that most of the system's sediment is trapped behind the reservoir to generate an entirely new system with muted sediment capacity and load that essentially behaves as a lower order stream. The relationship between the new reduced supply and the attenuated flow regime interact in complicated, system specific ways and can make the impacted system either more erosional, more depositional or both (i.e. more erosional for some grain classes and more depositional for others).

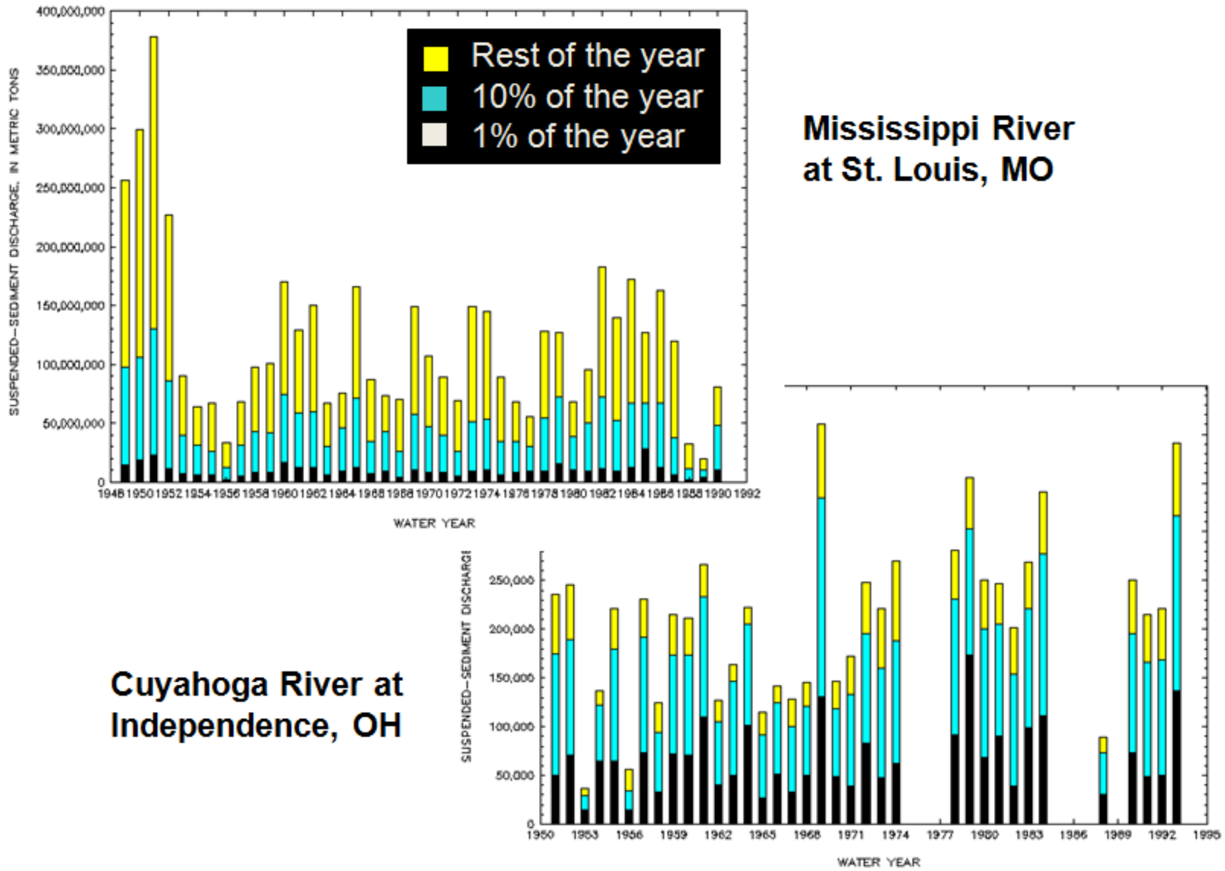

Figure 3: Examples of the dominance of infrequent, large flows, in transporting sediment in (a) regulated and (b) unregulated systems.

Supply Limitation

The Colorado River response to regulation is driven by its ‘supply limited’ condition. Topping *et al*. (1999) argue that the pre and post-dam conditions both had more capacity to move sediment than the available loads supplied. Both the non-linearity of transport and the supply limitation of this system are illustrated by the flow-load relationship depicted in Figure 4. Below 20,000 cfs the curve demonstrates the classical non-linearity of sediment transport processes. However, the relationship flattens above 20,000 cfs, illustrating the supply limitation of the system. Because capacity exceeds load, the actual sediment load (Q_s) associated with these flows is not limited by the capacity of the river to move sediment (G_s, which, presumably, continues to increase non-linearly) but by the amount of sediment available to be transported.

During most pre-dam years the system oscillated between seasonal depositional and erosional regimes (Topping *et al*, 2000). There was a lag between peak sediment inputs (supplied by summer thunderstorms flows the tributaries that drain the Colorado plateau[5]) and the peak main stem flows (from spring snow melt) that generated most of the main-stem transport capacity (Webb *et al*. 1999a). Temporal decoupling of supply and load meant that there were seasons on the Colorado River typified by sediment storage and seasons characterized by sediment evacuation. But on the annual and, especially, multi-year time scale, there was more system sediment capacity than supply.

