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The Effect of Dam Closure on Downstream Rapids

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The force of flowing water and the resistance of the largest boulder provide a means of evaluation of the stability of rapids in canyon rivers. Field measurements and calculations show that the closure of Flaming Gorge Dam, Utah, has had a significant effect on the stability of rapids in the canyons of the Green River in Dinosaur National Monument 68 km (42 mi) downstream from the dam. The reduction in peak flows by the dam has limited the competence of the river to move boulders deposited in the main channel by tributary processes, landslides, and prehistoric floods. Before the dam was closed, 62% of the rapids were stable, as indicated by the immobility of the largest boulder in each rapid. After the dam was closed, 93% of the rapids were stable as geomorphic/hydraulic features, though small boulders continue to move. A continuing buildup of boulders in the rapids will result from tributary contributions which are not affected by the dam.

INTRODUCTION

The closure of high dams in the American West for irrigation storage, power production, and river flow regulation has resulted in substantial obvious hydrologic and geomorhpic effects upstream from the dam sites. Partial flooding of valleys and canyons, artifically induced sedimentation, and slope destabilization are the by-products of many reservoirs, including those of the Colorado River system. In addition to these expected environmental adjustments, however, the installation of high dams has fostered unforeseen adjustments downstream from the dam sites. Some armoring of the channel floors downstream from the release points of sediment-free waters had been predicted and occurred to a limited extent [*Pemberton,* 1976]. Changes in water chemistry and temperature have affected aquatic life [*Bolke and Waddell,* 1975]. But it is now clear that the influence of the major dams such as Hoover (Boulder), Glen Canyon, and Flaming Gorge extends more than just a few kilometers downstream. The reduction of flood peaks, a justification for the projects, has had many beneficial effects on human use of the riverine environment [*U.S. Department of Interior,* 1946] but the elimination of very high flows has also produced serious problems.

In the Grand Canyon, for example, channel-side beaches, once replenished by sediments deposited in major floods, are now dwindling under constant erosion by sustained moderate-stage flows of clear water released from Glen Canyon Dam [*Dolan et al.,* 1974]. While the beaches, the only usable campsites along many reaches of the river in the canyon, continue to decline in size and number, the recreational demand remains the same [*National Park Service,* 1977c]. Limited by Park Service regulations, approximately 14,000 people pass through the canyon each year, concentrating their detrimental impacts on the near-channel environment in fewer and fewer sites. The Park Service is being forced to reduce party sizes and to initiate extensive control measures to accommodate the changing physical environments in the Grand Canyon, Dinosaur National Monument, and Canyonlands National Park.

The largest flood peaks also performed a cleansing process, with chemical and material pollutants being washed downstream and diluted [*National Park Service,* 1977c]. Reduction of these flood peaks by dams has permitted a dangerous buildup of waste materials in some sites along the canyon rivers, resulting in strict managerial controls on wastes, ranging from refuse to campfire ashes.

The increased severity of river rapids is an additional effect of the reduction of flood peaks that has been the object of speculation. No precise documentation or specific calculations are available to substantiate the effects of flood reduction on river rapids in canyons of the Colorado River system, but some new rapids have formed since the closures of the major dams, and boatmen on the rivers claim that the rapids are generally becoming more severe [*Dolan et al.,* 1974; W. Bender, personal communication, 1977]. River managers assume that the rapids have been affected by the altered flow conditions, but the degree of that response has not been established. The purpose of this paper is to determine through field observations and numerical estimations the probable impact of the closure of Flaming Gorge Dam on the stability of downstream rapids in Dinosaur National Monument.

Engineers, geomorphologists, and river recreationists seem to agree on the locations and identities of most of the rapids of the Colorado River system (for respective examples see *Herron* [1917], *Evans and Belknap* [1973], and *Hayes and Simmons* [1973]). A rapid is an accumulation of boulders in the channel where the particles are numerous enough or large enough to break the water surface at mean annual discharge (Figures 1 and 2). Such a definition includes all the commonly recognized rapids of the Colorado/Green system, but eliminates some boulder accumulations that produce 'white water' during low flows. Rapids produced directly by bedrock bars do not occur on the main channel of the Colorado or its major tributaries. Boulder rapids result from the accumulations of particles from flash floods on tributaries, mass movements along channels, and boulder bars produced by prehistoric floods.

