Geologic Controls on the Evolution of Rapids in the Grand Canyon

George Snyder, UC Davis Department of Earth and Planetary Sciences, March 7, 2018.

The rapids of the Grand Canyon are one of the canyon's most iconic features. They were a source of fear among early explorers, but today are the primary attraction for thousands of river runners every year. Many people view the rapids as a static part of the river, but, in fact, they are dynamic geomorphic features that have evolved over thousands of years, including significant alteration from human interference on the river over the last century.

Cenozoic History:

Understanding the geologic controls on the evolution of rapids in the Grand Canyon begins with understanding the formation of the canyon itself. Thousands of feet of bedrock were incised by the Colorado River to create the canyon we see today. However, the timing of canyon incision is contentious. Low-temperature thermochronometer studies support two competing models operating under vastly different timescales. Flowers and Farley (2012) argue for an ancient canyon, with the timing of maximum incision ~ 70 Ma; Karlstrom et al. (2008) propose a much more recent incision time of ~5 Ma. This younger Miocene-Pliocene incision of the canyon is supported by other geologic evidence such as basin deposits and fluvial geomorphology.

Regardless of its timing, the magnitude of incision has important implications for the shifting nature of sedimentation in the canyon. Sklar and Deitrich (2004) show that bedload of a river can effectively armor the channel bottom, thus inhibiting erosion. In addition, boulders can hamper channel erosion for decades or even millennia (Seidl et al., 1994). Therefore, the Colorado River must have been flowing through a mostly bedrock channel during periods of peak incision. With this in mind, the current state of the Colorado river—with large amounts of alluvium, boulder filled rapids clogging the main stem, and abundant bars and beaches—is a transient state when incision has temporarily ceased.

The most recent period of incision was in the late Pleistocene (Anders et al., 2005) when the climate was wetter and cooler overall. The milder temperatures of this period likely allowed for more widespread vegetation on hillslopes in the Grand Canyon. The increase in vegetation would have promoted greater infiltration of rainwater, disaggregation of bedrock, and the production of thicker layers of regolith. The wetter climate of the region also supported greater discharges on the main stem, where, beginning around 60 Ka, the Colorado River was incising bedrock (Anders et al., 2005). Strangely, the main stem and tributaries of the Colorado river aggrade and incise at alternating times, such that when the main stem incises, tributaries aggrade, and vice versa. When the climate warmed at the Pleistocene-Holocene transition, vegetation was reduced and regolith that had been accumulating was now free to be mobilized by the increasing intensities of southwestern monsoons. This is thought to have loaded the main stem with sediments and uncovered the tributaries for further erosion (Anders et al., 2005). Hence, the alluviated character of the river we see today has likely existed since the beginning of the Holocene.

Lithologic Controls on Rapid Formation:

The rapids of the Grand Canyon—with the exception of Bedrock Rapid—are all the eroded remnants of debris fans at the mouths of tributaries (Webb, 1996). These debris fans form when debris flows move downstream until they are deposited in the Colorado River.

Debris flows are fluidized mixtures of clays, water (10-40% by volume), and other clastic materials including large boulders (fig. 1). Debris flows are particularly effective at moving large particles for several reasons: (1) their rich clay content gives them high cohesive strength; (2) their high density creates greater buoyancy forces on entrained boulders; and (3) these characteristics combine to create very high shear forces on the boundaries of the flow that can overcome the inertia of large boulders (Webb et al., 1988).

