Debris Flows in the Grand Canyon

By Eric Buer

In March of 1996 when the first major controlled flood was implemented on the Grand Canyon there was a great deal of anticipation as to what the augmented flows would do to the downstream river habitat. The hope was that after years of sediment starvation and routine power generation flows, this event would be a step in the right direction towards restoring the natural processes that once governed the mighty Colorado River to a state of near equilibrium. The river, however, has never been a static system; nowhere is this more apparent than at the junction of the mainstem and its 740 plus tributaries, where steep narrow canyons spill out into the low gradient Colorado River dropping several tons of sediment and large boulders in the channel to form debris fans. This formation of fan-eddy complexes is perhaps the single most influential natural force on the geomorphology of the Colorado River, and produces some of the most important ecologic niches in the canyon. This process is also responsible for the current river profile of the Colorado, which is a series of gentle, deep pools, punctuated by rapid losses of elevation at rapids adjacent to debris fans.

SOURCE MATERIAL AND DEBRIS FLOW INITIATION

The debris fans, responsible for so much white knuckle excitement on the Grand Canyon, result primarily from deposition by debris flows and intermittent stream flow laden with sediment from Colorado River tributaries. Of these two processes, debris flows provide the majority of the sediment supplied, particularly larger sized clasts (Figure 1). These are large, highly viscous flows ranging from 10 to 40 percent water content are capable of carrying boulders up to several meters in diameter (Webb et al. 1988). The high density of the fluid combined with steep gradients of the tributaries allows debris flows to pick up boulders several meters in diameter and carry them towards the mainstem (Figure 1).

Figure 1 – An example of the types of clasts debris flows are capable of moving. Source: Highland et al. 1997.

This body of rock, mud, and water can reach speeds of up to 35 miles per hour and continues to grow in size as it descends towards the mainstem, eroding the walls and tearing out additional material as it races downhill (Webb et al. 1996, Highland et al. 1997). As an example of the raw kinetic energy thes flows exhibit, Webb et al. (1988) found clastic material strewn as high as 100 meters off the tributary bottom in Monument Creek by a flow that deposited 34 metric tons of debris at the tributary mouth.

INITIATION

In the Grand Canyon, there are three principle mechanisms for initiation; bedrock failure, the fire hose effect, and colluvium failure. Direct bedrock failure usually results in the largest debris flows that reach the mainstem. In the upper portions of Arizona temperatures frequently drop in to the freezing range throughout the winter. It is not uncommon for the Grand Canyon to see snow for at least a short portion of the year. Water within fine cracks expands when frozen, -- working with impressive speed for a geologic process -- breaking rocks apart, and driving open pre-existing joints. With many tributaries forming preferentially along faults (Dolan and Howard, 1978) the percentage of fractured and broken rock from tectonic activity that is accessible to frost wedging at any one time is fairly large. Rainfall percolates though these joints and into cliff forming rocks, simultaneously reducing cohesion between grains (a byproduct of the incompressibility of water) while increasing the load on basal strata. After sufficient saturation, the slope or cliff gives way (Figure 2). Intense rainfall following long periods of more gentle precipitation are particularly effective at pushing saturation to the final levels necessary for failure and often generate the largest of bedrock failures (Griffiths et al., 2004). Only a small percentage of the total number of debris flows that reach the mainstem are attributed to bedrock failure. Many simply contribute to growing piles of colluvium at the base of cliffs if failure occurs when there is insufficient water to generate a debris flow. Accumulating colluvium is not at rest though, rather, it provides source material for future flows which may be initiated through other mechanisms such as the much more effective fire hose effect and colluvium failure.