Previous research into the origin and dynamics of rapids in canyon rivers is not as extensive as investigations in alluvial streams. *Powell* [1875] was the first to describe and analyze the rapids of the Colorado River system in his historic journeys through the then unexplored region. *Leopold* [1969] reported on extensive depth-sounding traces of rapid and pool sequences in the Grand Canyon, and *Dolan et al.* [1978] showed the relationship between rapid location and geologic structure in the same area. *Silverston and Laursen* [1976] have simulated the hydraulic characteristics of the river profile in a series of pools and rapids similar to those encountered in the Colorado River in the Grand Canyon, while *Laursen et al.* [1976] have

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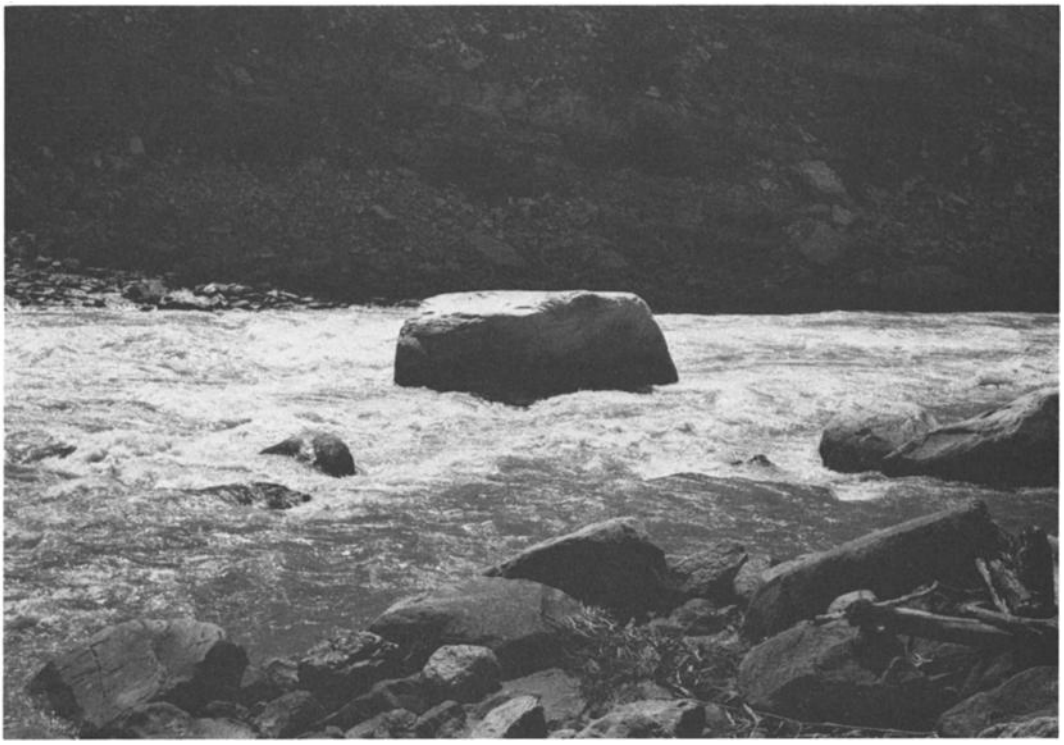

Fig. 1. Ingelesby Rapid in Split Mountain Canyon, a rapid typical of those in Dinosaur National Monument.

analyzed the movement of sediment through the canyon. In a previous paper I have explored the problems of rapid spacing and the balance between boulder resistance and the forces of natural flood flows [*Graf,* 1979*b*].

The canyons of the Green River in Dinosaur National Monument provide a useful study area for the investigation of the effects of the dam closure and the resulting unnatural flood flows on the stability of rapids (see Figure 3 for location and detail maps). The Canyon of Lodore, Whirlpool Canyon, and Split Mountain Canyon compose a combined total of 69 km (43 mi) of river reaches entrenched up to 1000 m (3000 ft) into the eastern flank of the Uinta Mountains [*Hansen,* 1975]. The canyons contain at least 55 rapids formed by tributary flash flood deposits, landsliding, or prehistoric floods on the

Fig. 2. Pool downstream from Pot Creek in the Canyon of Lodore, a pool typical of those between the rapids of Dinosaur National Monument.

main stream that deposited accumulations of boulders derived from the surrounding sandstones and limestones (for geologic summaries, see the works by *Untermann and Untermann* [1954, 1964].