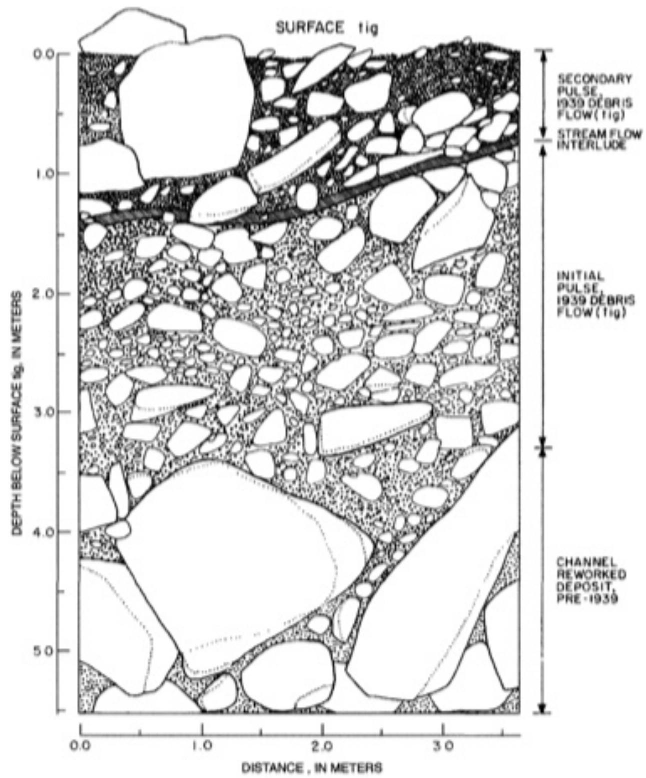

Figure 1: Stratigraphy of a typical debris flow deposit (from Webb, 1999).

Debris flows in the Grand Canyon are usually triggered during the summer monsoon season by large afternoon thunderstorms. Analysis of repeat aerial photography for 160+ debris fans from 1890 – 2003 shows that the Grand Canyon experiences an average of 5 debris flows per year (Griffiths and Webb, 2004). Some debris flows are initiated by hillslope failures triggered by increased pore pressure in sediment when storms saturate fine colluvium. The majority of failures, however, are triggered in tributary channels where surface runoff cascades directly into fine colluvium. This process is known as the "firehose-effect" (Griffiths and Webb, 2004). Debris flows can rapidly move large volumes of material downstream. The Monument Creek debris flow in 1984, for instance, traveled 4.5 km at 4 m/s, with discharge estimated to be ~ 120 m^3/s. The flow created a 7 m high dam at the river and transported boulders as large as 2.7 m in diameter (Webb et al., 1988).

Four units are responsible for 85% of the slope failures that lead to debris flows: Bright Angel Shale, Muav Limestone, Supai Group, and the Hermit Formation (Griffiths and Webb, 2004). This is largely because each of these units contain clay rich interbeds that provide a fluid medium when mobilized. Also, certain clay minerals in these units expand when saturated (e.g. montmorillonite) and mechanically disaggregate the rocks, such that these units tend to form ledges. Large boulders falling from the cliff forming units above collect on these ledges and eventually become the largest particles to be moved in a debris flow (Griffiths and Webb, 2004).

These same lithologies also influence the rapids on certain stretches of the river (Howard and Dolan, 1981). In places where these units crop out at river level, the channel walls are more easily eroded and the base of the canyon widens. Wider valleys create more space for debris flows to disperse once they enter the canyon, and the river has more leeway to route around debris fans. In contrast, where strong formations crop out at river level, such as the Zoroaster Granite, the river tends to be entrenched in a steep, narrow, channel. When debris flows enter sections like this, all the debris is deposited directly into the channel. The river has less space to adjust to the constriction and must flow directly through the steep gradient imposed by the debris fan (Howard and Dolan, 1981).

Structural features also play an indirect roll on rapid formation. Several major tributaries follow the strike of normal faults in the river. Aside from influencing the orientation of the tributary, faulting may contribute to small increases of relief at river level, and the Grand Canyon as a whole (Webb, 1999).

The Evolution of a Rapid:

The evolution of a rapid begins with the deposition of a debris flow into the main channel of the river (fig. 2). The main stem becomes dammed, causing water to pool behind the blockage until it rises and overtops the debris fan. By locally increasing the relief of the river profile and forcing water through a narrow channel, flow velocities in excess of 7.5 m/s can be generated (Kieffer, 1987). As the river continues to erode the deposit, the channel constriction widens and flow velocities through the rapid decline. Repeated flooding on the Colorado river progressively erodes the debris fan, widening the constriction further. The extent of the debris fan at any given time reflects the magnitude of the most recent flooding event (Kieffer, 1987).