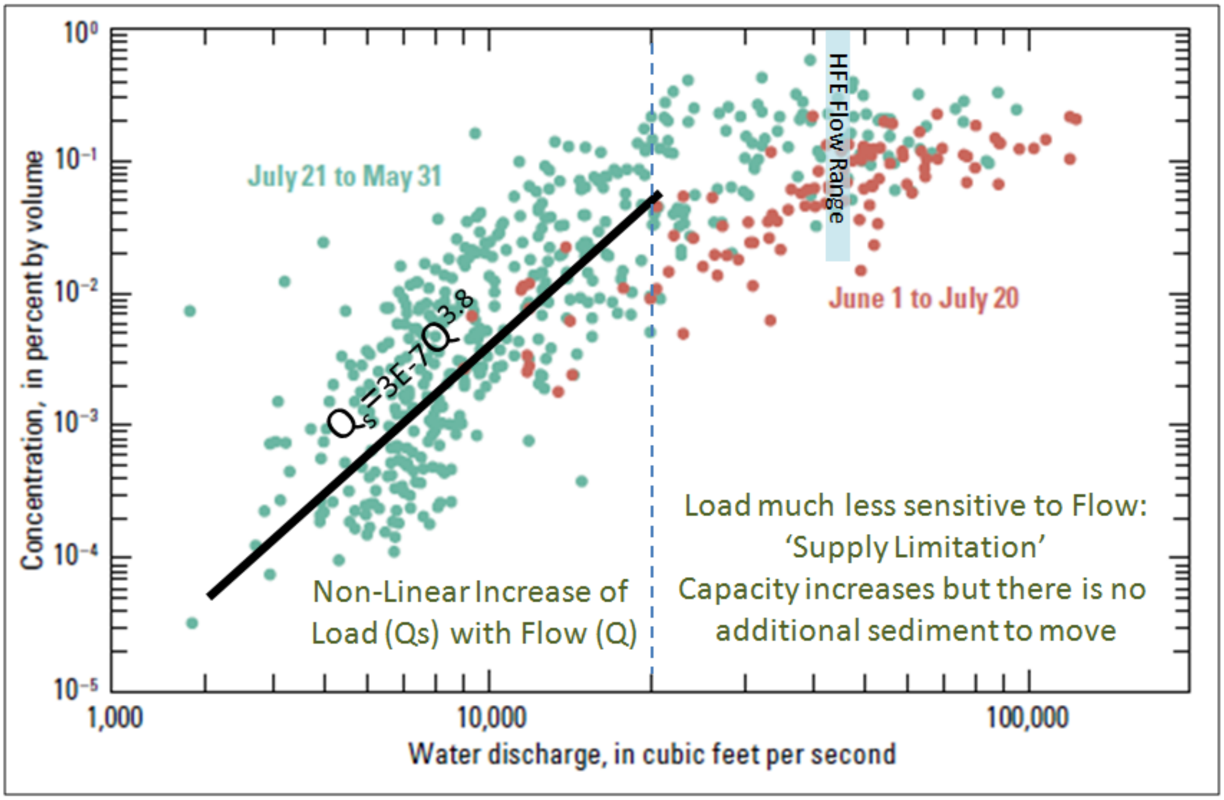

Figure 4: Flow-load relationship from 1944 to 1966 at river mile 88 (Mi 2012) (modified from Schmidt and Grams, 2011). A rough sediment rating curve (Qs is sediment load in tones per day and Q is flow in cms) has been fit through flows less than 20,000 cfs, which comports with the expected power relationship between flow and capacity (G_s). However, above 20,000 cfs, the curve 'bends over'. Presumably G_s (the capacity of the river to transport sediment) continues to increase non linearly but Q_s (the actual sediment transported) does not, because there is no additional sediment to transport. Also note, at large flows, sediment load is much more sensitive to whether the measurement was taken on the rising limb or falling limb of the hydrograph (see hysteresis discussion below). These are both classic signs of a supply limited system.

The regulated regime is also characterized by supply limitation and the temporal decoupling of load and capacity. The reservoir attenuates most of the high transport flows but, the moderate flows that dominate the current flow regime (