Flaming Gorge Dam, closed in 1962, is located 68 km (42 mi) upstream from the national monument. The dam releases a maximum of 170 $m^3 s^{-1}$ (6000 $ft^3 s^{-1}$), where the maximum flood of record, probably the 100-year event, before the dam closure was 510 $m^3 s^{-1}$ (18,000 $ft^3 s^{-1}$) [*National Park Service,* 1977*a*, *b*]. The hydrologic consequences of such changes are significant because of the 17,000 white water enthusiasts, who annually use the river and its rapids for recreation [*McCool et al.,* 1977].

METHODS

The analysis of sediment transport by flowing water has been most highly developed for small particles, those that are sand size or smaller [*Graf,* 1970]. The DuBoys approach to tractive force [*Leliavsky,* 1966], the Shields equation [*Baker,* 1974], the Einstein equation [*Einstein,* 1950; *Colby and Hembree,* 1955], and unit stream power [*Yang,* 1976] have had varying degrees of success, but they are not suited for particles as large as those in boulder rapids [*Bogardi,* 1974, p. 80]. *Komar* [1970] has adopted the Shields equation for large particles in turbidity currents. Attempts at interpreting the paleohydraulic records of geologic deposits have led to alternative approaches for massive particles and deep flows in studies by *Birkeland* [1968], *Baker* [1974], *Baker and Ritter* [1975], and *Ballard* [1976]. In this paper, empirical hydraulic techniques are abandoned in favor of a deductive physical one, an approach to geomorphic problems that was first specifically suggested by *Strahler* [1952, p. 923]. Because of the intricacies of hydraulic processes the method used here is only an approximation to reality. It represents an attempt to estimate broadly the stability of the largest boulder in each rapid by calculating (1) the particle resistance based on friction and buoyancy, (2) the downstream force of flowing water against the particle, and (3) the ratio of force to resistance as a measure of stability.

Figure 4 outlines the basic algorithm, a series of steps designed to evaluate force, resistance, and stability. Data required for input include discharge information from gaging records; channel roughness, width, and gradient as surveyed in the field; and boulder density and dimensions as measured in the field. The algorithm produces as output the force and resistance as measured in dynes (in gram centimeters per second per second) or newtons (in kilogram meters per second per second).

The method determines resistance of the largest boulder by calculating its frictional resistance to movement. Since only the initiation of motion is considered, inertia is disregarded.

The method determines the force imparted from the flowing water to the boulder as mass per unit time m times velocity V:

$$f = mV \qquad (1)$$

The mass per unit time of flowing water that is involved is

$$m = Ay_fV \qquad (2)$$

where S is cross-sectional area of the boulder that obstructs the flow of water and y_f is the density of the fluid, which is assumed to be 1.15 to account for sediment-laden flood water. Substituting (2) into (1),

