THE EFFECT OF GLEN CANYON DAM ON THE STABILITY OF RAPIDS IN THE COLORADO RIVER, GRAND CANYON, ARIZONA

by

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ABSTRACT

Rapids in the Colorado River in the Grand Canyon occur primarily at channel constrictions caused by debris fans deposited by tributary flash floods. Prior to the completion of Glen Canyon Dam, the Colorado River eroded portions of these debris fans, thus controlling the increase in debris fan size and severity of the rapids. A decrease in the mean annual maximum discharge from 86,000 ft^3/s (2,434 m^3/s) to 36,000 ft^3/s (1,020 m^3/s) due to the operations of Glen Canyon Dam has reduced the competence of the Colorado River to remove material accumulating on the debris fans of rapids. The impact of Glen Canyon Dam on the stability of rapids in the Grand Canyon was examined. Rapid stability was determined by comparing the force of flowing water to the resistance of two different particle sizes located on the debris fans. Calculation of rapid stability using the largest boulder (d_{max}) and the mean particle size (d_{50}) revealed increases in rapid stability of 72.7% and 37.3% respectively from the pre-dam to the post-filling period. As long as main stream processes are controlled by Glen Canyon Dam, further increases in the stability and severity of rapids can be expected. Periodic releases of pre-dam magnitude discharges may be desirable to remove material accumulating on the debris fans, thus controlling the increase in severity of the rapids.

DEDICATION

To my wife, Sally Lucy Wright, who has unselfishly given of herself during the completion of this endeavor. Her motivation, confidence in my research, and sense of humor provided encouragement during periods of indecision. For her help in the field as well as her continued support and understanding during the writing of this thesis, I am forever grateful.

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CHAPTER I. INTRODUCTION

Introduction to the Problem

The construction of high dams in the American West for water supply, flood control, and electrical power generation have had substantial impacts on river systems upstream and downstream of the dam sites. Glen Canyon Dam, completed in 1963, has dramatically altered the Colorado River in the Grand Canyon. The major effects downstream of the dam include a reduced discharge, a reduced sediment load, and a change in water temperature. These in turn have caused a series of complex changes throughout the entire Grand Canyon region (Carothers and Dolan 1982; Johnson and Carothers 1987). The impact of the dam on resources in the Grand Canyon is the major research focus of the recent Glen Canyon Environmental Studies sponsored by the Bureau of Reclamation.

Rapids in the Colorado River in the Grand Canyon occur primarily at channel constrictions caused by debris fans from tributary flash floods. Prior to the completion of Glen Canyon Dam, the Colorado River eroded portions of these debris fans during annual floods, thus controlling the increase in debris fan size and severity of the rapids. A decrease in the mean annual maximum discharge from 86,000 ft^3/s (2,434 m^3/s) to 36,000 ft^3/s (1,020 m^3/s) due to the operations of Glen Canyon Dam has prevented the Colorado River from removing the larger material accumulating on the debris fans. Hamblin and Rigby (1968) predicted "One would expect that the small debris fans built up at the mouths of tributaries will grow very large in the future." Since 1968, several flash floods or debris flows have occurred in various tributaries and have altered the configuration of the debris fans and rapids in the Colorado River (Webb et al. 1987). In 1966, a flash flood in Crystal Creek significantly increased the size of the debris fan and created a rapid that is one of the most difficult to navigate in the Grand Canyon.

The purpose of the present research was to examine the impact of Glen Canyon Dam on the stability of rapids in the Grand Canyon. Rapid stability was determined by comparing the force of flowing water to the resistance of the boulders located on the debris fans. The results of this study indicate the effects of Glen Canyon Dam on the stability of rapids in the Colorado River, a field in which limited work has been done. It also provides information for resource managers on the complex changes which occur in river systems as a result of dam construction. Lastly, it provides river recreationists with information on changes that have occurred in rapids which may be useful for safer navigation during river trips.