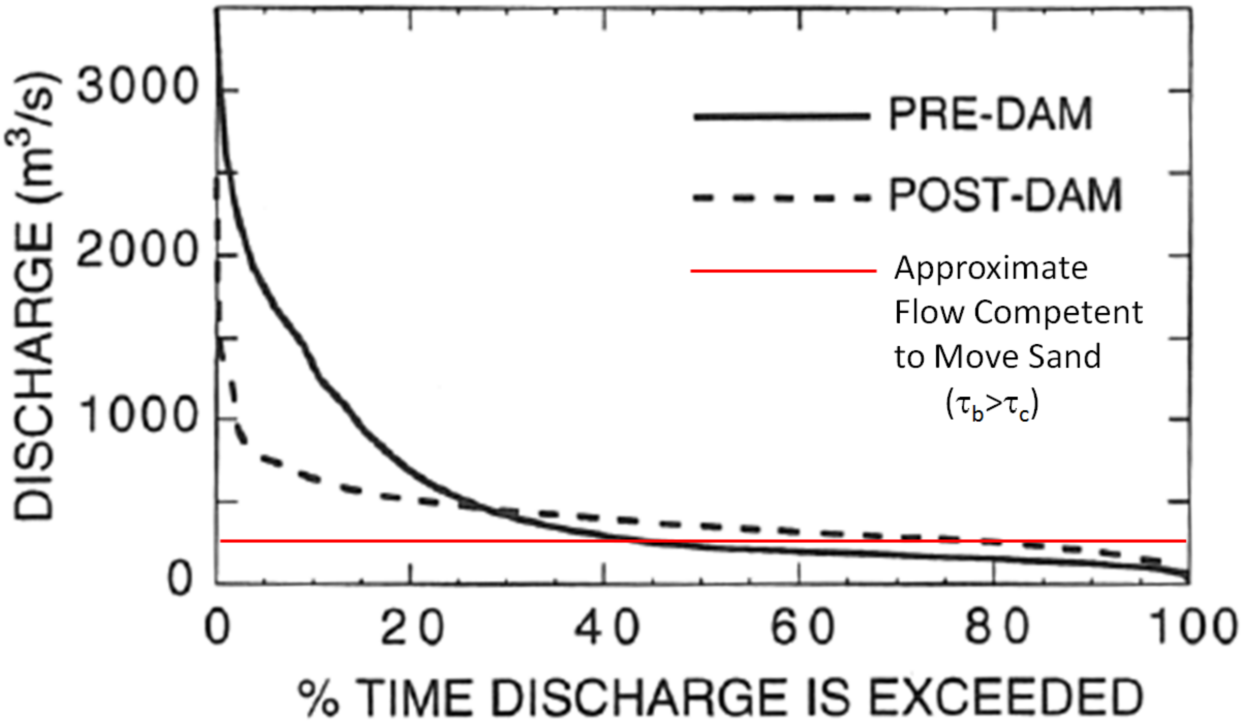

Figure 5) have are capable of mobilizing sand particles (Topping *et al.* 2000a). Therefore, even though both load and capacity are dramatically lower in the regulated system, the relative difference between capacity and load increased. In other words, the regulated flow regime exacerbated the supply limitation and the attending processes, making the system more eroional.

Processes That Store Sediment and Remove it from Storage

Making an erosional system more erosional does not automatically tell the story of retreating sediment deposits. In a supply limited[6] river sediment must be 'protected' from transport processes in off-channel deposits if it is to persist in long term storage. Secondary circulation currents (Figure 6) associated with large flow events generate transverse, cross current water velocities, which transfer sediment into marginal, low velocity, regions removing it from transporting flows. In the Colorado River these low velocity depositional zones are generally associated with the flow separation zone downstream of debris fans (generating fan-eddy complexes- See Bartolomeo in this volume).

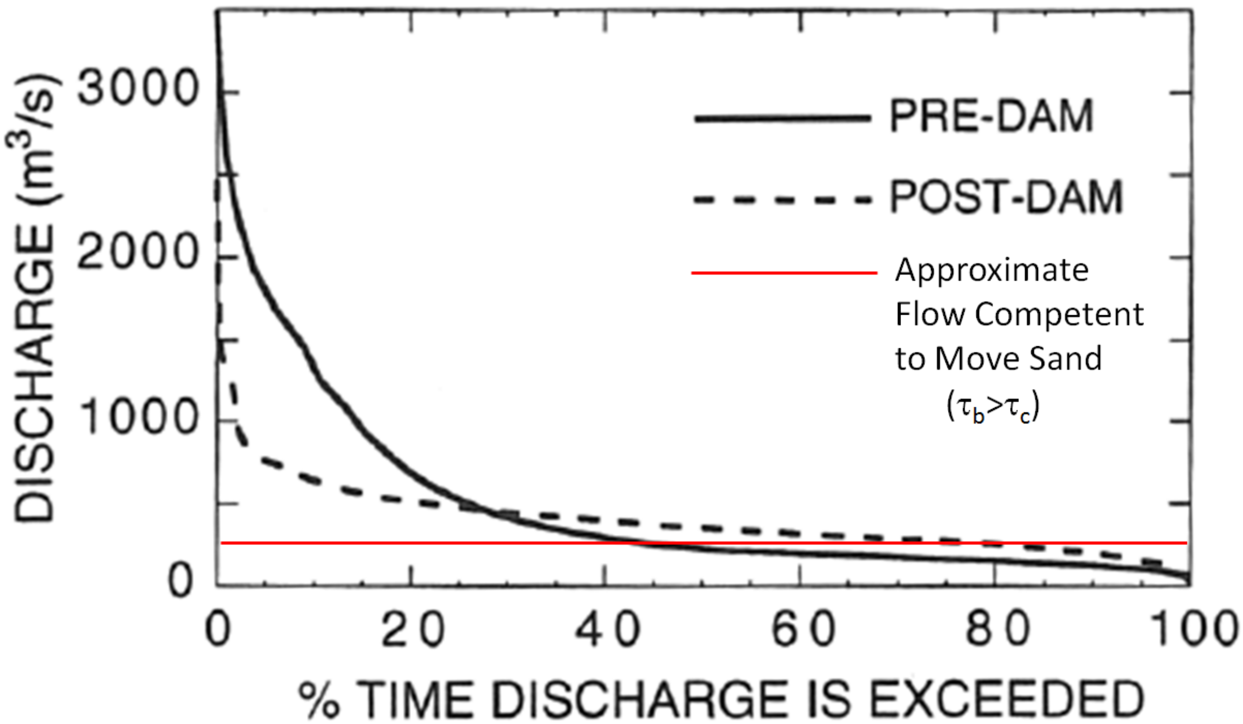

Figure 5: Flow curve of natural and regulated flow regimes (Webb *et al*, 1999) overlain with Topping *et al*.'s (2003) estimate of flow competent for sand transport (255 cms or 9,000 cfs). The regulated flow regime has a much higher duration of flows (~80% compared to just over 40%) that exceed the critical shear of the sand deposits.