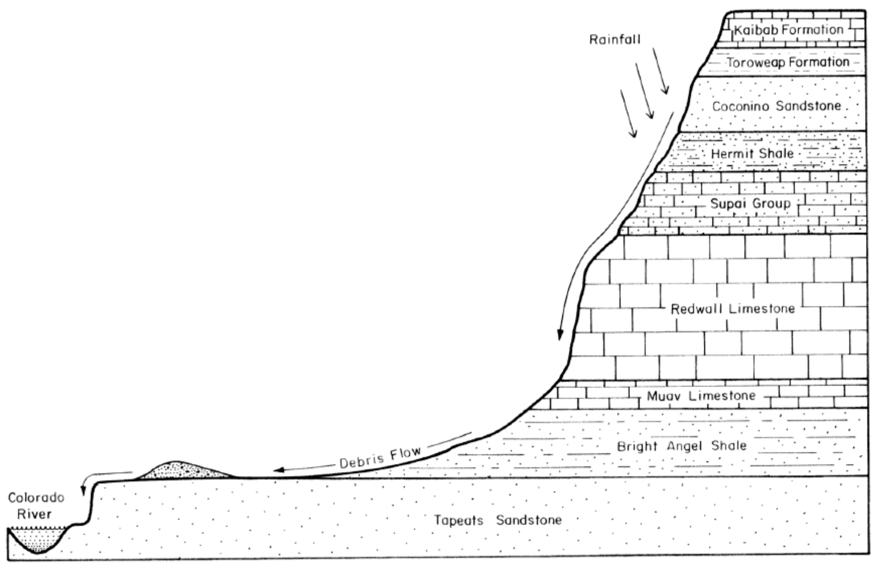


Figure 2 – Bedrock failure producing a debris flow. Alternatively, if insufficient water was available, or the failure is small, the loosed bedrock adds to the colluvium at the base of the cliff. Source: Griffiths et al. 2004.

The fire hose effect is responsible for 62% of all flows that reach the canyon (Griffiths et al. 2004. Hard rain from convective summer thunderstorms in the summer, or as part of larger winter systems often provide more precipitation than the landscape can absorb, leading to massive and sudden runoff events. Those streams which pour over cliffs and onto colluvial wedges provide the kind of torrential water supply needed to initiate rapid failure within the wedge (Figure 3). Storms with normal precipitation capped by downpours are particularly effective (Webb et al., 1996), but sustained light rainfall may also ultimately prove sufficient in watersheds with sufficient catchments. Unlike most of the bedrock failures the fire hose effect enjoys an ample supply of water to mix with in the first few seconds of its descent and frequently forms debris flows with enough momentum to reach the Colorado.

Figure 3 – The fire hose effect in action, Prospect Canyon 1995. Source Webb et

Colluvium failure is similar to the fire hose effect, but rather than pouring directly onto the colluvial wedge, flows may saturate or undercut the deposit until failure occurs. This mechanism is far less effective than the fire hose effect, but still more frequent than bedrock failure, bringing down roughly 18% of all debris flows to reach the mainstem (Griffiths et al., 2004).

SOURCE MATERIAL

Griffiths et al. (1996, 2004) documented the particular importance of shale in initiation of flows. Shale is a common sedimentary rock, and is composed of fine clays and mud particulates. In the Grand Canyon, it makes up a number of stratigraphic units, most notably the Hermit and Bright Angel shales, both of which appear repeatedly in debris fans. These shale layers are poorly indurated, and easier to erode than some of the much more resistant sandstone units with which both share contacts. Clays are often highly absorbtive of water and typically have low yield stresses. Such poor structural integrity further promotes failure when well indurated sandstones support large overburden on top of shale layers, exerting sizable normal forces. Failure in a shale layer leads to collapse of overburden as well. As Figure 4 notes below, a failure in the Bright Angel shale could easily produce large volumes of material for colluvium if no water were present or bedrock debris flows during a rainstorm.

