Serial Discontinuity and the Geomorphology of Tributary-Mainstem Interactions on the Green River

By Robert P. Thompson

ABSTRACT

The Serial Discontinuity Concept predicts dams to have large impacts on a river directly downstream, with conditions gradually naturalizing with distance downstream, largely due to unregulated tributary inputs. Geomorphic structures caused by tributary-mainstem interactions should also follow this pattern of being most altered near a dam, with these alterations decreasing in magnitude as one travels downstream. General tributary-mainstem theory, as described in the Network Dynamics Hypothesis by Benda et al. (2004a), makes predictions about the effect of tributaries on variation and disturbance, describes general characteristics of confluence geomorphology, and predicts the likelihood of a tributary causing observable geomorphic effects based on factors such as basin size ratio, basin shape, confluence angle, and the type of tributary input. In the Green River system downstream of the Flaming Gorge Dam, debris flows are the most significant tributary input, creating numerous debris fans in several canyons, and greatly modifying the river hydraulics and deposition with the creation of fan-eddy complexes and associated habitat. Reduction of the frequency and magnitude of peak flows by the Flaming Gorge Dam has led to decreased reworking of debris fans and to channel narrowing on portions of fan-eddy complexes. These dam related impacts should decrease in magnitude and severity with distance downstream from the dam, with the largest difference occurring below the Yampa confluence, where the flows should be much closer to their natural state.

INTRODUCTION

The Serial Discontinuity Concept (SDC) asserts: “rivers have an innate tendency to reset ecological conditions toward natural or unregulated conditions as distance downstream from the dam or point of regulation increases (Stanford and Ward 2001).” This concept acts to modify the River Continuum Concept (RCC), which states: “from headwaters to mouth, the physical variables within a river system present a continuous gradient of physical conditions (Vannote et al. 1980).” The Natural Flow Regime Paradigm holds that in its natural state, each river has a certain flow pattern, characterized by the magnitude, frequency, duration, timing, and rate of change in the flows, that regulate the natural river ecosystem (Poff et al. 1997). Applying these concepts to the Green River and the Flaming Gorge Dam, one would infer that prior to the construction of the Dam, there was a natural flow state that drove the geomorphology and ecology of the river system. Construction of the dam disrupted this natural flow regime, creating a discontinuity in the river continuum, with river conditions gradually returning to a more natural state with increasing distance downstream from the dam (Figure 1).

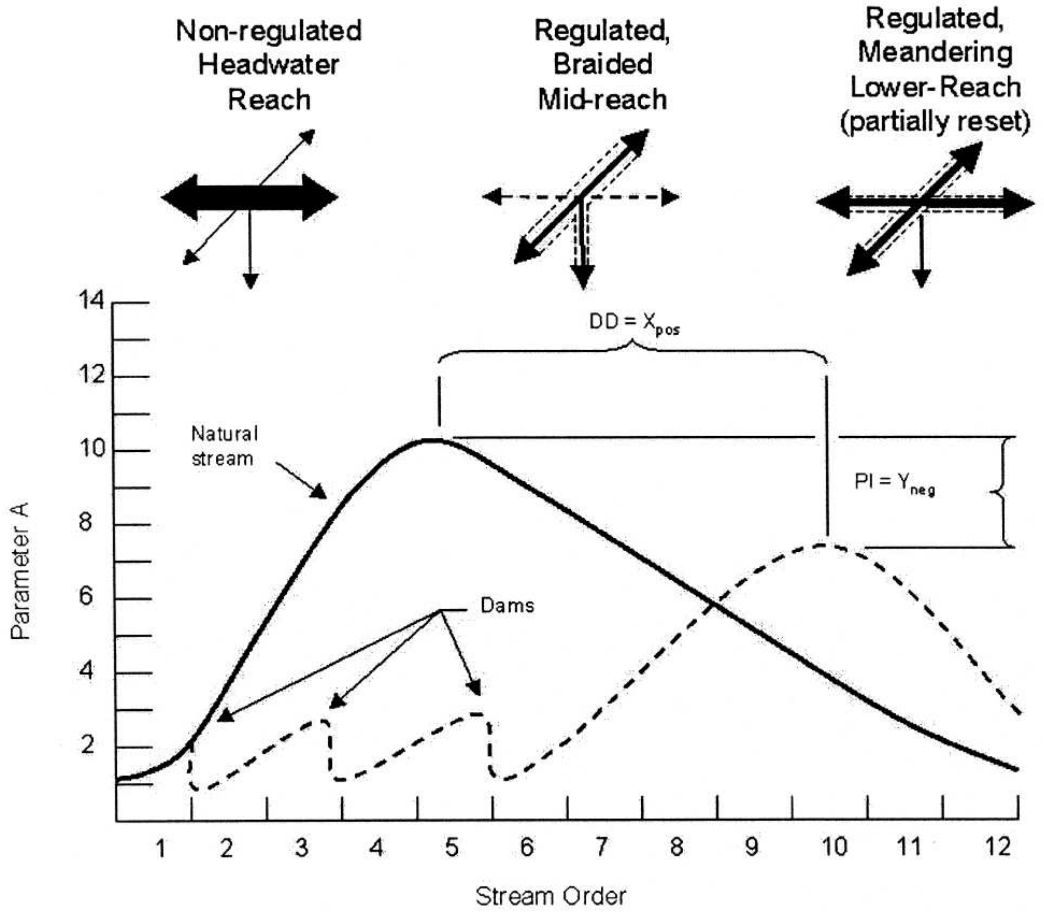

Figure 1. The Serial Discontinuity Concept. Dams disrupt the natural flow regime, which gradually resets itself with distance downstream, largely due to the effect of unregulated tributary contributions of flow and sediment (from Stanford and Ward 2001).