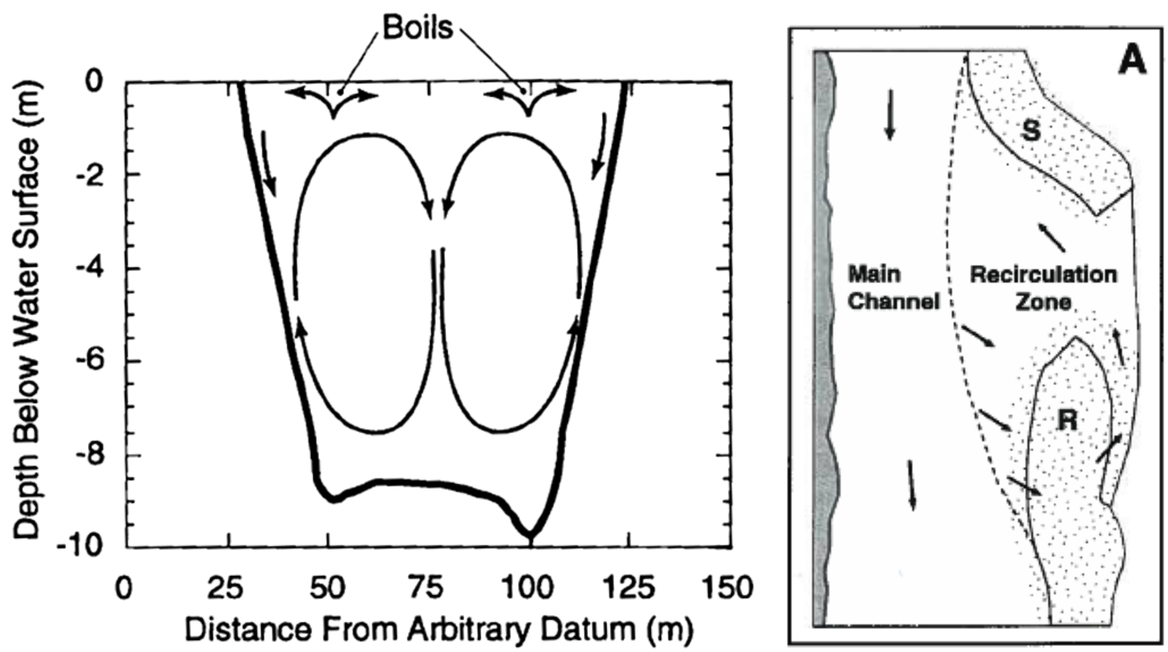

Figure 6: Schematics of secondary circulation in cross sectional (Smith, 1999) and plan view (Hazel *et al*., 1999). These multi-dimensional flow complexities can abstract sediment at high flows to off-line storage in the low velocity zone in the wake of debris fans where they can persist as long term system storage despite the overall supply limitation of the system.

Topping *et al.* (2003) point out that, moderate flow events typical of the regulated flow regime exceed the sand's critical shear stress (