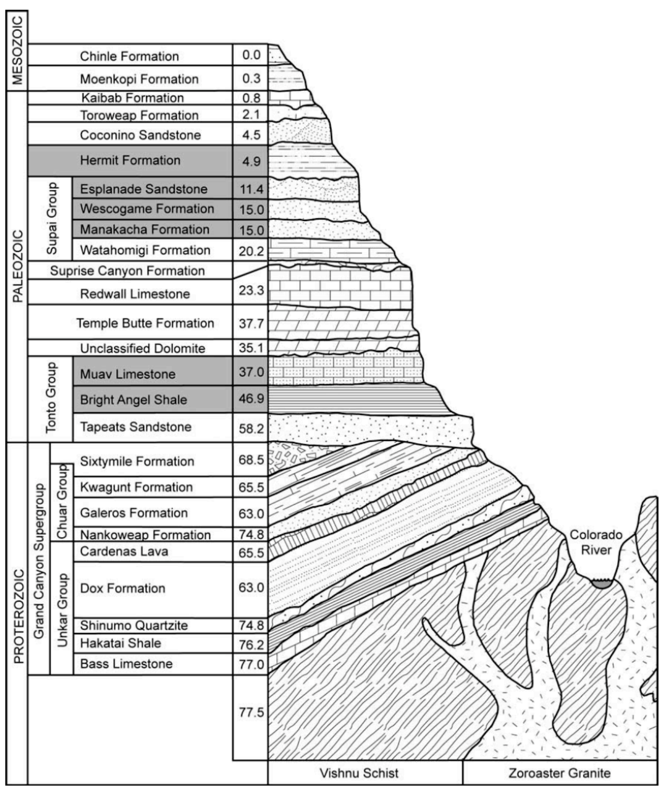


Figure 4 – A stratigraphic column of the Grand Canyon. Common failure strata are highlighted. Source: Griffiths et al. 2004.

Clay content is a key factor in producing debris flows since it is easily suspended in water and the resulting fluid is dense enough to be capable of carrying anything from small gravel to large boulders. The Hermit Shale is both younger and higher than the Bright Angel, and so may at times be to high cause debris flows in smaller tributaries, particularly in lower reaches of the river. Other important units include the Esplanade Sandstone and Muav Limestone, both of which share contacts with shale layers as well. Finally, at Prospect canyon, the Vishnu Schist (a type of medium grade metamorphic rock which begins as shale) has been a particularly important source of failure for flows that reach the Colorado (Webb et al. 1996).

FORMATION OF FAN EDDY COMPLEXES

Debris flows which reach the river are greeted with a sudden opening of the tributary walls out into the main channel. The immediate effect of this change in surroundings is a reduction of speed as the flow spreads out -- much like river water pouring through a broken levee – and deposition of entrained sediments. Very large flows may have enough material to form substantial fans in a single event, perhaps even damming the river temporarily (Kieffer, 1985, Webb et al. 1996). Smaller events may form channels in existing debris. Repeated flows within entrenched channels like that pictured in Figure 5 build up the channel bed and smooth its profile.

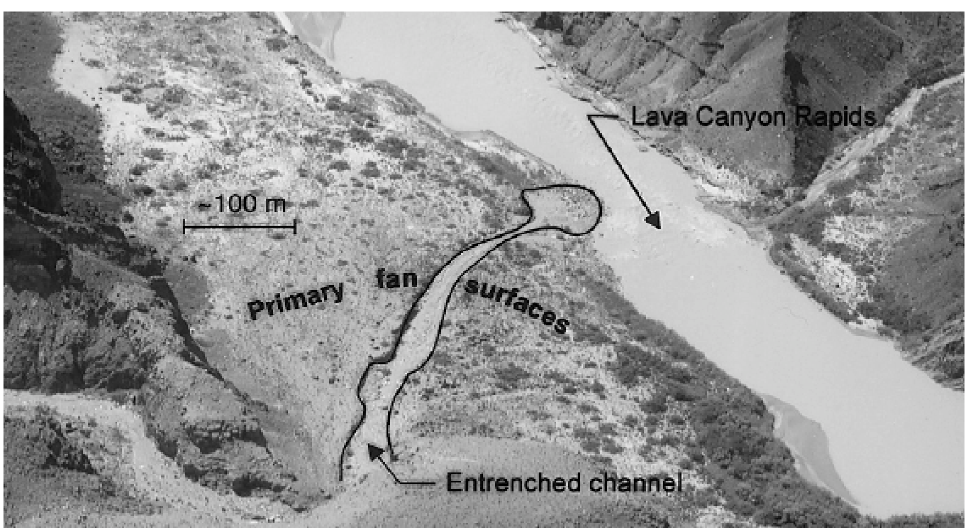
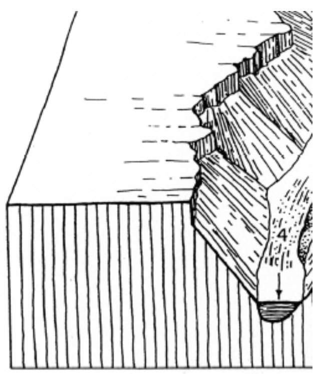


Figure 5 – An example of an entrenched channel within a debris fan. Source Hereford et al. 1998.