Tributaries play a major role when applying the SDC to the Green River. It is the unregulated tributaries that act to reset the natural flow regime with an influx of natural flow and sediment. But tributaries also interact with the mainstem to create geomorphic changes that are affected by the disruption caused by the Flaming Gorge Dam discontinuity. These interactions include formation of structures such as fans and bars, changes to the longitudinal profile, alterations in deposition and erosion, and local flow alterations. The effects of disturbances such as fires, floods and storms are also amplified at these confluences. Most of the variation and heterogeneity of a river occurs around tributary junctions. The magnitude and occurrence of these effects depend on a variety of factors, including the relative basin sizes of the tributary and mainstem, the network geometry (basin shape), the confluence angle, and the type of tributary input (Benda et al 2004a).

Network Dynamics Hypothesis

Benda et al. (2004a) present the Network Dynamics Hypothesis (NDH) as a way of understanding the effect of channel confluences in river networks and a framework to develop testable predictions about these confluences and networks. As opposed to the RCC, the NDH focuses on the variation created by confluences in river networks. Whereas the RCC predicts gradual downstream change from headwaters to mouth of a river in such parameters as slope, substrate, bank erosion, and channel width, the NDH predicts rapid variation and deviations to these parameters at tributary inputs, which may represent either modifications of the central tendency of RCC predictions or may eliminate these central tendencies altogether (Benda et al. 2004a, Figure 2).

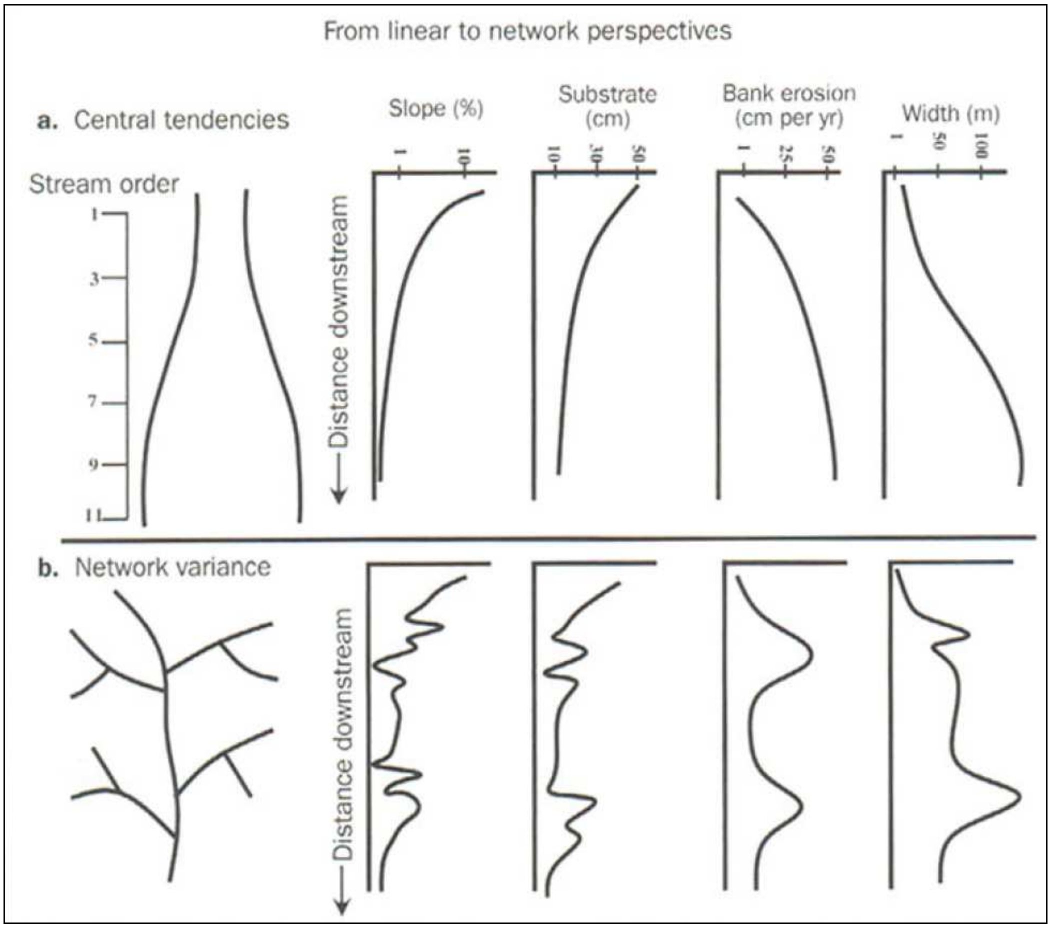

Figure 2. Comparison of RCC with NDH. RCC predicts gradual downstream changes from headwaters to mouth, while the NDH predicts significant variation associated with tributary inputs that may modify central RCC tendencies or eliminate them (from Benda et al. 2004a)

Disturbance

Tributary junctions also act as nodes at which disturbances from upper catchments are impressed on the mainstem (Benda et al. 2004a). These disturbances range from short temporal scale events such as annual flow and sediment variation to more infrequent events such as fires and large floods. Annual fluxes in sediment from tributaries may result in annually varying shapes and sizes of depositional features such as fans, bars, terraces, logjams and secondary channels (Benda et al. 2004a). Large floods, fires, and debris flows may produce features that persist or vary on longer timescales.