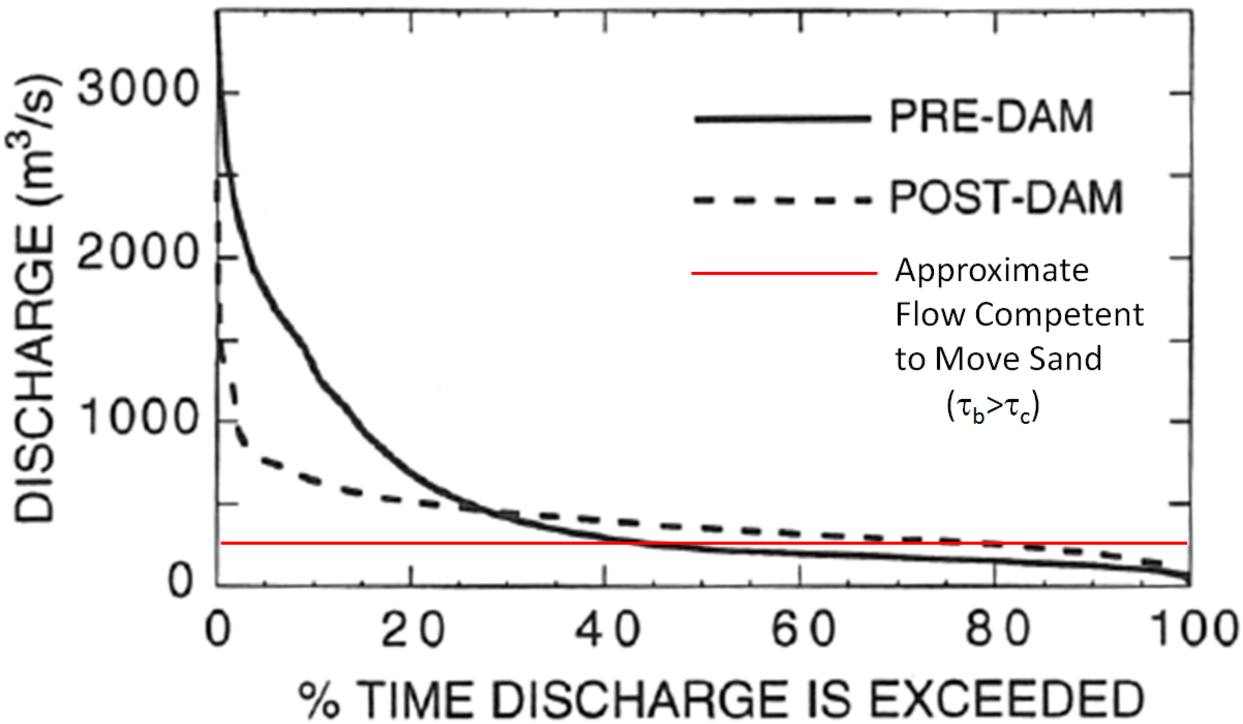

Figure 5) and argue that this is the primary reason for retreating sand bars. The new flow regime increases the total amount of time that sand bars are exposed to flows that exceed the critical shear of the material and 'attack' the lateral deposits without allowing any flows high enough to rebuild the deposits. In this conceptual model, sand bars scour because of the increase in the total duration of *moderate* flows that simple exceed the critical shear stress of sand. They conclude that in the regulated regime the sand bars are exposed to flows competent to move sand as much as 80% of the time compared to 44% in the natural regime.

Topping *et al.*'s (2003) increased base flow argument, which is essentially invokes a critical shear model[7] rather than transport capacity or stream power models appears to be the prevailing hypothesis explaining sand bar reduction. However, there is a geotechnical model of bar shrinkage that could be at least as important if not dominant (Budhu and Gobin, 1995 cited in Booth, 2005).[8] Slopes composed of unconsolidated soils are most prone to failure during a rapid hydraulic recession. In the unregulated flow regimes water surfaces fell gradually, transitioning from high flows to low flows once or twice per year, on time scales measured in weeks or months. Gradually falling water surfaces do not tend to generate sand slope instabilities because the pore water elevation drops at approximately the same gradual rate as the water elevation in the river. In the natural flow regime soils had an opportunity to drain slowly and the hydrostatic force of the river stabilized the bank as it drained. In the oscillating regulated regime, water surfaces river drop too for the hydrostatic forces to appreciably stabilize the bank as it drains. Interstitial water elevations end up 'perched' above the river during the rapid recession and the weight and buoyant forces of the interstitial fluid destabilize the bar. In this model, it is not the persistent moderate flows that are driving bar erosion but the frequency of the oscillation.

Additionally, a second geotechnical hypothesis has been offered and, despite achieving little traction in the literature, it is intriguing enough to mention. Pre-dam sand bars had higher clay contents than post-dam bars (Schmidt and Graff, 1990). Clay particles exert electrochemical binding forces (i.e. cohesion) which, in theory, could have made historic bars more resistant to erosion.[9] This led Webb *et al*. (1999) to advance a counter-intuitive hypothesis that sand bar contraction be related to a post-dam *clay* deficit in addition to the heavily studied changes in the sand budget.

Sediment Hysteresis

One additional complicating property of supply limited systems requires attention in order to understand how sand moves through this system and responds to the HFE management strategies. Supply limited systems, including the pre- and post- dam Colorado River (Topping *et al*., 2000a), are characterized by sediment hysteresis (Figure 7). Hysteresis is a condition in which a process moves between high and low states by alternate 'arrival' and 'return' paths. These processes tend to plot as characteristic looped functions. Most flow-load curves are already typified by mild hysteresis because of supply processes. Early in a rainfall event there is more loose, easily mobilized watershed material, so the rising limb of the hydrograph generally delivers more sediment than comparable flows on the falling limb. Therefore, a power function is already a simplification of most flow-load relationships.

But hysteresis is exaggerated in a supply limited reach. If there is a limited amount of channel sediment, finer sand will be disproportionately removed on the rising limb of the hydrograph[10], leaving deposits composed almost entirely of coarser sand for the falling limb to transport. Transport capacity of coarse sand is roughly an order of magnitude smaller than fine sand. Therefore sediment loads are larger and finer on the rising limb of the hydrograph than for comparable flows on the falling limb. Sediment hysteresis in supply limited systems can also be complicated by stratigraphy of sand deposits (Figure 8). If coarse particles settle first, causing channel and bank deposits to fine upwards, stratified deposits act as a positive feedback to the system hysteresis as subsequent transporting flows will have access to surficial fine deposits first. However, if sediment deposits coarsen upwards, stratigraphy can mitigate hysteresis effects (and potentially slow bar erosion) by regulating the availability of fine sand.