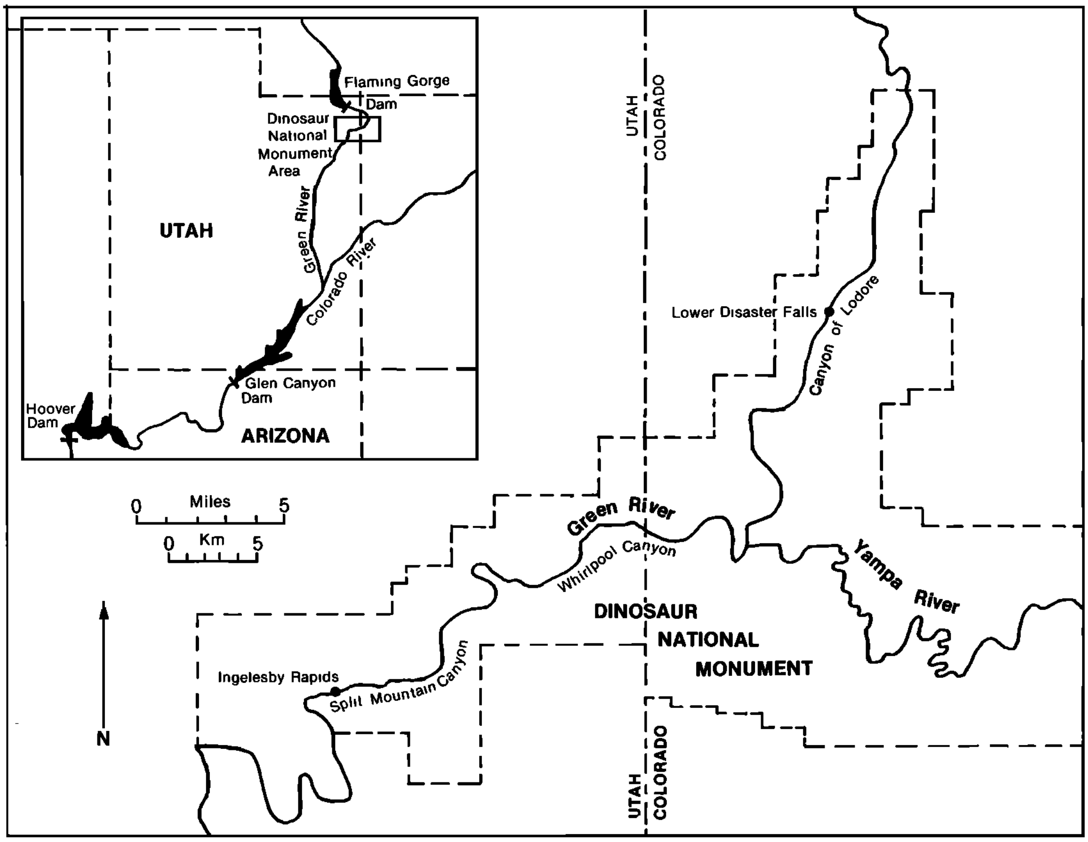

Fig. 3. Major dams of the Colorado and Green River systems and the canyons of Dinosaur National Monument.