Tributary confluence effects

Tributaries can have varied effects on the receiving channel morphology. Alluvial fans, terraces, secondary channels, and wider floodplains are a few examples (Benda et al. 2004a). This impact can extend both upstream and downstream. Common upstream effects include: lower gradient, wider channel, wider floodplain, increased bank erosion, finer substrates, greater lateral connectivity, and higher disturbance magnitude (Benda et 2004a). Downstream, higher gradients, larger substrate sizes, deeper pools, more bars, and greater magnitude and frequency of disturbance are common impacts (Benda et al. 2004a).

Sediment deposits from the tributary at the mainstem, forming bars and fans, can often obstruct flow, resulting in a flattening of the gradient upstream and a corresponding gradient steepening downstream. The ponded flow upstream can increase meandering as well as floodplain and terrace width, and will also cause coarser sediment to fall out of the stream as flow is backed up. More rapid flow downstream will increase substrate size, increase channel width and pool sizes, and increase the likelihood of bars. Accumulations of boulder sized sediment associated with flash flood and debris flows can lead to rapids adjacent to the tributary inlet (Benda et al. 2004a).

Role of Basin Size

Of course not all confluences create observable geomorphic effects, and some produce greater effects than others. Benda et al. (2004a) present several parameters by which the likelihood of the occurrence and magnitude of geomorphic impacts at a confluence can be predicted. Chief among these is the size of the tributary basin relative to the mainstem. The ratio of tributary drainage area to mainstem drainage area is typically used to describe this relationship. Figure 3 plots the drainage area of the mainstem versus the drainage area of the tributary for a number of confluences at which “geomorphically significant” morphological effects were observed. There is very clearly a positive correlation: the larger the mainstem, the larger the tributary needs to be to have a geomorphic impact. Benda et al. (2004a) determine a threshold of a tributary:mainstem ratio of 0.6 to 0.7 as the point at which geomorphically significant effects are likely to occur. This plot also differentiates between alluvial tributaries and debris flows/flash floods. It is clear that relatively small debris flows and flash floods can have an impact on significantly larger mainstems, but that alluvial tributaries need to be of comparable size to the mainstem to have an impact.

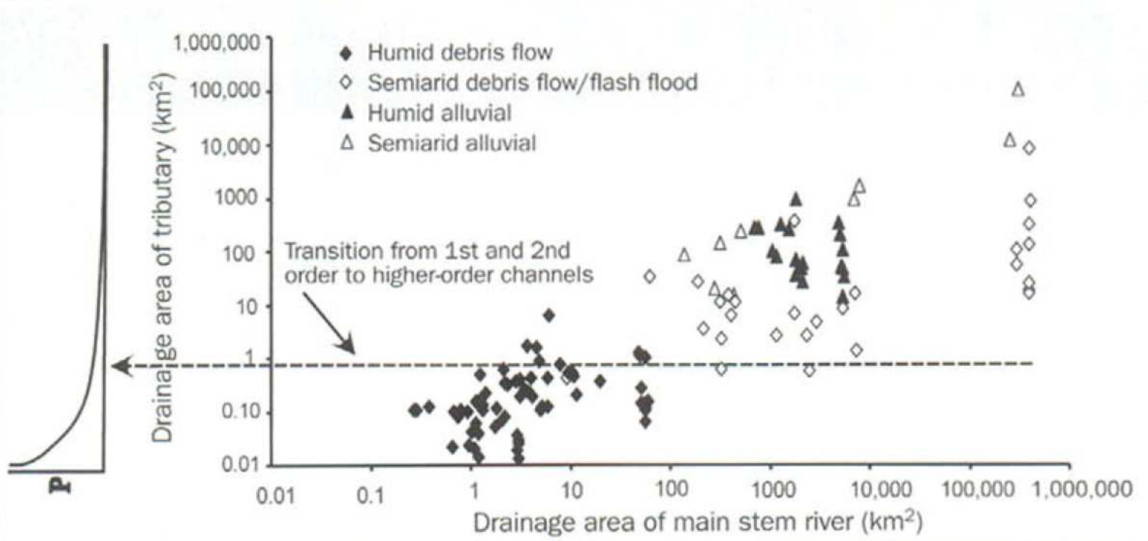

Figure 3. Role of Basin Size. As drainage area of mainstem increases, only larger tributaries continue to create geomorphically significant effects (from Benda et al. 2004a).

Role of Basin Shape

Benda et al. (2004a) present the shape of the local network geometry as another parameter that can be used to predict the likelihood of geomorphic impacts. In this view, basins are characterized into three categories based on the shape of the network: heart shaped (most compact), pear shaped (moderately compact), and rectangular (most elongate) (Figure 4). The shape of the network theoretically determines the likelihood of continuing geomorphic effects as one travels downstream along the mainstem of a river. Compact basins will have the greatest chance of having geomorphically significant confluences along the length of the river as tributaries join together to form higher order streams prior to joining with the mainstem. Elongate basins will have greatly reduced occurrences of significant confluences as the mainstem continues to grow because tributary sizes do not increase substantially downstream (Figure 4, Benda et al. 2004a).