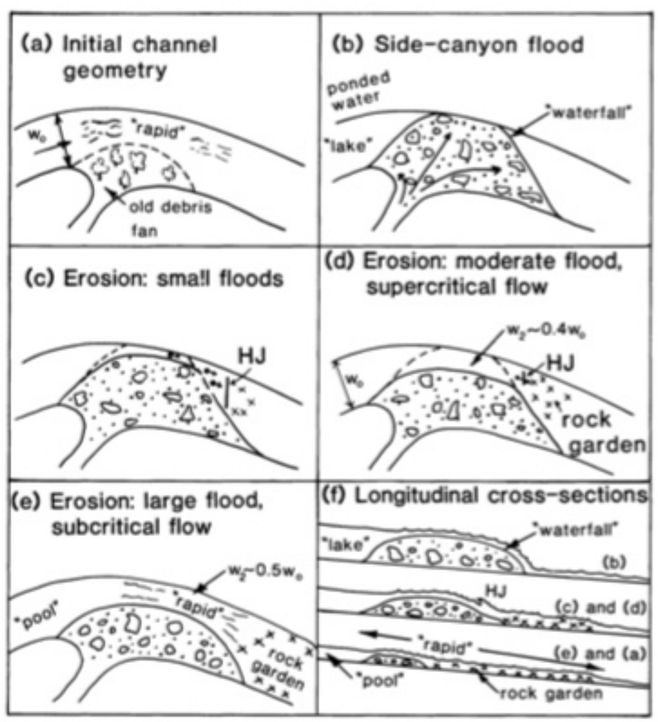

Figure 2: The evolution of a rapid following the emplacement of a debris fan (from Kieffer, 1985).

The largest boulders deposited by debris flows, however, can be ~3 m in diameter, and even the largest floods on the Colorado River cannot move them. These rocks form the "core" of rapids, dictating the pattern of large standing waves and flow paths (Kieffer, 1985). Dissolution of minerals and abrasion by suspended particles over centuries or millennia are the only way that these rocks are removed (Whipple et al., 2000).

Aggradation of Rapids in the Grand Canyon:

Given enough time, a river will erode irregularities in its longitudinal profile and adjust the gradient of its channel to a smooth “graded” profile. But, owing to debris fan deposition, the Colorado river displays a stepped longitudinal profile of “rapids and pools” (fig. 3). Maintaining these irregularities requires that debris fan activity remains active to counter river incision (Hanks and Webb, 2006).

The rapids themselves represent small-amplitude deviations in the longitudinal profile of the Colorado River—no more than ~5 m high, and a kilometer long. Larger amplitude and wavelength convexities also occur along the Colorado River’s profile. Hanks and Webb (2006) studied these convexities and found that they tend to be centered around areas with the highest degrees of debris flow activity. These areas contribute largest amount of sediments into the river, which locally increases the river profile convexity. Over time, these sediments redistribute and accumulate over a larger swath of the river.

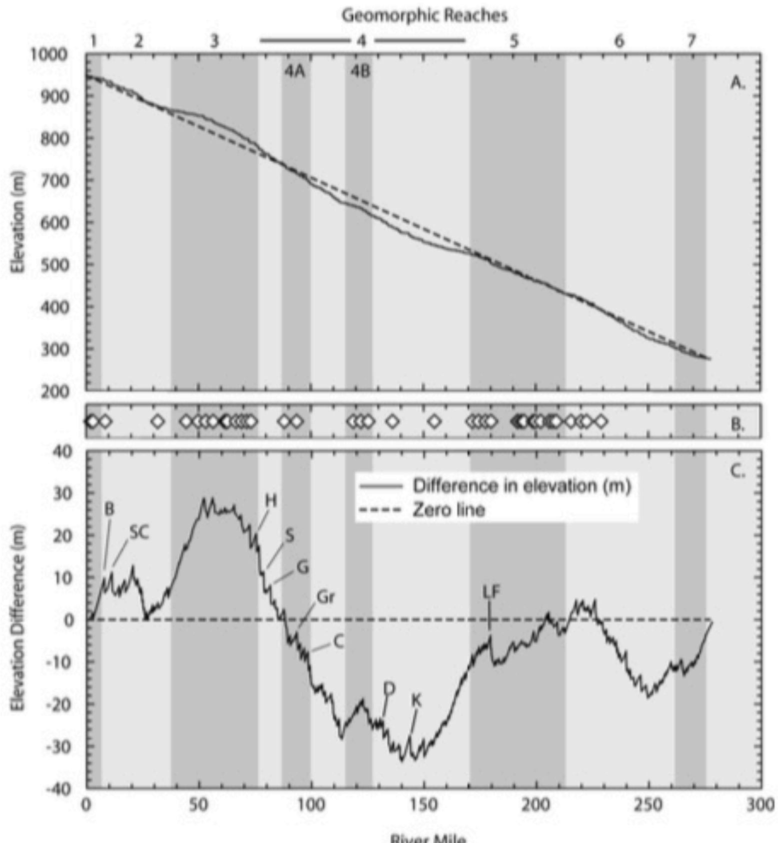

Figure 3: (A) Longitudinal profile of the Colorado River in the Grand Canyon (thick line) shown with the average gradient of 0.0015 (dashed line). (B) Locations of alluvial islands in the Grand Canyon. (C) Differences between the average and measured profiles, and the locations of major rapids. Note the small gradient spikes associated with rapids superimposed on the large convexities caused by thick alluvium in areas of more frequent debris flows (from Hanks and Webb, 2006).