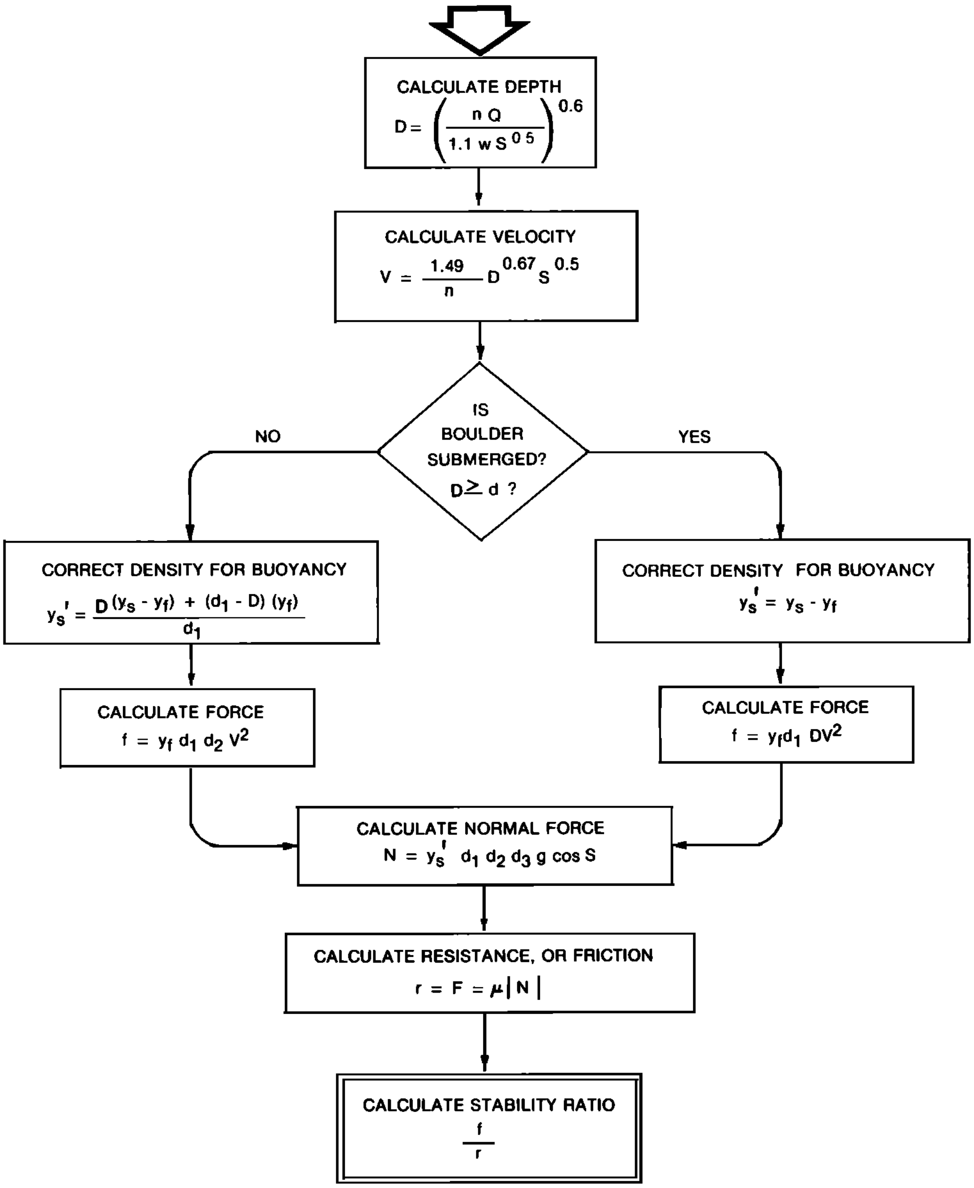

Fig. 4. Method for calculating the stability of the largest boulder in rapids. Symbols with dimensions: D is the depth of flow (in meters); $d_{1,2\ldots}$ are the primary dimensions of the boulder (in meters); F is the friction (in newtons); f is the force of flowing water against upstream face of the boulder (in newtons); g is the acceleration of gravity (in meters per second per second); u is the coefficient of friction (dimensionless); N is the normal force (in newtons); n is the Manning roughness coefficient (dimensionless); Q is the discharge (in cubic meters per second); S is the gradient (dimensionless); w is the channel width (in meters); y_f is the density of the fluid (in kilograms per cubic meter); y_s is the density of the boulder and y_s' is the density of the boulder corrected for buoyancy (in kilograms per cubic meter).

$$f = y_f A V^2 \tag{3}$$

The cross-sectional area considered may include the entire surface of the boulder facing upstream if it is submerged:

$$A = d_1 d_2 \tag{4}$$

where $d_{1,2,\ldots}$ are dimensions of the boulder. If the depth of flow is not great enough to cover the boulder, the cross-sectional area considered is only

$$A = d_1 D \tag{5}$$

where D is the depth of flow.

The stability ratio of force divided by resistance is a summary comparison between force and resistance. If the ratio is less than 1.0, resistance is greater than force, and the particle in question is potentially stable. If the ratio is greater than 1.0, the force of flow is dominant, and the particle is potentially unstable. A similar line of reasoning has been followed by *Graf* [1979*a*] and *Bull* [1979] for small particles.

The method can be considered only as a first approximation to the actual forces and resistances because several factors are simplified or eliminated by limitations of the field data. The largest boulder in each rapid is the only particle considered, since the majority of the particles are submerged beneath fast-flowing water. The largest boulders are significant, however, because they frequently occupy substantial portions of the channel cross section. The packing of particles was not accounted for as in White's method [*Leliavsky,* 1966] because the largest boulders protrude above the general surface of the rapid. The boulders are assumed for purposes of calculation to have smooth rectangular faces, an assumption that is frequently violated but not to a great degree, since the boulders are produced from angular joints in fractured sandstone. Forces involved in water prying under the boulder as it moves and rotational motions are not accounted for, but the complexity of measurements and calculations for such torque forces may be excessive for the amount of informational return. Impacts from floating or saltating debris in the channel are not accounted for, and their role remains unknown. Use of the Manning equation and estimates of its channel roughness factor introduce some unavoidable error. See *Statham* [1977, p. 119] for further discussion of the problems of comparing force and resistance.

Despite these reservations the calculations provide estimates of the forces and resistances in rapids that permit some generalizations concerning potential stability of the features. If the largest particle in a rapid is stable, then the rapid itself is also likely to be stable despite movements of smaller particles. The method specifies a threshold of resistance of the largest particle: if the force of flood waters falls below that threshold, stability of the rapid ensues. The calculations provide a way to evaluate the probable effect on rapids from a reduction in flood flows by determining whether or not the forces involved are changed enough to cross this threshold of stability.

RESULTS

Field measurements were made in the canyons of Dinosaur National Monument in the summer of 1977, with subsequent calculations being made for two cases: (1) for a discharge of 510 m^3/s (18,000 ft^3/s) as the maximum flood of record before the closure of Flaming Gorge Dam and (2) for a discharge of 170 m^3/s (6000 ft^3/s) as the maximum probable flood now that the dam is in operation. The results are discussed below for a specific single rapid as an at-a-site example, followed by the downstream situation, where the entire length of the canyons is considered.