Ev

entually the adjacent surfaces to the channel are substantially steeper than the channel itself and flows move to one of these surfaces -- a process know as avulsion – forming a new channel. Over time channels sweep back and forth across the debris fan building it up. More substantial flows may suddenly decelerate when exiting the tributary canyon, forming a plug which can also force the active entrenched channel to shift. Large boulders may be suspended within very large flows, but most subsequent flows deposit them in the river channel where potential energy is at a minimum. The change in flow velocity leads to the formation of eddies both above and below the constriction and deep pools at the base of the rapid, where excess stream power proves very effective at eroding the river bottom. Further downstream as the river begins to rework the sediment load a secondary rapid forms where entrainment values drop enough at higher flows to build up a secondary debris bar and small secondary rapid (Figure 6).



The fan-eddy complex (Figure 7) is one of the most dynamic geomorphic features on the Colorado River, and balance is constantly swinging from debris flow dominated to river dominated.

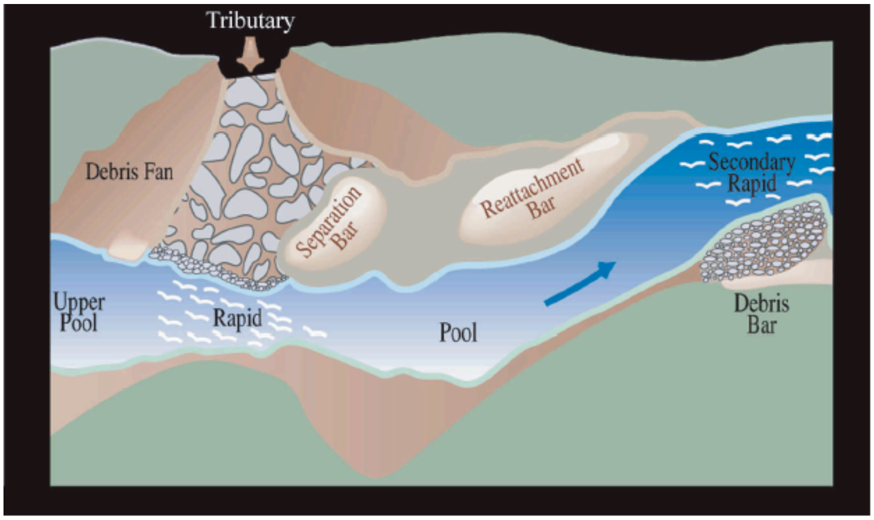


Figure 7 – A fan-eddy complex in map view. Source: Webb and Griffiths 2001.

These complexes serve as important sources of habitat for native fish such as the Humpback Chub (Webb and Griffiths 2001, Buss 2005, Campos 2005, this volume) and backwater embayments of the banks which are rich in spawning habitat and protected waters where juveniles have an opportunity to mature. The are 161 rated rapids that have formed at debris fans on the Colorado, and combined they make up for half of the vertical drop in the 450 km run of the canyon (Dolan and Howard, 1978). In between fan-eddy complexes, deep, slow pools dominate the river, trapping finer sediments along the bed and providing sightseeing opportunities.

REWORKING THE FAN-EDDY COMPLEX

Reworking is a complicated process in which fresh fan deposits are subjected to the erosive regime of the river at a variety of discharges. The degree to which the fan is reworked is closely correlated with river discharge. The faster water moves, the greater its competence (the ability of the river to carry sediment). With increased competence comes an increased entrainment values (the river’s ability to pull sediment off the bed of the river) (Mount 1995). So, not surprisingly, rising water levels are able to move larger and larger sediment clasts by either pulling them into the water column, or dragging them along the river bed using the shear force of passing water. Immediately following a debris flow, the constricted river experiences an increase in velocity adjacent to the fan, which begins the process of winnowing away fines while leaving cobbles and boulders. In these first stages of reworking, water very often times moves fast enough that cobbles may be entrained and then dropped downstream where the river widens forming a secondary rapid or debris bar (Howard and Dolan 1981, Webb et al. 1988, Webb and Griffiths 2001).