Despite early claims that the rapids were mostly unchanging in the modern flow regime (Graf, 1979), net aggradation of the rapids over the last century has been observed. Magirl et al. (2005) compared water surface heights and rapid morphologies from a stadia rod survey conducted by the USGS in 1923 to a LiDAR survey of the canyon in 2000 (fig. 4). Average aggradation across the 80 rapids surveyed was +0.26 m, indicating a mean aggradation rate of 3 cm/decade. Additionally, the rapid-and-pool character of the river had intensified. In 1923, 50% of the river drop occurred over the 9% of the river comprised of rapids. In 2000, 66% of river drop occurred over the same distance.

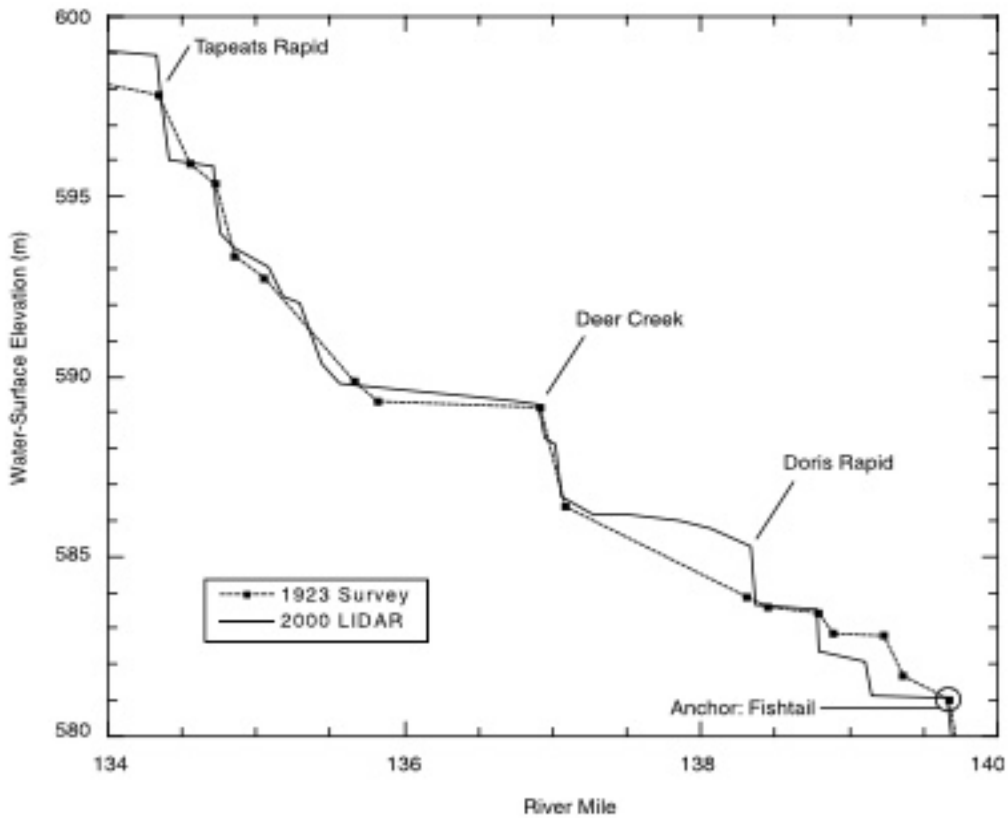

Figure 4: Longitudinal profile of a section of the Colorado River comparing the 1923 USGS survey and the 2000 LiDAR survey. Note the aggradation at Tapeats Rapid and the creation of Doris Rapid (from Magirl et al., 2005).

Not every rapid grew over this time interval. Several rapids were degraded, and others were entirely removed. Doris rapid, which was recorded in explorer Robert Stanton's diary in 1880 as being 2.4 – 3 m tall, was a minor riffle in 1923 but had risen to 1.6 m in 2000. Magirl et al. (2005) conclude that this rapid had been removed between Stanton's expedition and the USGS survey by a flood of ~ 4,800 m^3/s in 1921.