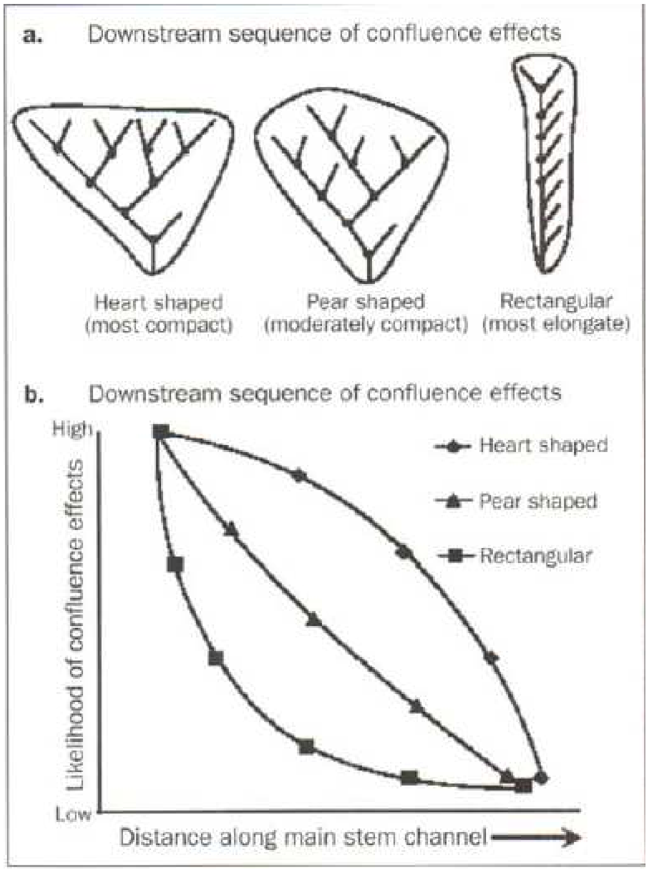

Figure 4. Role of Basin Shape. Compactness of basin determines the likelihood of geomorphic effects with distance downstream (from Benda et al. 2004a).

Role of Confluence Angle

Confluence angle can alter the relative impact of a tributary junction. Flume studies and field observations have shown that the geomorphic impact of a tributary increases with increasing angle from the mainstem (Benda et al. 2004b). This can impact bar size, bar location and scour depth. Angles greater than 70° tend to increase the amount of deposition and resulting confluence effects (Benda et al. 2004b).

Type of Input

Tributaries influence the mainstem by contributing flow and sediment, which can influence the local geomorphology of the junction. Normal runoff, flash floods, and debris flows are the primary mechanisms by which tributaries contribute sediment and influence the channel morphology. Normal runoff contributes finer grained sediments such as clay, silt and sand in suspension or as bedload. Flash floods occur less frequently and can bring larger sized materials to the mainstem. Debris flows occur relatively infrequently but transport large volumes of unconsolidated sediment that typically persists for longer time frames.

Green River and the NDH

The Green River system can be divided into three categories of reaches: fixed meanders, restricted meanders, and debris-fan dominated canyons (Grams and Schmidt 2002, Eustis 2006, Nichols 2006)). Tributaries in the meandering reaches are typically low gradient alluvial flows, which can be expected to contribute mainly fine grained sediment except during flood events, during which coarser sediments may be transported. With the exception of the Yampa, all of these tributaries are much smaller than the Green. According to Benda et al. (2005a), the geomorphic impact of these tributaries should be small to insignificant. The Yampa, comparable in flow to the Green River itself (Agnew 2006, this volume), meets the Green in Echo Park, a restricted meander. The erosion resistant bedrock underlying this confluence restricts the possible geomorphic effects, which are limited mainly to sandbar formation. Tributaries in the debris-fan dominated canyons, however, may cause dramatic geomorphic changes, as debris flows from even a very small catchment can deposit very large sediment that is difficult for the river to move.

Debris Flows

Debris flows are typically initiated by a combination of intense precipitation and subsequent slope failure (Griffiths et al. 1996). Debris flows in the canyons of the Green River are very similar to those in the Grand Canyon. The Grand Canyon literature often cites four primary mechanisms for these debris flow initiations: bedrock failure, the firehose effect, failures in colluvium, and combinations of the above. Bedrock failures involve intense precipitation directly causing a slope failure which then leads to a debris flow. Failures in colluvium (loose bodies of sediment transported by gravity) occur when colluvial wedges that form on or at the base of canyon walls become sufficiently moist for failure to occur, typically resulting in small debris flows (Griffiths et al. 1996). Much larger debris flows can occur with the firehose effect, in which runoff flows over a cliff face and directly impacts colluvial wedges, leading to bulk failure (Griffiths et al. 1996, Figure 5).

The Green River contains several reaches dominated by debris flows. These reaches are characterized by high canyon walls composed of stratified geology directly adjacent to the river. These reaches include: Red Canyon, Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon (Grams and Schmidt 1999, Grams and Schmidt 2002).

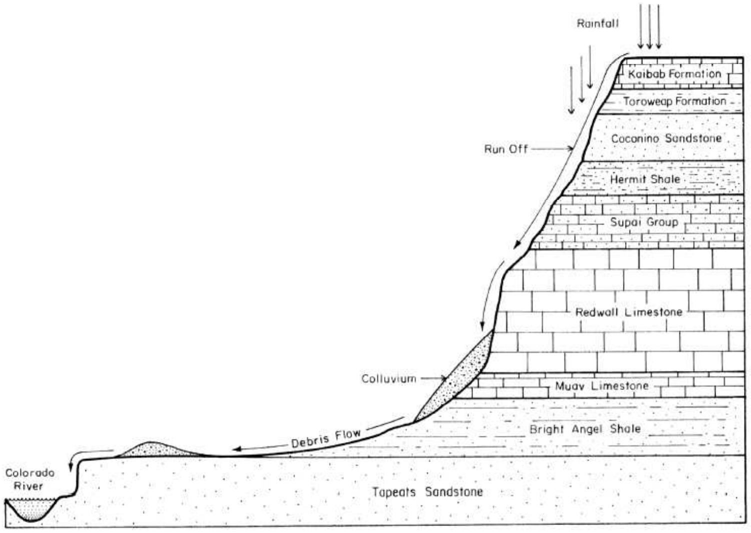

Figure 5. Schematic of a debris flow in the Grand Canyon. Intense precipitation and overland flow down the canyon face leads to a failure in colluvium (from Griffiths et al. 1996).