Unlike the debris fan, these secondary debris bars are usually exclusively supported by large clasts rather than fine matrix material. Cobbles may not reach the secondary bar during a single reworking event. They often become stranded in the deep pools below each rapid where water slows during modest flows. In the largest of spring and summer events, these pools were traditionally cleared of stranded cobbles, which were then emplaced on the secondary bar as the river lost competence further downstream. Large boulders are much to massive for the relatively flat Colorado River to move, even during the largest discharge events since they require entrainment values that could only be found in fast moving mountain rivers with high gradients. Boulders may be shifted thanks to erosion of underlying sediments and supporting material, but for the most part remain in place until they are broken, dissolved or eroded down to sizes which more modest flows can entrain and push downstream (Howard and Dolan, 1981).

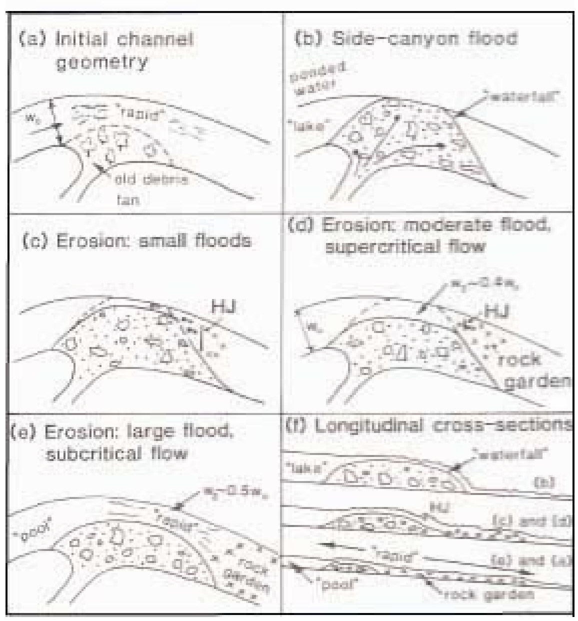


Figure 8 – Stages of reworking a debris fan. Not all fans experience all of these steps. Source Keiffer 1985

During the reworking process (Figure 8), banks are scoured by high flows and new backwater habitats are created that become exposed as the waters recede. Riparian vegetation adjacent to the water is scoured away clearing the banks and creating identifiable high water marks above which long lived mesquites and other canyon phreatophytes become established (King 2005, this volume). Perhaps most visibly, the constriction of the river is reduced to a stable configuration (Kieffer 1985, Howard and Dolan 1981, Larsen et al. 2004, Webb et al. 1984, 1999a, 1999b).

The final stable configuration of debris fans has important implications for Colorado River management since tributaries to the river remain unregulated, and continue to unleash debris flows of every size, many of which reach the mainstem. With Glen Canyon Dam in place, the debris fans have been given a strong advantage in the swinging balance that exists with the mainstem. This implies that without a better understanding of how to reach stable configurations the Colorado River may undergo a dramatic change in morphology over the next century.

Kieffer (1985) saw reworking of debris fans in terms of the stability of the rapid adjacent to the fan, which was a reflection of mainstem constriction. The rationale was that fans which had not been recently aggraded but were relatively old all seemed to approach a constriction of about one half that of the main channel. In fact, most of the fans on the Grand Canyon seemed to hover around this value. Kieffer proposed that reworking was a product of supercritical flow (flow which is dominated by inertial forces rather than gravitational forces) at the fan-eddy complex, and so these fans must have experienced flows so large that enough material was eroded away to leave only some of the largest boulders and a channel wide enough to prevent supercritical flow from occurring again. Naturally subsequent lower flows would be unable to reach supercritical velocities, leaving the rapid, and the fan, in stable state. The magnitude of these flows this model required were substantial, estimated at 15000 cubic meters per second to bring currently unbalanced complexes into equilibrium, and prevent further reworking at lower flows. This type of event would have been exceedingly rare on the Grand Canyon, and with the numerous dams now in place, such flows would pose a number of logistical problems in addition to the lost water storage.

The high discharges that were deemed necessary by Kieffer were rare events for the Colorado River even before the first dams were constructed. Furthermore, there were numerous other rivers in the west with similar morphology which seemed able to achieve equilibrium over relatively short periods of time and with much more modest flows. Hammack and Wohl (1996) proposed a different route to equilibrium measuring rapid stability as a ratio of the flow force versus the resistance of large boulders on the Yampa River, Colorado. Stable rapids still maintained subcritical flow during high discharge events, but this could be obtained through moderate flows given enough time to rework the deposits. Initially after a debris flow, the river again begins headward erosion and a widening of the constriction, but unlike in previous studies, Hammack and Wohl (1996) concluded large boulders and medium cobbles could reach stable configurations through these moderate discharges as the sediment surrounding larger clasts was removed.