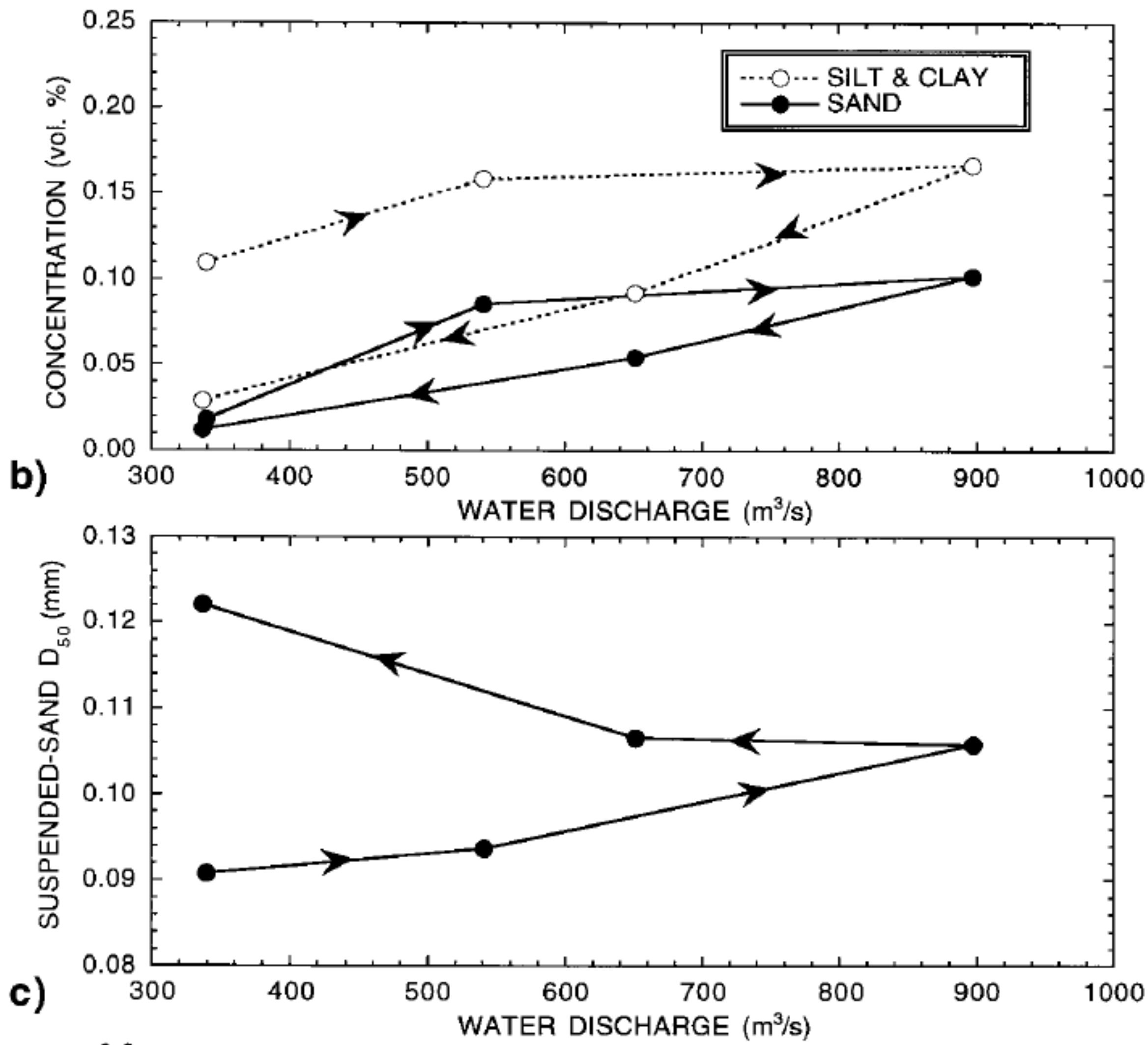

Figure 7: Load and gradational hysteresis generated by supply limitation on the Colorado River (Topping *et al.*, 2000a). There is a limited quantity of sediment that arrives before the transporting flows, therefore early flows disproportionately transport finer material until it is exhausted, leaving coarser sediments to be transported by later flows. Because finer material is easier to move, this gradational evolution of the available sediment leads to much higher sediment loads on the rising limb of the hydrograph than comparable flows on the falling limb.

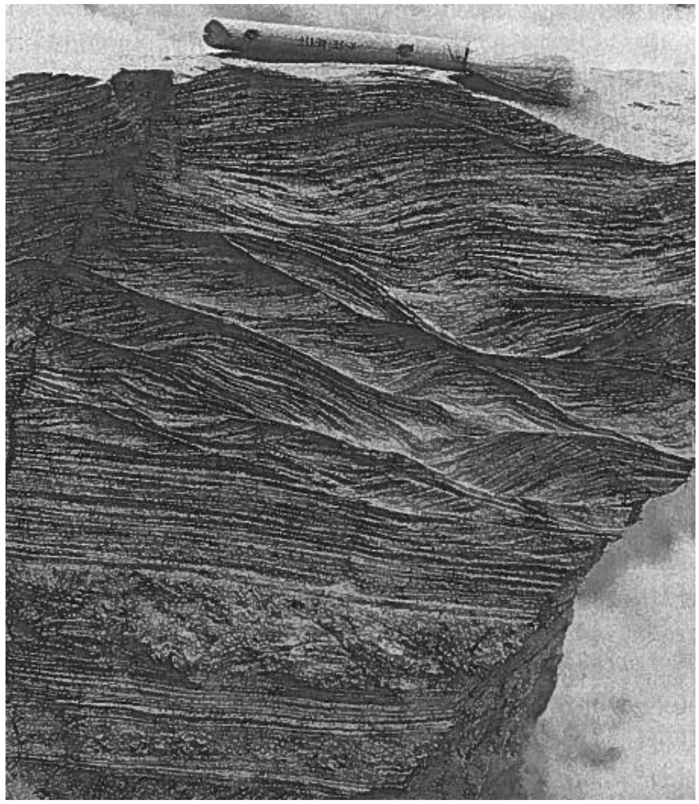

Figure 8: Sediment hysteresis can generate stratified sediment deposits which can exacerbate future hysteresis (if they fine upward) or mitigate future hysteresis (if the coarsen upwards). (From Topping *et al*. 1999.)