Literature Review

There has been a vast amount of research on the Colorado River and the Grand Canyon over the past century. Spamer's *Bibliography of the Grand Canyon and the Lower Colorado River, 1540 - 1980* (1980) illustrates the broad scope of studies conducted in this area. The bibliography includes works on the biology, ecology, exploration, geography, geology, and history of the Colorado River and the Grand Canyon. The present study addresses a small segment of this immense field; the effect of dam construction on the stability of rapids in the Colorado River. The following literature review is divided into four sections: early exploration and river descriptions; research on the formation and spacing of rapids; post-dam studies on the effects of Glen Canyon Dam upon the Colorado River and the Grand Canyon; and results of the recent "Glen Canyon Environmental Studies".

The first account of rapids in the Colorado River was written by John Wesley Powell during his exploration of the canyons of the Green and Colorado Rivers in 1869 and 1871. Powell was instrumental in the development of the western United States and provided the first documented account of the canyons of the Green and Colorado Rivers in 1869. He viewed the rapids as hazards (Powell 1957):

> We are now ready to start on our way down the Great Unknown. Our boats, tied to a common stake, are chafing each other, as they are tossed by the fretful river...We are three quarters of a mile in the depths of the earth, and the great river shrinks into insignificance, as it dashes its angry waves against the walls and cliffs, that rise to the world above; they are but puny ripples, and we but pigmies, running up and down the sands, or lost among the boulders. We have an unknown distance yet to run; an unknown river yet to explore. What falls there are, we know not; what rocks beset the channel, we know not; what walls rise over the river, we know not.

The expedition reached the Grand Wash Cliffs on August 29, 1869, after three months and six days of exploring the canyons of the Green and Colorado Rivers. Although the expedition successfully traversed the canyon, the scientific data collected during the trip was insufficient and Powell immediately planned another trip.

Powell's second expedition in 1871, funded by the U. S. Federal Government, was more successful due to a more scientifically oriented crew and a better knowledge of the river. The group included two photographers who recorded many parts of this "Great Unknown" (Dellenbaugh 1908; Freeman 1923; Lavender 1985; Powell 1957; Rabbitt 1981; Stegner 1954).

The next great expedition of the Colorado River in the Grand Canyon was conducted by Brown and Stanton in 1889. Robert Brewster Stanton was hired by Frank M. Brown, President of the Denver, Colorado Canyon, and Pacific Railroad, to be chief engineer of a survey team that was to determine the engineering feasibility of building a river-level railroad along the course of the Colorado River. Stanton, like Powell, encountered several difficulties while traversing the canyons of the Colorado, and he abandoned the expedition after the death of Frank Brown and two other members of the party in Marble Canyon (Freeman 1923; Lavender 1985; Stanton 1965). Stanton later completed the river survey; although he felt the railroad was feasible, he did not receive financial support for the project.

The first topographical maps of the Grand Canyon region were completed by Francois Emile Matthes of the U. S. Geological Survey in 1902-05 (Hoffman 1987). In the early 1920's, further U. S. Geological Survey work, led by C. H. Birdseye, completed a series of expeditions through the canyons of the Green and Colorado Rivers with the objectives of mapping the canyons and examining potential dam sites along the river. Birdseye was assisted by E. C. LaRue, chief hydrologist for the U. S. Geological Survey, who was in charge of determining the dam sites. Twenty one maps (Birdseye 1923) were produced showing for the first time the location and configuration of rapids and tributaries along the Colorado River in the Grand Canyon.

Another type of river description is the river guide (Belknap 1969; Crumbo 1981; Hamblin and Rigby 1968, 1969; Péwé 1968; Simmons and Gaskill 1969; Stevens 1983). These guides explain the biology, ecology, geology and history of the Colorado River and the Grand Canyon. They also provide information on the elevation drop and rating of the rapids using the scale of one (least difficult) to ten (most difficult).

In the past twenty five years, the amount of research on rapids in the Colorado River and the effects of Glen Canyon Dam on the river environment has increased dramatically. The increase is partly due to the concern about the fragile nature of the Colorado River and the Grand Canyon. Earlier studies focused on describing, surveying, and inventorying rapids. More recent research has examined the formation and spacing of rapids as well as the effects of Glen Canyon Dam on sediment transport and channel changes along the Colorado River.