Hammack and Wohl held out that higher flows may entrain some cobbles, but argued extremely large floods were not mandatory for the river to reach an acceptable configuration. This was an important discovery for management of the Colorado, since it implied that with modification, current releases may be effective at maintaining some of the historic balance that once existed. This was later affirmed by Larsen et al. (2004) through a study in the Uinta Mountains which demonstrated significant reworking of debris fans could take place with flows as small as 75% of the 2 year flood. The key to using moderate flows as effective reworking tools lay in the timing of the release. Larsen et al. found that if moderate floods occurred soon after a debris flow, and without several antecedent small flows to armor the deposit, moderate flows were quite effective at reworking debris fans. The importance of proximity for moderate flows to the time of aggradation cannot be overstated for effective reworking of debris deposits. The practice of repetitive, stable flows released singularly for power generation armors the upstream face of fans and increases their resistance to reworking by higher flows (Webb et al. 1999b).

Glen Canyon Dam

Since its closure in 1963, Glen Canyon Dam has superseded debris flows as the largest geomorphic influence on the Grand Canyon portion of the Colorado River. The long, deep reservoir which has formed behind the dam captures virtually all but the finest sediment supplied by the upper Colorado River. Today, less than one percent of the sediment which enters the Grand Canyon is coarser than one half of one millimeter (Webb et al. 1999a). Clear aquamarine water now exits Glen Canyon Dam, a drastic change from the days when the Colorado carried a muddy slurry for significant portions of the year. The once highly variable seasonal flows have been replaced with highly predictable and regular daily power releases that rarely exceed the maximum capacity for power generation of 940 cubic meters per second. This new human dictated flow regime lacks the power of unregulated spring snowmelt, and is unable to even move cobble sized debris under normal flow circumstances. Howard and Dolan noted this in 1981, and commented that while historically these cobbles were rapidly broken into smaller particles during the transport process that made up part of the canyon's through-flow sediment load, today they lie immobile on the river bed below a thick layer of sand supplied by the Colorado's tributaries.

While those debris fans that had reached stable configurations before the construction of Glen Canyon Dam, and have not been significantly aggraded since that time have remained stable, it is only a question of time for each before the next large debris flow brings new material into the mainstem. Roughly five events reach the canyon every year (Griffiths and Webb, 2004) and 25 percent of existing fans have already experienced some level of aggradation since Glen Canyon Dam was closed (Webb et al. 1999a). The river has is now unable to respond to these changes and the subsequent increase in constriction and gradient it is experiencing at fan-eddy complexes. This is a trend that spells trouble for native species seeking out backwater habitat, as well as tourists interested in experiencing the canyon as rapids change from exciting rides to dangerous, steep, boulder sieves which are proceeded by lengthy statements of indemnity against litigation by commercial outfits. Howard and Dolan (1981) predicted an increase of up to 1.8 times the present gradient for every fourfold reduction in flows, a substantial increase when riding in a large touring raft. In recognition of this, along with shrinking sandbars and declining habitat quality throughout the Grand Canyon reach, in 1996 an artificial flood was released with the intention of restoring some of the natural balance that once existed.

The 1996 Controlled Flood Experiment

Most debris fans lost area in the 1996 flood and many experienced the first reworking in many years on their upstream faces that left coarse deposits where there were previously generous quantities of sand present. After several years of regular high and low flows each day, the width of the reworked zone doubled in many places as water rose above the established high water marks (Webb et al. 1999b). A study by Pizzuto et al. (1999) tracked the boulder movement at Prospect Canyon, adjacent to Lava Falls Rapid, during the course of the flood and returned some encouraging new findings about debris management. Most boulders began to experience entrainment much earlier than anticipated. Medium sized boulders (<.5 m diameter) were entrained off the edge of the debris fan by flows as low as 1270 cubic meters per second. Conventional wisdom, such as that provided by Kieffer (1985), held that these clasts would remain in place until flows had risen substantially higher. Unconsolidated debris was reworked through lateral erosion – something Hammack and Wohl (1996) supported – in deposits that had experienced flows of no more than 670 cubic meters per second. Pizzuto's study also found that for several of the same large cobbles that were selected for tracking, flows were insufficient to push them through the deep scour pool below Lava Falls. The placement of more large cobbles and boulder fragments in this region could lead to lengthening of the rapid over time unless flows substantial enough to push these clasts downstream are released.