Coarse Sediment Transport

Finally, it is important to note that a river does not have a single 'sediment budget'. The story of inputs, outputs and storage can vary by grain class. Increasing base flows and/or increasing the rate and frequency of water surface recession exacerbates the supply limitation with respect to the sand-sized grain classes, which are important for building bars. Sand capacity exceeds supply. But the coarse material budget (e.g. gravel, cobble and boulders) follows a more classical story of the loss of non-linear, large transport events in the regulated flow regime reducing sediment supply and generating a sediment surplus in the reach.

Coarse material, delivered to the river by debris flows (See Selander in this volume), can only be moved by very large flows. But very large historic flows could periodically move large clasts through the system. Large flows moved them from debris fans to the pools and very large flows scoured the pools and moved them downstream.[11] The regulated flow regime does not generate sufficient stream power for either of these processes, leaving the large particles essentially in place, leading to expanding debris fans which progressively impinge on the river (See Selander in this volume). However, Pizzuto *et al.* (1999) performed a 'tagged particle' analysis during the 1996 HFE and demonstrated that HFE flows (peak of 1180 m^3/s or 45,000 ft^3/s) were sufficient to mobilize particles as large as 2 m and to move cobbles (~10-30 mm) and average of 230 m until they "deposited in the pool immediately downstream." Similarly, Webb et al (1999b) reported that debris fan area decrease between 3 and 34% in response to the same event. This suggests that the HFEs are sufficient to move coarse clasts from the debris flows to the pools but are not sufficient to scour them from the pools and move them through the system. Therefore, the regulated canyon has become a gravel and cobble sink with nearly 100% localized trap efficiency with or without the HFEs.

3. HOW DO THESE CONSIDERATIONS AFFECT MANAGEMENT DECISIONS AND HFEs?

HFE management has cycled through a series of credible hypotheses that have been subsequently modified or rejected. Initially the idea of exacerbating the system sediment deficit by increasing annual capacities with HFEs (because of non-linear transport potential of high flows) without introducing new loads was met with skepticism. However, refinement of the sediment budget and extensive field work pointed to a supply limited condition, suggesting that higher water surface elevations could induce sufficient concentrations and secondary currents to put more sediment into off-line storage in the debris fan separation zones (Topping *et al*., 2000).[12] The first HFE (1996) was expected to mine latent channel deposits and move them to high elevation bars. This event did build high elevation bars in the eddy zones (Figure 9) but mainly by scouring lower elevation bars rather than mobilizing channel deposits (Schmidt and Gonzales, 1999). There was no significant transfer of sediment from the channel to the bars because channel sediment deposits in the Colorado River are evacuated within weeks of delivery from the tributaries under normal regulated flow regimes (Rubin *et al*. 2002). Topping et al. (2003) actually argued that a poorly timed, extended HFE could be detrimental as it increased the total amount of time that sand bars are exposed to flows that exceed the sand's critical shear. They also argued that HFEs were more likely to build sand bars if they took advantage of system hysteresis.

Therefore, subsequent HFEs focused on timing the releases to coincide with the tributary loads,[13] getting these materials into high concentration suspension at elevations sufficient to inundate eddy bars before they could pass through the system. The finer, early sediment loads are also more evenly distributed vertically in the water column. Because of smaller fall velocities finer sands are more susceptible to secondary current processes and lateral, cross current transport into off-line storage.[14] Therefore, timing the HFE with the Paria inflow resulted in more total sand bar deposition in the upstream portion of the reach in 2004. But the maximum total bar building occurred in 2008 which followed back to back high sediment yield years on the Paria, bringing the muli-year channel storage hypothesis back into play (Schmidt and Grams, 2011).

Understanding the sediment budget, supply limitation, and the processes that store sediment and remove sediment from storage despite an overall sediment deficit have, arguably, made each successive HFE more effective at building high elevation sand bars. But the sediment story will also determine if the current management strategy is ultimately effective for the related system dependencies covered in the rest of this volume and if these releases are ultimately sustainable.[15]