Figure 5 shows the calculated values of force of flowing water and resistance of the largest boulder in Lower Disaster Falls in the Canyon of Lodore. Resistance decreases slightly with increasing depths of flow because of the effects of buoyancy, but once the boulder is completely submerged at a depth of 1.7 m (5.1 ft), this factor is no longer variable. During the maximum predam flood of record, water depth at the rapid was 3.4 m (11.1 ft), sufficient to generate enough force to overcome the resistance of the largest boulder, as shown in Figure 5. During the maximum postdam flood the depth of flow was only 1.8 m (5.8 ft), and the generated force is now less than resistance. These calculations suggest that before dam closure, Lower Disaster Falls was an unstable feature, though it has existed for at least a century because explorer John Wesley Powell wrecked a boat in the rapid in 1869, thus providing the rapid with its name [*Powell*, 1875]. Since dam closure, however, the rapid has become a stable feature, which will most likely be a focal point for an increasing accumulation of boulders. The change in flood regimes has crossed a significant threshold (Figure 6).

The switch from unstable to stable conditions at Lower Disaster Falls is not necessarily characteristic of all the rapids in Dinosaur National Monument. Similar calculations for predam and postdam conditions for rapids in all the canyons show a variety of situations. In Split Mountain Canyon most of the rapids were stable before the dam was built, so there the impact of the dam may have been to restrict the movement of some small particles, but the largest particles and the rapids themselves simply became more stable (Figure 7). Most of the debris in rapids of Split Mountain Canyon came from mass

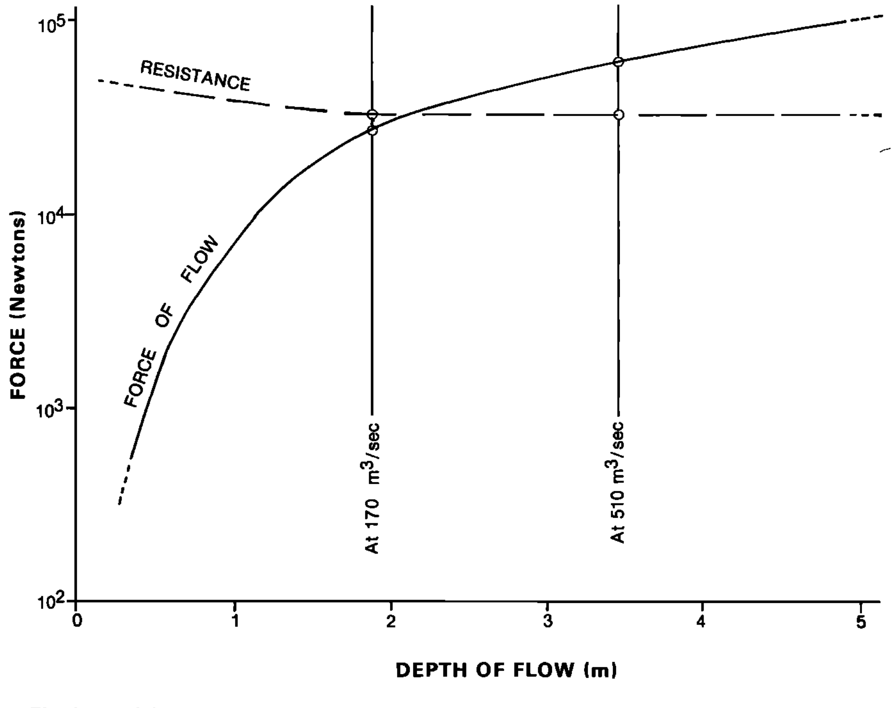

Fig. 5. The force of the flow of water and resistance of the largest boulder calculated by the method shown in Figure 4 using data from the Lower Disaster Falls rapid in the Canyon of Lodore. The two measures are juxtaposed in their relationship to each other when comparisons are made for maximum predam flood (510 $m^3\ s^{-1}$) and postdam flood (170 $m^3\ s^{-1}$).