Lava Falls rapid became a more dangerous run thanks to the 1996 flood (Figure 9). The debris fan was a textbook perfect example of reworking by higher flows, which removed some 5700 cubic meters of sediment and coarse debris from the upstream face of the fan, and altered boulder configurations as well as the mainstem constriction to a state that resembled Lava Falls before it's 1995 aggradation (Figure 9) (Pizzuto 1999, Webb et al. 1999b, Schmidt et al. 2001).

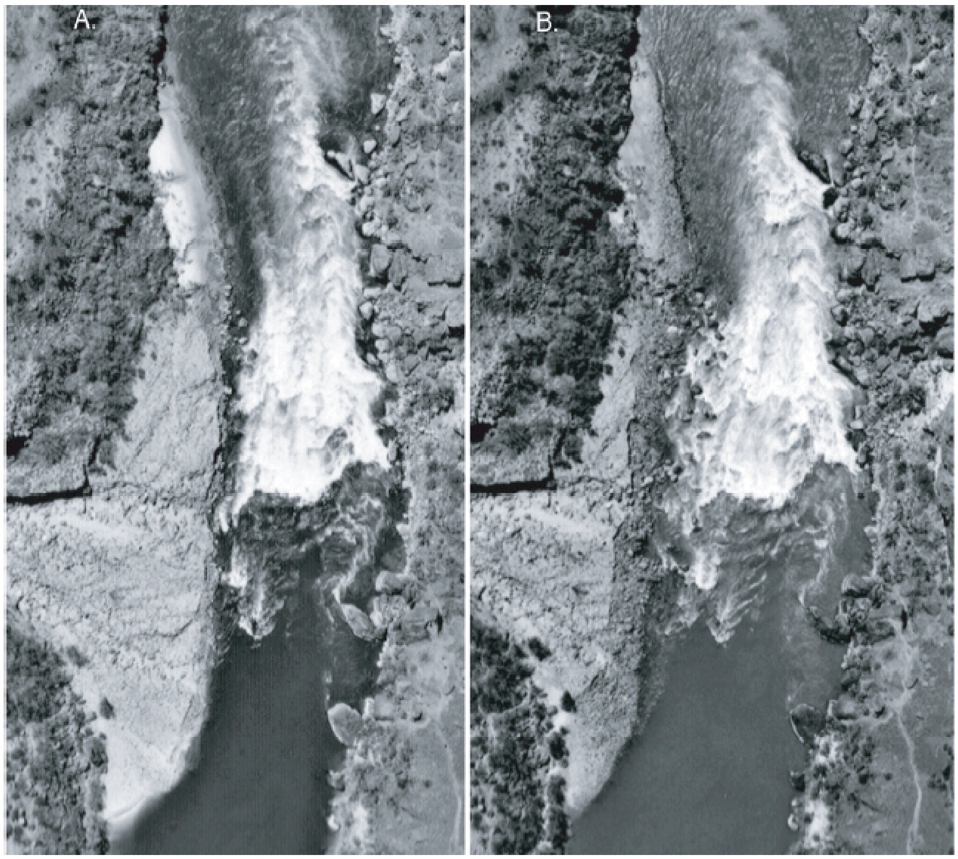


Figure 9 – Lava Falls rapid before (A) and after (B) the controlled flood of 1996. Note the volume of sediment lost from the upstream side of the fan in the image on the left. Source Webb and Griffiths 2001

Crystal Rapid on the other hand, defied expectations and responded to the 1996 flood by becoming a more stable and safe rapid, supporting Hammack and Wohl (1996) as well as Larsen et al.'s (2004) later studies (Webb et al. 1999a, 1999b) that moderate flows can be effective reworking tools. This poses a problem in understanding the reworking process, since the debris flow which made Crystal Rapid significantly more dangerous occurred in 1966. In the 30 years that passed since this aggradation, there have been enough impressive flood events, such as that in 1983, that Crystal Rapid should have experienced little or no reworking during the more modest 1996 event. Conversely, Lava Falls was aggraded less than two years before the controlled flood, and appropriately showed significant reworking effects. The reworking at Crystal Rapid provides new encouragement that modest discharges can be effective tools for managing debris fans over the short term, but should not generate overly optimistic predictions. The reworking of the Crystal Creek debris fan was modest, and moved large clasts relatively little.