Debris Fans

Debris flows that flow into the river channel form debris fans. Composed of unsorted sediment ranging from clays to boulders, these fans contribute sediment to the river as well as forming erosion resistant features with significant geomorphic effects immediately upstream, downstream, and at the junction itself. The geomorphic structure created by a debris flow is termed a fan-eddy complex.

Fan-Eddy Complex

As a river flows past an obstruction such as a debris fan, the flow becomes constricted and if the flow is great enough it will become separated downstream of the fan (Figure 6), causing slow eddy circulation to form behind the fan, until the flow re-attaches at some point downstream. The obstruction can create backwaters extending miles upstream of the fan, as well as rapids adjacent to the fan and an increased downstream gradient.

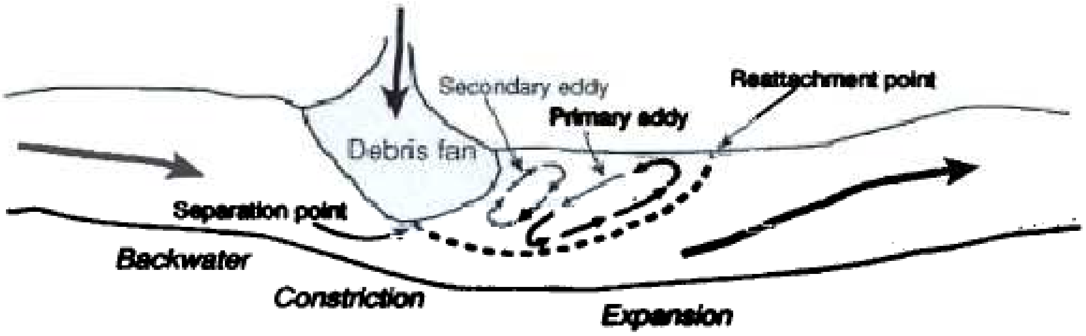

Figure 6. Fan-eddy complex. Debris fan creates obstruction, leading to ponded backwater upstream, rapids adjacent to fan, and eddies just downstream (from Grams and Schmidt 1999).

Deposition

The hydraulic structure described above leads to the unique depositional features of the fan eddy complex. Separation and reattachment bars are formed within the eddies as secondary circulation carries sand from the rapids into the slow moving eddy, where it settles out. In the Green River these two sand bars are often merged, indicating high sediment transport rates in the river (Grams and Schmidt 1999). Expansion gravel bars ranging from one to three channel widths usually form as the flow expands past the eddy (Grams and Schmidt 1999, Figure 7). Sand will also be deposited in the backwaters before the constriction, forming channel-margin deposits (Figure 7). All of these deposits provide unique habitat for aquatic organisms.

Reworking

Reworking of debris fans can occur during both high and low magnitude floods, with differing results. Once reworked, the debris fan typically becomes more resistant to erosion as only larger sediment sizes remain, armoring the fan surface. Lower magnitude floods rework debris fans by entraining individual particles, and by lateral erosion that causes bank failure, which can assist in moving larger clasts that the flow would not normally carry (Larsen et al. 2004). Low magnitude floods typically only carry these larger clasts to the pool downstream of the rapids, rather than the expansion bar further downstream resulting from larger magnitude floods (Figure 7).

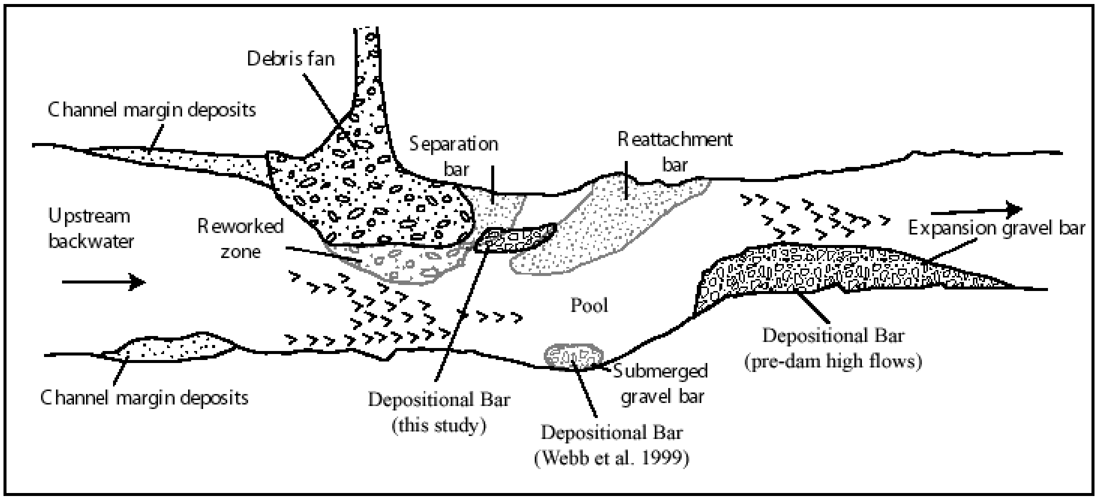

Figure 7. Schematic of debris fan reworking. The outer edge of the debris fan is eroded and larger clasts are deposited downstream, in either the pool just downstream or the expansion bar further down, depending on the magnitude of the flood (from Larsen 2003).

Larsen et al. (2004) present a study of the reworking of two recently aggraded debris fans on the Green River: Snow Ranch in Whirlpool Canyon, and Wild Mountain in Lodore Canyon. The hydrograph of the floods causing significant reworking are shown in Figure 8: the Wild Mountain flood was 90% of the predam two-year flood (10,912 ft^3/s), while at Snow Ranch there were two floods, about 75% and 65% of the predam two-year flood (16,209 cfs and 14,443 cfs).