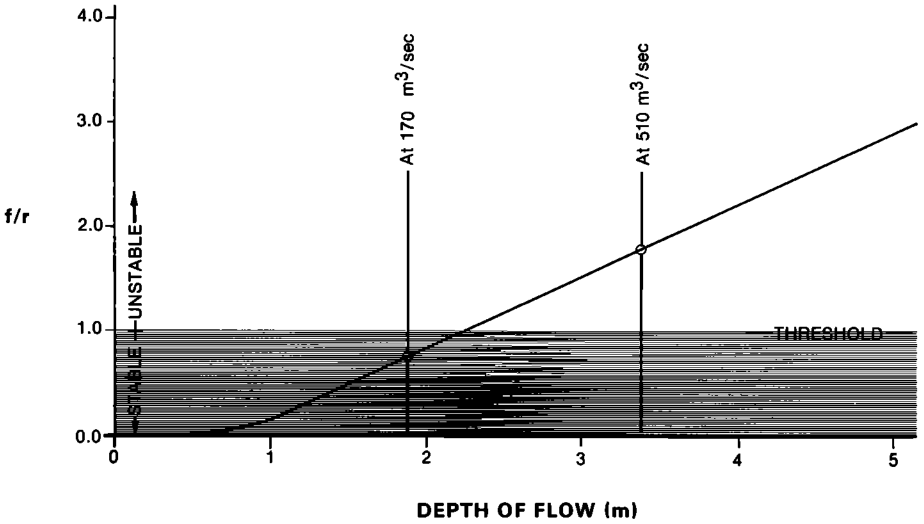

Fig. 6. The stability ratio calculated by the method shown in Figure 4, using data from Lower Disaster Falls rapid in the Canyon of Lodore. By adjusting the peak flood from a predam level of 510 m^3 s^{-1} to a postdam level of 170 m^3 s^{-1} the stability threshold is transgressed, and the previously mobile particle becomes stationary.

movements on the canyon's cliffs where tributary alluvial fans have constricted the canyon floor and caused undercutting opposite the fan. The main stream has been unable to develop depths of flow and associated forces great enough to move the boulders, and dam closure insures that that situation will continue.

The case of Whirlpool Canyon is in striking opposition to Split Mountain Canyon (Figure 8). In Whirlpool Canyon the majority of the rapids were unstable during the maximum predam flood, but after dam closure only 25% were unstable during the maximum expected flood. The closure of Flaming Gorge Dam has had a significant effect on the mobility of materials in Whirlpool Canyon, and buildup of boulders brought down to the main stream by tributaries will continue at an accelerated rate. Mass movement on canyon sides is less of a significant factor in Whirlpool Canyon than in Split Mountain Canyon.

The rapids of the Canyon of Lodore are most strongly affected by dam closure (Figure 9). Before the completion of Flaming Gorge Dam, nearly half of the rapids were unstable during the predam flood, but under present conditions all but one rapid are stable. Tributary processes in Lodore include mass movement in steep chutes leading from cliffs to debris cones along the channel and a few major streams that have built alluvial fans onto the canyon floor. Buildup of boulders will probably continue in these sites without movement caused by floods in the main channel.

In all the rapids some boulders smaller than the ones analyzed here will continue to be moved by flood flows. Though these particles have been observed to move in the past [*Graf*, 1979*b*], the immobility of the largest boulders insures the survival of the rapids as geomorphic features despite adjustments among some of their constituent parts.

CONCLUSION

Before the closure of Flaming Gorge Dam, at least 62% of the rapids in the Green River Canyons of Dinosaur National Monument were stable during the maximum flood. After the completion of the dam the resulting limited flood flows leave 93% of the rapids stable. As large boulders continue to accu-

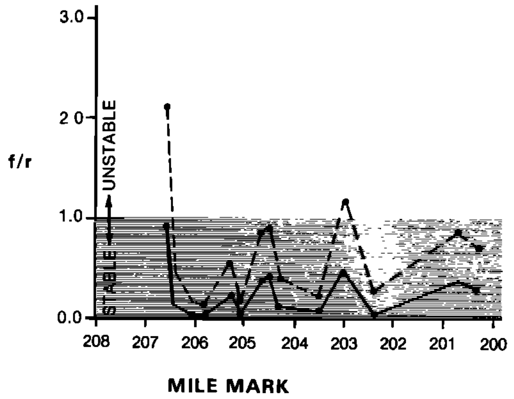

Fig. 7. The stability ratio calculated by the method shown in Figure 4 and field data from Split Mountain Canyon. Dashed line shows predam conditions; solid line shows postdam conditions. Mile marks as surveyed by *Herron* [1917], also found in the works by *Evans and Belknap* [1973] and *Hayes and Simmons* [1973].