Both Webb et al. (1999b) and Pizzuto (1999) noted that the most effective period of reworking occurred while the flows within the river were changing, and that perhaps the seven day duration of the experiment was excessive for controlling the aggradation and reworking of debris fans. This sentiment was echoed Hammack and Wohl (1996), and was reiterated later by Larsen et al. (2004).

Recommendations for Future Management

Fan-eddy complexes remain one of the most important natural influences on the geomorphology of the Grand Canyon. They provide habitat for native species and are responsible for the present pool and drop profile of the Colorado River. However they have always been balanced by a powerful mainstem with a highly variable seasonal flow regime. In contrast to this, the current flow regime has proven to be ineffective for managing the coarse sediment and boulder load which is delivered to the canyon on an annual basis. The continued practice of releasing water on demand for power generation, and holding back larger flows, has for all practical purposes completely halted the mainstem from reworking debris fans in the Grand Canyon. This leaves debris flows with increased geomorphic influence, causing substantial increases in rapid gradients, accumulation of coarse debris both at complexes, and eventually downstream, and a reduction in native species habitat throughout the Grand Canyon. Furthermore, as these debris fan deposits remain submerged below the regular flows from Glen Canyon Dam, present fan-eddy complexes will become increasingly immune to artificial reworking through sporadic increases in flow (Webb et al. 1999b).

To best combat these trends some attempt must be made to restore the dynamic equilibrium which once existed between the river and its tributaries. This would ideally come in the form of a more natural flow regime which made use of shorter duration high magnitude controlled floods (Webb et al. 1999b). Timing of releases should respect the period when debris flows are most susceptible to reworking, releasing often and soon after major debris flows or inflow events. The variation in flows should increase, including some which make use of the spillways at Glen Canyon Dam in order to scour higher sections of the debris flow and push eddies on both sides up the banks promoting backwater creation. There is now evidence to show that moderate flows can be effective tools for reworking most debris fans, but this emerging trend points to later problems as boulders and coarse debris are deposited immediately downstream of rapids in scour pools. Rare but prolonged, large magnitude flows may help to continue to push these clasts downstream to secondary debris bars rather than extending present rapids, increasing the risks of navigation.

Finally, the importance of low magnitude flows needs to be considered. Historically the Colorado surged in June and dwindled during the winter months, allowing the bases of many debris fans out of the water. This may have helped to prevent some of the imbrication and packing idenitifed by Webb et al. (1999a) by allowing water to drain from the complex and exposing the lower levels of the fan to reworking as water rose after prolonged periods of exposure. As the Colorado River flows dwindled in the late summer, convective thunderstorms would have provided conditions appropriate for generating debris flows, and fresh aggradation to fans. As waters rose with mid-winter storms, and again in the spring, fans would be subjected to a wide variety of rising and falling waters that reworked all elevations of the debris fan. This would take advantage of the lateral erosion noted by Hammack and Wohl (1996), reworking the lowest parts of the fan first, and allowing matrix supported boulders to shift and tumble to more stable configurations as fine and mediums sized sediment is removed. Pizzuto et al. (1999) also observed this type of stabilization at Lava Falls in 1996 as cutting banks collapsed and larger boulders were dropped into the mainstem. This approach to reworking from the base up would make the most of a limited water supply and prevent future resistance to reworking.

The management of the Colorado River is a complex issue, the scope of which extends far beyond the narrow focus of this paper. However the biologic processes and endemic species which make such effective head lines have evolved within the confines of a physical system which has since been pushed far from its original state of equilibrium. The receding sandbars and encroaching riparian vegetation within the canyon provided the catalyst for new management and the first controlled flood, but the de-facto control on river morphology continues to reside with tributary debris flows and the subsequent formation of fan-eddy complexes. The current imbalance between the mainstem and its tributaries percolates into every other management issue from fisheries in need of backwater habitat to recreational interests throughout the canyon. It is sensible therefore that the importance of these physical processes be given proper consideration in any future management plan.

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