Leopold (1965) suggested that rapids are associated with a fairly regular occurrence of gravel accumulations with an average spacing of 1.6 miles (2.6 km). He attributed this regular spacing of rapids to the river's attempt to maintain a state of quasi-equilibrium and a uniform longitudinal bed profile. Hamblin and Rigby (1968) stated that "Without exception rapids in the Grand Canyon are produced by debris from tributary streams which have partially choked the main channel of the Colorado River." They accredited this accumulation of debris to a greater competence of steeper tributaries to transport larger materials during flash floods. Dolan, Howard, and Trimble (1978) argued that rapids form at steep tributaries associated with local and regional fracture zones. Graf (1979) concluded that rapids in the Grand Canyon are distributed randomly or slightly more regular than random and show little tendency toward equal spacing. Kieffer (1985) discussed the increase in severity of Crystal Rapids after the severe flash flood of 1966 and proposed a model of river-debris fan evolution in the Grand Canyon. Webb et al. (1988) discussed the hydrologic effects of the 1984 debris flow in Monument Creek on Granite Rapids and the effects of debris flows in the Grand Canyon on the formation and maintenance of rapids.

Another major research emphasis has focused on the effects of Glen Canyon Dam on the Colorado River and the Grand Canyon. Dolan, Howard, and Gallenson (1974) addressed the impact of Glen Canyon Dam on the Colorado River and the Grand Canyon and discussed adjustments that were occurring due to the reduced discharge and sediment load. Several studies (Beus, Carothers, and Avery 1985; Howard and Dolan 1979, 1981; Laursen, Ince, and Pollack 1976; Pemberton 1976) examined effects of the dam on sediment transport and erosion of beaches in the Grand Canyon. Prior to the dam, beaches used by commercial river runners were replenished with new sediment during annual floods. With a decrease in the mean annual maximum discharge and a reduction in new sediment below the dam, these beaches are experiencing erosion and may disappear in 100 to 200 years (Laursen, Ince, and Pollack 1976). Howard and Dolan (1979, 1981) established a series of baselines to measure beach erosion and sediment transport. Further research was completed by Beus, Carothers, and Avery (1985) to determine the effects of pre-dam magnitude floods in 1983 and 1984 on deposition and erosion of beaches along the Colorado River.

Turner and Karpiscak (1980) examined changes in vegetation along the river by comparing pre- and post-dam aerial photographs. Their study revealed increases in the density of many species, introduction of exotic species such as tamarisk, Russian olive, and elm, and changes in sand and silt deposits. Other research (Carothers and Dolan 1982; Johnson and Carothers 1987) studied the complex ecological changes resulting from the reduced discharge, reduced sediment load, and changes in water temperature. Dramatic changes in vegetation, the extinction of native fish species, and the proliferation of exotic fish species were discussed as well as the increases in the number of birds, mammals, and reptiles.

The latest series of studies being conducted in the Grand Canyon are the Glen Canyon Environmental Studies (GCES) supervised by the Bureau of Reclamation (BOR). Several government agencies including the U. S. Geological Survey, National Park Service, and U. S. Fish and Wildlife Service, along with researchers from private groups and universities, investigated the potential impacts of various operating strategies for Glen Canyon Dam on environmental and recreational resources in the Colorado River corridor. Data collected from 1983 to 1986 on the hydrological, biological, and recreational resources of the Grand Canyon addressed two main questions:

> (1) Are current operations of the dam, through control of the flows in the Colorado River, adversely affecting the existing river-related environmental and recreational resources of Glen Canyon and Grand Canyon?
>
> (2) Are there ways to operate the dam, consistent with Colorado River Storage Project (CRSP) water delivery requirements, that protect or enhance the environmental and recreational resources?

The results of over thirty separate studies on various river resources were incorporated into a final report with detailed Sediment, Biology, and Recreation Subteam Reports. According to the final report (U. S. Department of the Interior 1988) the results "were not intended nor designed to lead directly to changes in dam operations but to provide the technical information necessary to enable decision makers to assess the significance of impacts."