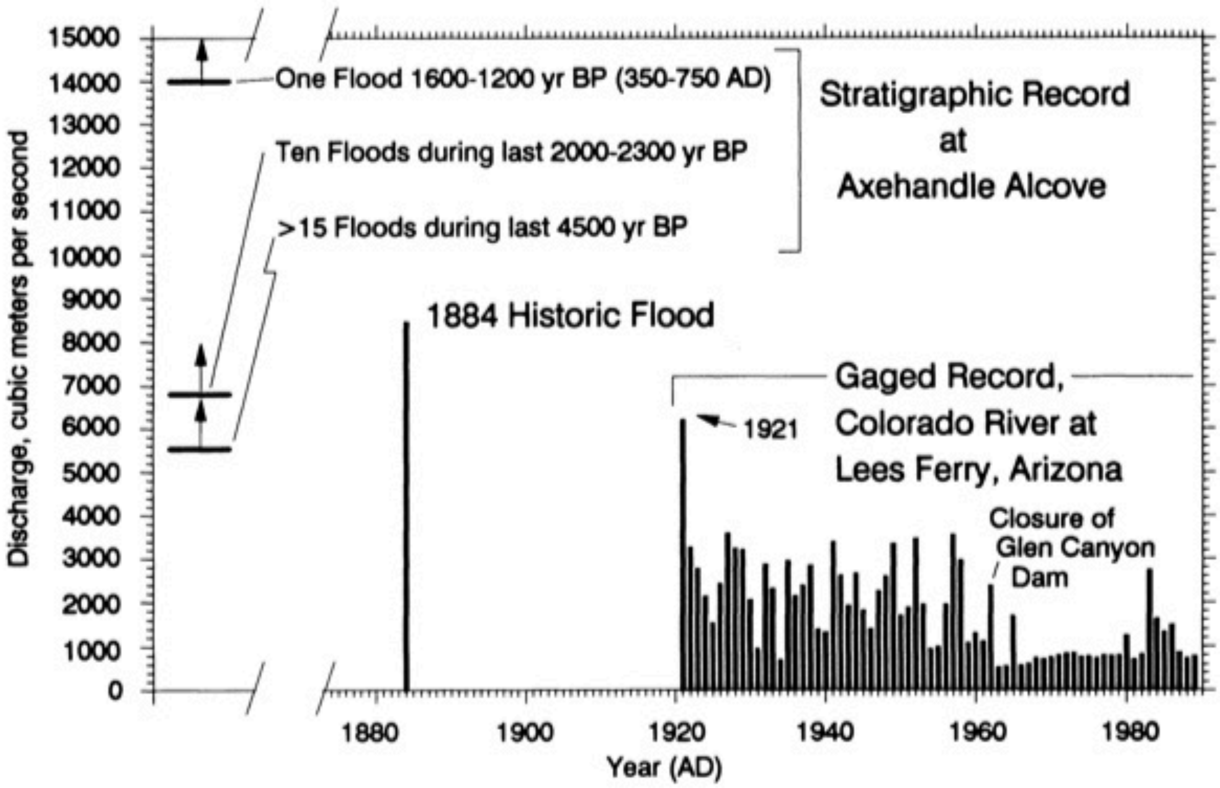

Figure 5: Stratigraphic records of discharge levels at Axehandle Alcove compared to gauged records of discharge at Lees Ferry (from O'Connor et al., 1994).

Influences of Flooding on Rapid Morphology:

Sedimentological records of Holocene flooding in the canyon inform us of how flow discharges on the river since ~ 4.5 ka have shaped the rapids (O'Connor et al., 1994). During large flooding episodes when water levels rise above sheltered benches or alcoves in the canyon walls, sediments entrained in the flow can be deposited, leaving a marker of high water level. Analysis of these flood stage deposits shows that discharges on the river in the recent past were far greater than anything observed historically. The largest of these floods occurred 1,600-1,200 years ago with a discharge of ~ 14,000 m^3/s—twice the magnitude of the highest gauged flood ever recorded (fig. 5). Ten floods over the last 2000 years had discharges exceeding 6,800 m^3/s, and many more were over 5,300 m^3/s (O'Connor et al., 1994). This supports the early suggestion of Kiefer (1985) that the rapids are likely relict features that were shaped by exceptionally large floods with discharges of ~ 11,320 m^3/s.

By the end of the 1900's it was becoming apparent that the large historical floods on the river were crucial for refreshing ecological systems, sediment bars and beaches, and even the rapids (Collier et al., 1997).