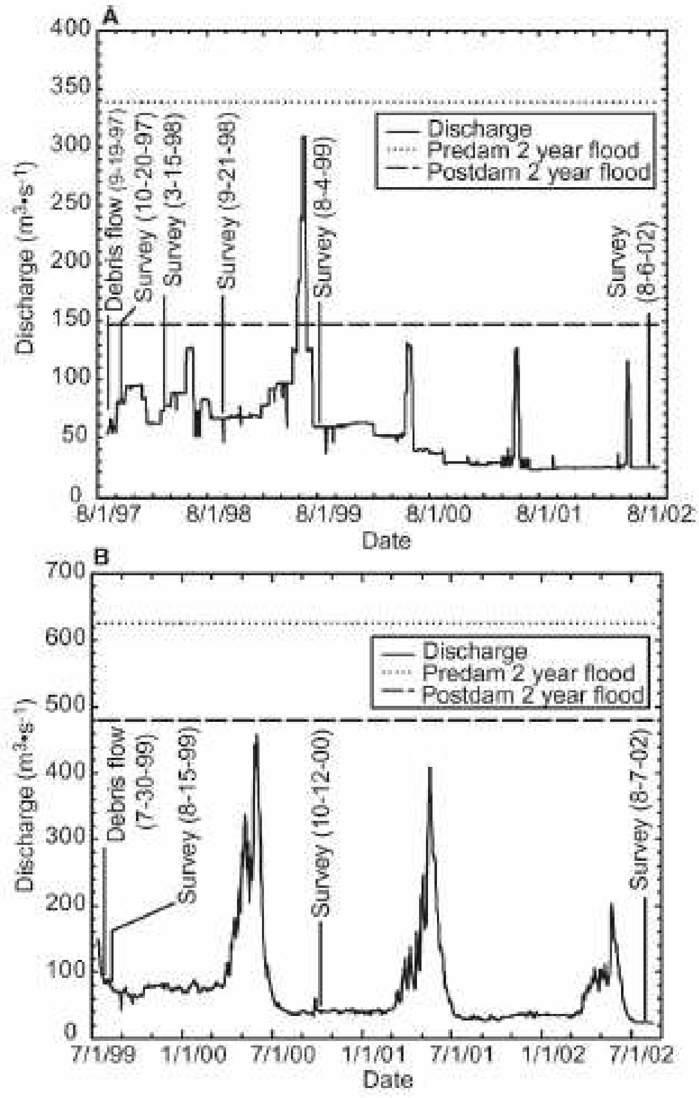

Figure 8. Hydrographs of reworking floods for Wild Mountain and Snow Ranch. The Wild Mountain flood was 90% of the predam two-year flood, while the Snow Ranch floods were 75% and 65% (from Larsen et al. 2004).

The June 1999 flood that reworked the Wild Mountain debris fan was the second largest since the completion of the Flaming Gorge Dam. Floods eroding the Wild Mountain fan prior to this did not exceed the power plant capacity of 4,590 cfs or 40% of the predam 2-year flood, and caused little reworking, limited to some lateral erosion on the distal margin (Figure 9b). The June 1999 flood, however, caused extensive reworking (Figure 9c). Up to 11,300 cubic feet of material was eroded, with over 1,271 cubic feet deposited just downstream, in a small gravel bar connected to the fan (Figure 9c). Armoring of the fan surface from this flood prevented further erosion during subsequent smaller floods (Figure 9d).