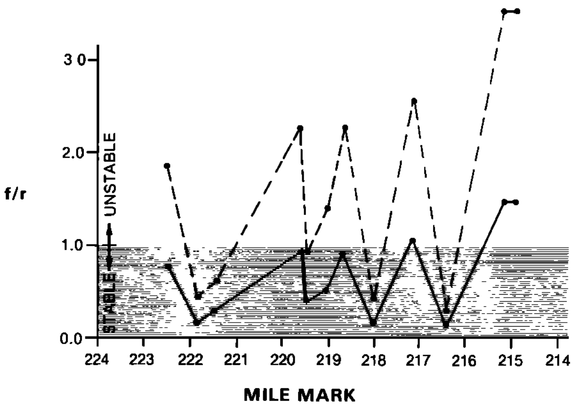

Fig. 8. The stability ratio calculated by the method shown in Figure 4 and field data from Whirlpool Canyon. Dashed line shows predam conditions; solid line shows postdam conditions. Mile marks as surveyed by *Herron* [1917], also found in the works by *Evans and Belknap* [1973] and *Hayes and Simmons* [1973].

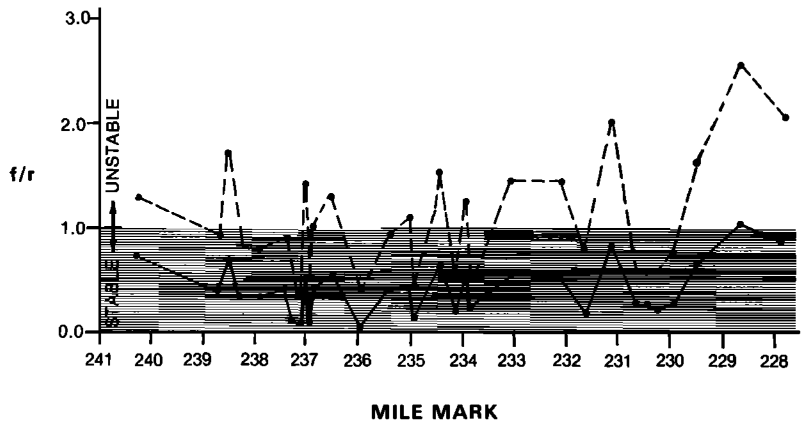

Fig. 9. The stability ratio calculated by the method shown in Figure 4 and field data from the Canyon of Lodore. Dashed line shows predam conditions; solid line shows postdam conditions. Mile marks as surveyed by *Herron* [1917], also found in the works by *Evans and Belknap* [1973] and *Hayes and Simmons* [1973].

mulate from tributary processes, river managers and white water recreationists must expect increasingly severe conditions in the rapids. New rapids may form in localities where under completely natural circumstances the main channel would wash out the rapid but where now floods are not of sufficient magnitude to flush the debris. In the summer of 1976, for example, a flash flood on an unnamed tributary deposited a boulder fan and formed a new rapid near the Utah/Colorado state boundary where it crosses the Green River in Whirlpool Canyon.

Tributary processes, of course, are not affected by closure of the dam on the main stream: flash floods, landslides, debris falls, and undercutting of canyon walls continue unabated. As far as large caliber debris in the rapids of the main channels are concerned, input processes are proceeding at 'normal' rates (subject to changes of climate and—for the floods of large tributaries—land use practices), while the output processes have been artificially slowed. This arrangement is in marked contrast to the situation for small size sediment (such as silt and sand), which is primarily the contribution of the main stream. Siltation behind the dam slows the input, while output in the form of erosion and transportation by relatively clear water continues at a 'natural' or even at an accelerated rate. *Dolan et al.* [1974] have shown that the result of this inbalance in the Grand Canyon is the destruction of channel-side beaches and bars. The loss of these fine-grained sediments and the geomorphic features they form has already begun to affect the management of the river environment as a recreation resource.

It is unlikely that the increasing severity of rapids will become a problem as quickly as the problem of channel-beach erosion. The movement of fine particles is nearly continuous, while the large boulders of the rapids move only occasionally during low-frequency events. For 62% of the rapids, lowering of flood peaks has had little effect because even without the dams, flood flows were not sufficient to move the particles in the main channel. The buildup of these rapids and concommitant increases in white water severity were occurring before the dam closure, so that the dam has not caused the transgression of a process threshold in many cases. From the standpoint of the river manager these rapids would have become more severe with or without the dams.

In summary, over half of the rapids of the Canyon of Lodore, Whirlpool Canyon, and Split Mountain Canyon were stable and building before the closure of Flaming Gorge Dam upstream. However, almost all of the remaining rapids have been stabilized by the reduction in flood peaks by the dam, so that the hydraulic and geomorphic conditions of the channel are much different from their predam states. The impact of high dams is far reaching not only upstream but downstream as well.

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