A debris flow emplaced at Crystal Rapid in 1966, for example, constricted the channel to a quarter its original width and created a formidable 6 m standing wave. Dozens of rafters were seriously injured and one person drowned attempting to run the rapid, causing the park to shut down this stretch of the river (Kieffer, 1985). In 1983, unusually high precipitation in the drainages feeding the Colorado River forced the Glen Canyon Dam operators to run the turbines, jet tubes, and spillways simultaneously, with maximum discharge of ~ 2,800 m^3/s. Crystal Rapid went from being constricted to 25% of the upstream channel width to just 40% (Kieffer, 1985).

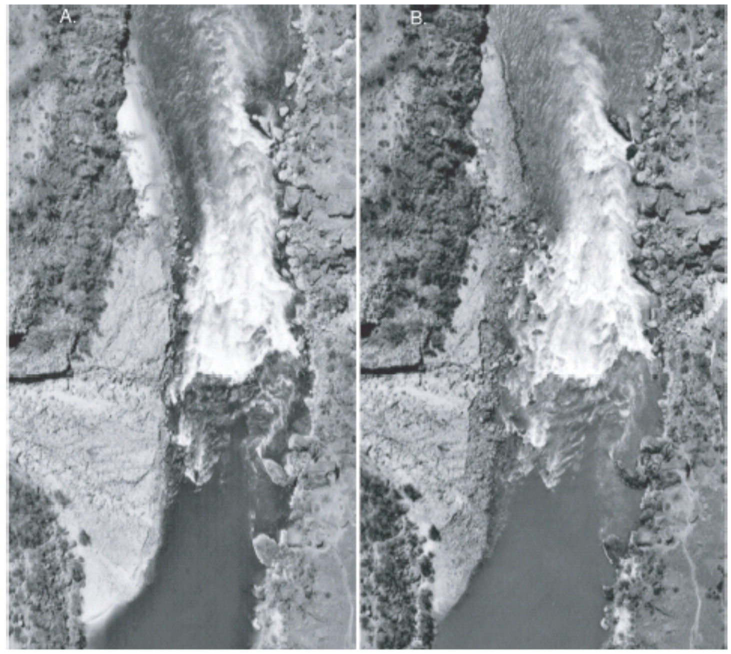

Figure 6: Debris flow deposits at Lava Falls Rapid, before the 1996 flood (left), and after (right), (from Webb et al., 1997).

Similarly, a debris fan encroaching on Lava Falls Rapid in 1995 was almost entirely removed by a controlled flood with a discharge of 1,370 m^3/s in 1996 (Webb et al., 1999). Surface water velocities on the edges of the rapid decreased by 50% and the area of the debris fan decreased by 21% (fig. 6). Hence, despite the greatly reduced discharge possible in the canyon, controlled flooding has been able to reduce the severity of two of the largest rapids on the river (Collier et al., 1997).

The Rapids as a Commodity of the River:

The hydrology of the Colorado River has markedly changed since Powell's landmark expedition in 1869. The frequent flash floods that used to drive the geomorphology of the canyon are now precisely regulated by the operations of Glen Canyon Dam (Dolan et al., 1974). Consequently, the evolution of the rapids, and the experience of rafting the canyon, is largely under the influence of dam operations.

Even on a daily timeframe, guides must take the diurnal fluctuations of dam outflows into consideration when running certain rapids, as many can be far more dangerous when river levels are too low (Dolan et al., 1974). On a longer timescale, the nature of the rapids that rafters will be faced with is also at the mercy of Glen Canyon Dam operations. The current trend of long term aggradation and increased difficulty of many rapids in the canyon over the last century will continue (Magirl et al., 2005). High flow experiments have proven efficacious at rejuvenating the rapids to a certain extent (Collier et al., 1997). However, these experiments will never reach the magnitude of historical floods in the canyon, so returning the rapids to their original pre-dam condition would be impossible.

The ever-changing morphology of the rapids indicates that they are still in the process of adjusting to the reduced flow regime. Eventually the rapids may reach a new dynamic equilibrium, where planned flooding could effectively scour accumulated debris over the year. It is uncertain how long it will be until the river reaches this state, and what the character of the rapids will be like, but it will be entirely dependent on the magnitude and frequency floods.

With this in mind, the rapids must be managed just like any other environmental resource in the Grand Canyon. River running brings an estimated 21 million dollars annually to the regional economy (Hjerpe and Kim, 2007) and is undoubtedly one of the most alluring experiences of the Grand Canyon. Maintaining the rapids is crucial both for the safety of this recreational activity and in preserving the mystique of adventure in the Grand Canyon.

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