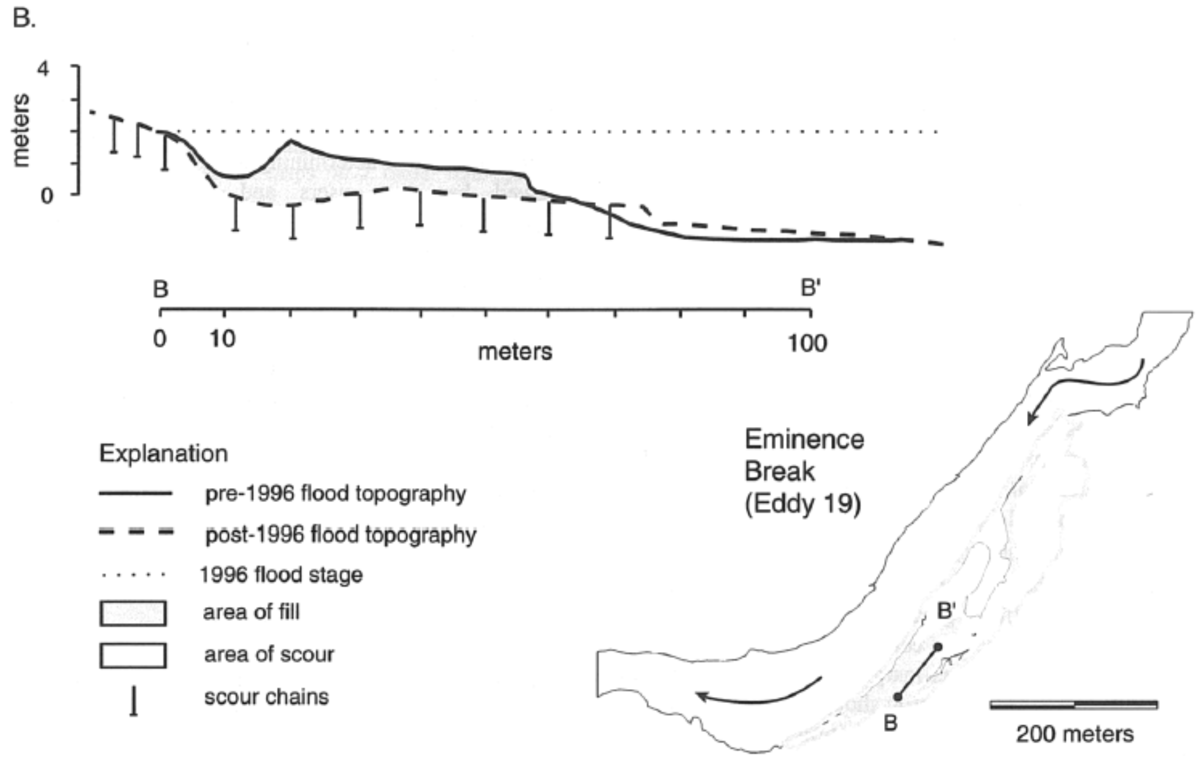

Figure 9: Example sand bar profile change in response to the 1996 HFE (Shmidt and Gonzales, 1999). High elevation sand bars deposited while lower elevation portions of the bars scoured.

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NOTES:

[1] The Paria data appears to be legitimately non-stationary (Schmidt and Grams, 2011). Sediment loads computed for successive periods of record increase with time. Therefore, the post dam Paria loads are larger than the pre-dam loads despite being directly unaffected by the structure. This is probably due to land use changes but could be coupled to flow non-stationarity.

[2] Webb et al (1999a) puts the ungaged tributary contributions as high as 25%, demonstrating the lack of consensus on this.

[3] For those new to the sediment world, welcome to our most confusing linguistic idiosyncrasy. Because of the logistic nature of sediment size distributions sediment taxonomy requires a term that communicates if a sediment mixture is composed mostly of like particles or is composed of a heterogeneous mixture of different sized particles. Geologists use the term 'sorted' and engineers use the term 'graded'. Unhelpfully, they are opposite scales. So if the particles are mostly alike, the mixture is 'well sorted' or 'poorly graded' and if the mixture is composed of many different size classes the mixture is 'poorly sorted, but 'well graded.'

[4]Any basic mass balance has inputs (Q_i loads), outputs (Q_o~ capacity) and the difference (ΔS – deposition or erosion) is stored or removed from storage such that Q_i-Q_o=ΔS. In a sediment budget, the transport capacity drives the output. Changes in sediment storage are generally the difference between supply and capacity…unless a system is supply limited.

[5] Like the Paria. The major exceptions to this are the tributaries that come in from the south east, mainly the San Juan and the Little Colorado, which are usually double peaked with hydrograph spikes during late winter and early spring (See Burley Figure 3 in the Volume).

[6] The non-linearity story is not the dominant story.

[7] In the technical jargon, they focus on competence (the ability of water to mobilize sediment) rather than capacity (how much sediment a given flow can move as a function of hydrodynamics). The competence approach rarely tells the story, but in a supply limited system that runs a long term sediment deficit, sand only has to be mobilized from off-line deposits in order to move all the way through the system.

[8] I suspect this process has been underrated.

[9] However, sand-clay mixtures drain more slowly, so they would maintain negative pore water pressures longer in the repeated drawdown scenario of recreational regulation.

[10] The removal of fine material from a river bed sediment mixture is often referred to as 'winnowing.'

[11] It is intuitive to think of riffles, rapids, and runs as the high velocity, erosive zones of a river and the pools as the low velocity, deposition portions of a river. But this could not be a stable fluvial configuration in the long term. Eventually the riffles would erode and the pools would fill. The counterintuitive feature of pools is that the reason they are deep and slow moving at low flows is that they represent reaches with the highest transport capacity during the highest flows, (usually because of some lateral control). Therefore, rare, large flows, which are generally absent from a regulated flow regime, periodically scour pools and build riffles.

[12] According to Schmidt and Gonzales (1999), "scientists and river runners alike" refer to the von Carman vortex generated by the debris fans, generating a low velocity zone that recruits sand bars, the "eddy fence." I guess "eddy fence" is catchier than "von Karmen vortex wake"

[13] The 2004 HFE was timed to the Paria sediment loads. It improved bar building in the upstream reach but provided no real advantage downstream. The 2008 event was more effective throughout the system, presumably because particularly high 2006 *and* 2007 Paria sediment loads did persist in the system over multiple years, so the 2008 event redistributed multiple years of sediment.

[14] It also utilized hysteresis by depositing large fine loads first and then following them with more modest, coarser loads. This was expected to generate a helpful inversely graded statigraphy where the most difficult particles to erode were deposited on the surface.

[15] There are other long term sediment management alternatives on the table. For example, the US Bureau of reclamation (Randle *et al*, 2007) is investigating sediment bypass structures that will pipe Colorado River sediment around the dam and into the lower reach at high flows.