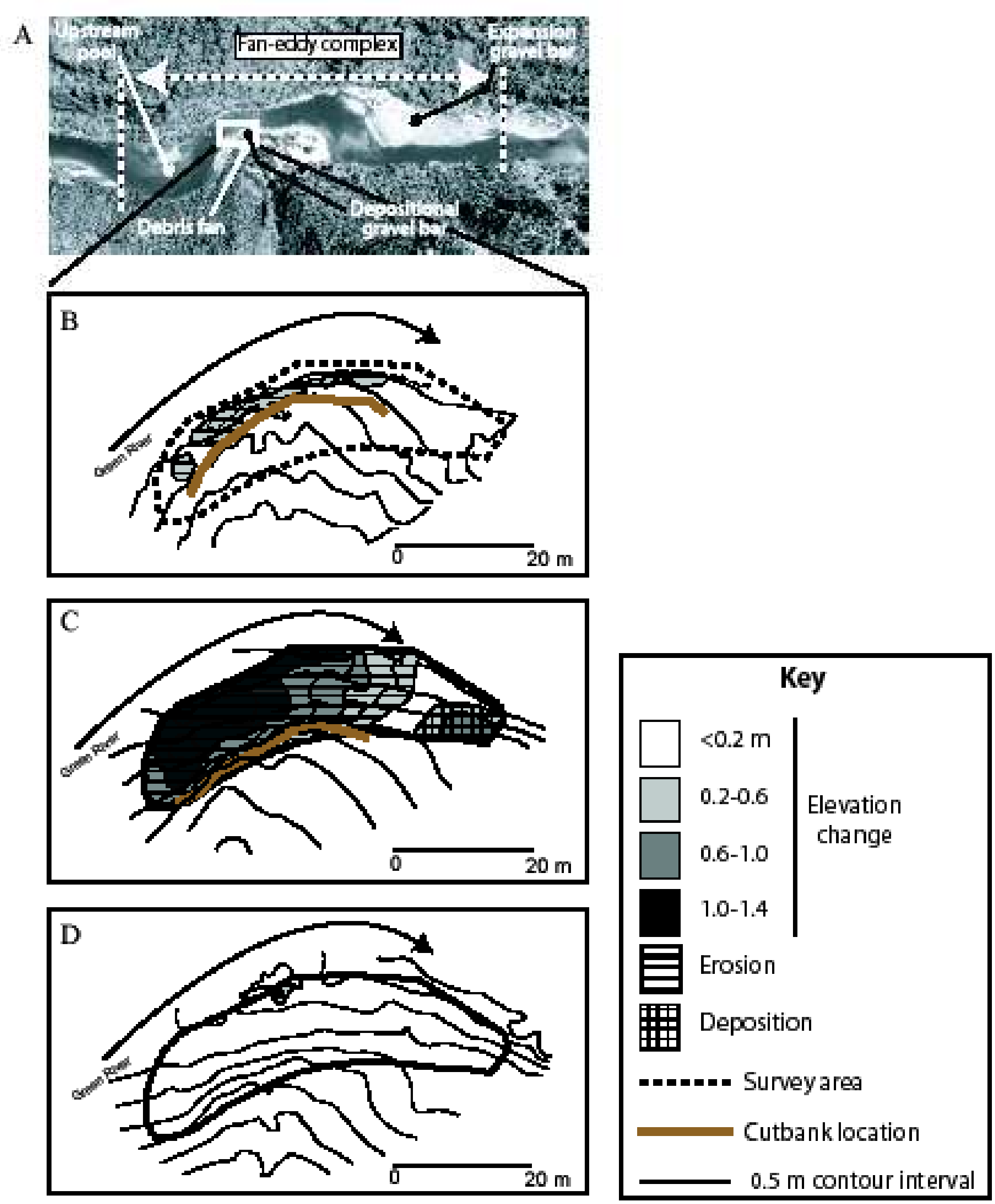

Figure 9. Wild Mountain Debris Fan reworking. B: Minimal erosion occurring with cutbank prior to June 1999 flood. C: Significant reworking occurred during flood, with deposition attached to downstream end of flood. D: No erosion occurred in smaller floods afterward, due to armoring of the fan surface (from Larsen 2003).

The Snow Ranch debris flow was reworked primarily by a 16,209 cfs spring flood in 2000, with a slightly smaller 14,408 cfs flood occurring the following spring. Although both floods were comparable in size, only the 2000 flood caused significant reworking, eroding 11,406 cubic feet of material (Figure 10b), compared to 353 cubic feet for the 2001 flood (Figure 10c), again due to armoring of the fan surface. Once again, much of the eroded material was deposited at the downstream edge of the fan.

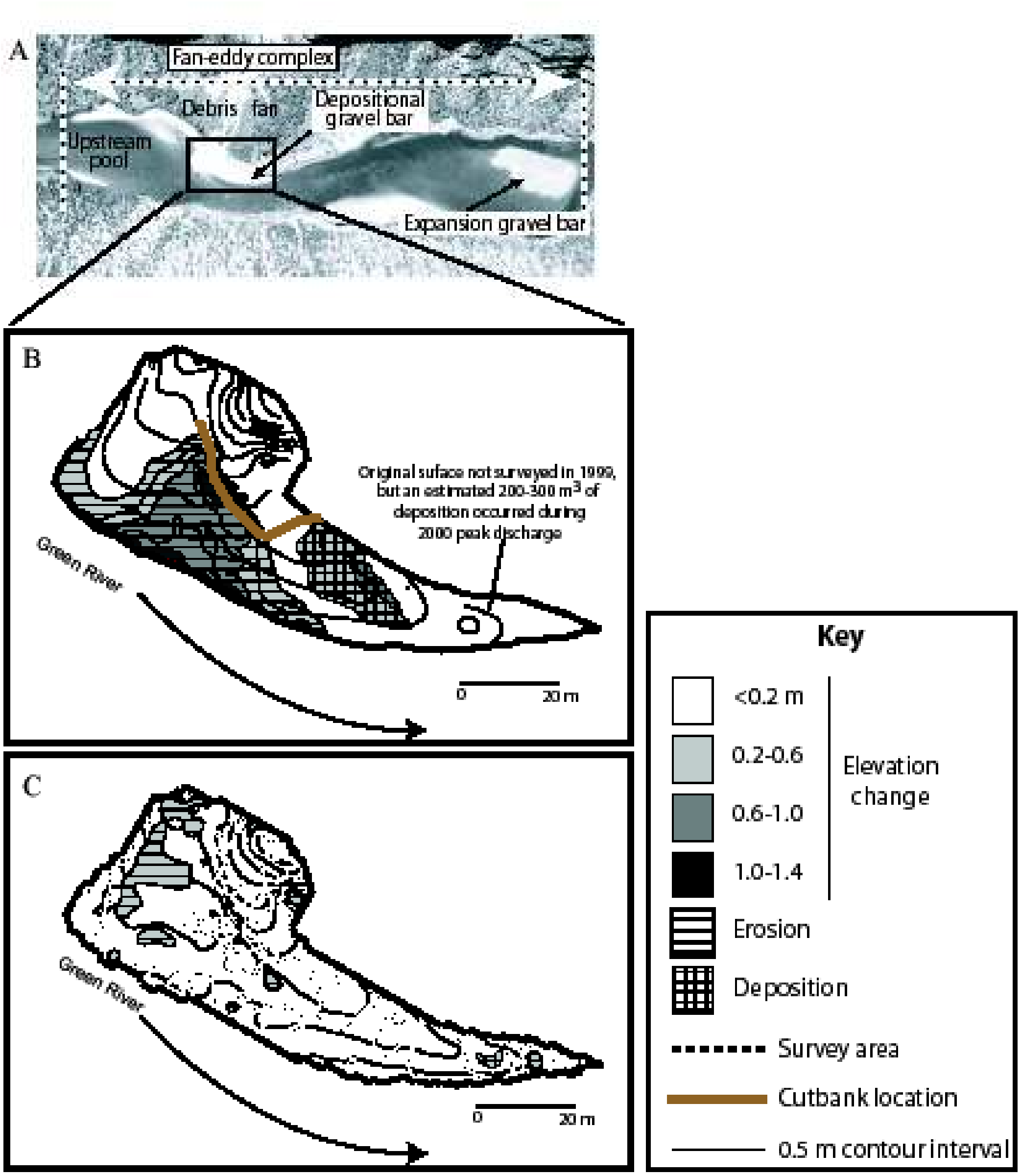

Figure 10. Reworking of Snow Ranch debris fan. A: Aerial photo of fan. B: Significant reworking occured during the Spring 2000 flood. Very little reworking occured during a comparable flood the next year, due to armoring of the fan surface (from Larsen 2003).

This study demonstrates that reworking can occur at flows less than the predam two-year flood, though these floods are rare since they are greater than the powerplant capacity of the dam. Additionally, the reworking that does occur is not as extensive as during predam conditions, as most of the gravel is now being deposited just downstream of the fan, rather than the expansion bar further downstream. Due to armoring, the first major flood that occurs after a new debris fan is created is the most significant, as the magnitude of this flood will determine the amount of reworking that occurs. Obviously the greatest potential for reworking exists downstream of the Yampa when the Flaming Gorge Dam times a maximum release with peak Yampa flows.

Channel Narrowing

Another impact of the Flaming Gorge Dam on debris fans is that of channel narrowing. Channel narrowing has been linked to low flows and the encroachment of non-native vegetation such as tamarisk (Grams and Schmidt 2005). The reduced high flows from Flaming Gorge Dam has reduced stream power, which shows a relationship to increased channel narrowing in debris fan dominated reaches (Figure 12, Grams and Schmidt 2002). In fan-eddy complexes, this channel narrowing occurs largely due to fine grained sediment accumulating on previously active gravel bars, forming postdam floodplains and intermediate bench surfaces (Grams and Schmidt 2005).

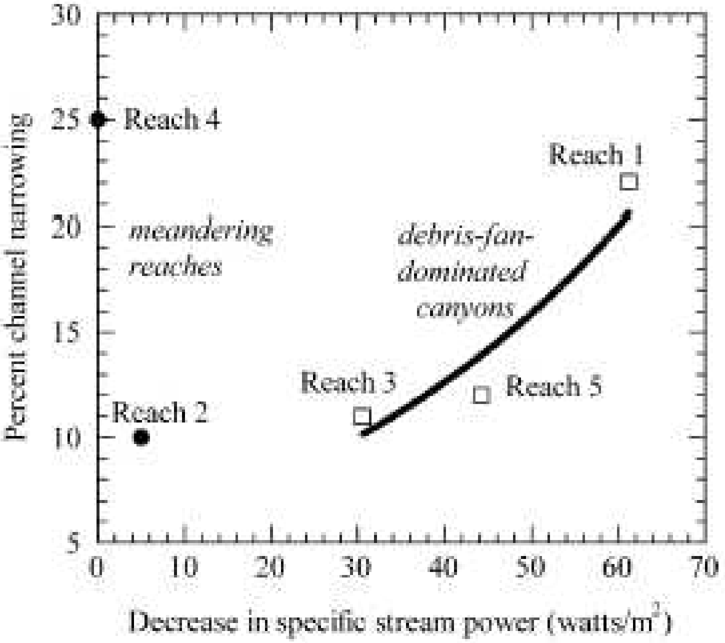

Figure 11. Relationship between reduction in stream power and channel narrowing. In debris fan dominated canyons of Lodore Canyon (Reach 1), Whirlpool Canyon (Reach 3), and Split Mountain Canyon (Reach 5), decreased stream power due to Flaming Gorge Dam has increased channel narrowing (from Grams and Schmidt 2002).

Conclusion

According to the SDC, the impacts of the Flaming Gorge Dam on geomorphic structures such as debris fans should decrease with distance downstream from the Flaming Gorge discontinuity. For the debris fan dominated canyons, this should manifest itself through increased debris fan reworking and decreased channel narrowing as one travels downstream of the dam, as flows and flood magnitudes increase towards their natural levels due to tributary inputs. This observation should hold for the meandering reaches as well, though to a lesser extent since the majority of tributaries are not large enough to expect major geomorphic impacts at the confluences. However, it would be reasonable to expect that the incidence and magnitude of geomorphic effects will decrease downstream, as the flow levels and flood magnitudes increase.

Red Canyon, being directly below the dam, should be the most strongly impacted, and show the most narrowing and least reworking since the flows are controlled entirely by the dam. Through Browns Park, a restricted meander, there should be a greater than normal incidence and magnitude of geomorphically significant effects, due to the reduced flows. Lodore Canyon should be very similar to Red Canyon, but may be in a slightly more natural flow state due to the input of small tributaries such as Red and Vermillion Creek. Echo Park contains the Yampa confluence, which should exhibit limited geomorphic effects due to the constraining geology of the fixed meander, but should also have a much greater impact on the downstream geomorphology due to the input of a very large, unregulated tributary. Thus Island Park, another restricted meander, should have very few, if any, geomorphically significant confluences. Whirlpool Canyon and Split Mountain Canyon, being downstream of the unregulated Yampa, should have the greatest reworking and the least narrowing, and be the closest to the river's natural state of all the debris fan dominated canyons.

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