The results of nine studies comprised the Sediment Subteam report which deals with various aspects of sediment transport and beach erosion along the Colorado River (See U. S. Department of the Interior 1988, GCES Final Report, Sediment Subteam Report for more detail). Two of these studies (Kieffer 1987b; Webb et al. 1987) specifically addressed rapids. Kieffer (1987b) examined channel configuration and hydraulics at ten of the largest rapids.

Also included in the report is a video cassette (Kieffer 1986) showing the major hydraulic features of these rapids and ten hydraulic maps showing wave structures, boulder location, and velocity streamlines (Kieffer 1987a). Webb et al. (1987) examined the role of debris flows in supplying sediment to the Colorado River and their influence on the development of rapids. Detailed studies were conducted of debris flows in Lava-Chuar Creek, Crystal Creek, and Monument Creek. Evidence was also found of recent debris flows in twenty-one of thirty-six other tributaries examined. According to the study (Webb et al. 1987), "A thorough understanding of debris-flow magnitude and frequency is important to long-term estimates of sediment transport in the Colorado River."

The results of the GCES were reviewed by the various participating agencies, a committee of the National Research Council of the National Academy of Sciences, and the Secretary of the Interior. GCES is currently entering its second phase and will continue to collect data and monitor resources in the Grand Canyon. The results of the present research will be helpful to the GCES´s assessment of the impact of Glen Canyon Dam on white-water recreation in the Grand Canyon.

<u>Research Question</u>

This review of research conducted on rapids in the Grand Canyon indicates a need for further research on the effects of Glen Canyon Dam on rapids. Kieffer (1987b) noted a need for research on the mobility of the larger boulders on debris fans. The research conducted by Graf (1979, 1980) on the impact of Flaming Gorge Dam on rapid stability in Dinosaur National Monument provides a basis for a comparative study on the effects of Glen Canyon Dam on rapid stability in the Grand Canyon. The present study addresses the following research question; What effect has Glen Canyon Dam had on the stability of rapids in the Grand Canyon?

A reduction in the mean annual maximum discharge due to the operations of Glen Canyon Dam, has reduced the competence of the Colorado River to transport large materials accumulating on the debris fans. Since tributary processes have not been affected by the dam, an increase in debris fan size and severity of some rapids has occurred, especially rapids that experienced intense tributary flash flooding during the post-dam period, e.g., Lava-Chuar Creek, Crystal Creek, and Monument Creek.

Rapid stability is determined by a comparison of the force of flowing water to the resistance of the largest boulders on the debris fans to that force. If force exceeds resistance, the particle will move, and the rapid is considered unstable. However, if resistance exceeds force, the particle will not move, and the rapid is considered stable.

Description of the Study Area

Location and Topography. The Grand Canyon is located in the southwestern corner of the Colorado Plateau physiographic province, an area approximately 130,000 square miles located between the Rocky Mountain and Basin and Range physiographic provinces (Figure 1.1). The Colorado Plateau is characterized by horizontal sedimentary formations, structural upwarps, and elevations ranging from 5,000 feet to 11,000 feet above sea level (Hunt 1967). The Grand Canyon section extends from northwest Arizona southeasterly along the Mogollon Rim. It is characterized by broad plateaus formed on Kaibab Limestone and by north-south trending faults that dissect the canyon (Hamblin and Rigby 1968). The Grand Canyon is approximately 280 miles (451 km) in length, 1 mile (1.6 km) deep, and ranges in width from 4 to 15 miles (6.4 to 24.1 km). It is divided into two sections; the Marble Canyon section, which cuts through the Marble Platform and the Grand Canyon section to the west, which cuts through the Kaibab Plateau Although the Marble Platform is 2,000 to 3,000 feet (610 to 914 m) lower in elevation, it consists of the same rock formations as the Kaibab Plateau, which dip down from the Kaibab in a large fault called the East Kaibab Monocline (Whitney 1982).

Geology. The Grand Canyon displays perhaps one of the best known sequences of geologic history in the world. Over 5,000 feet (1,524 m) and 2.5 billion years of rock formation

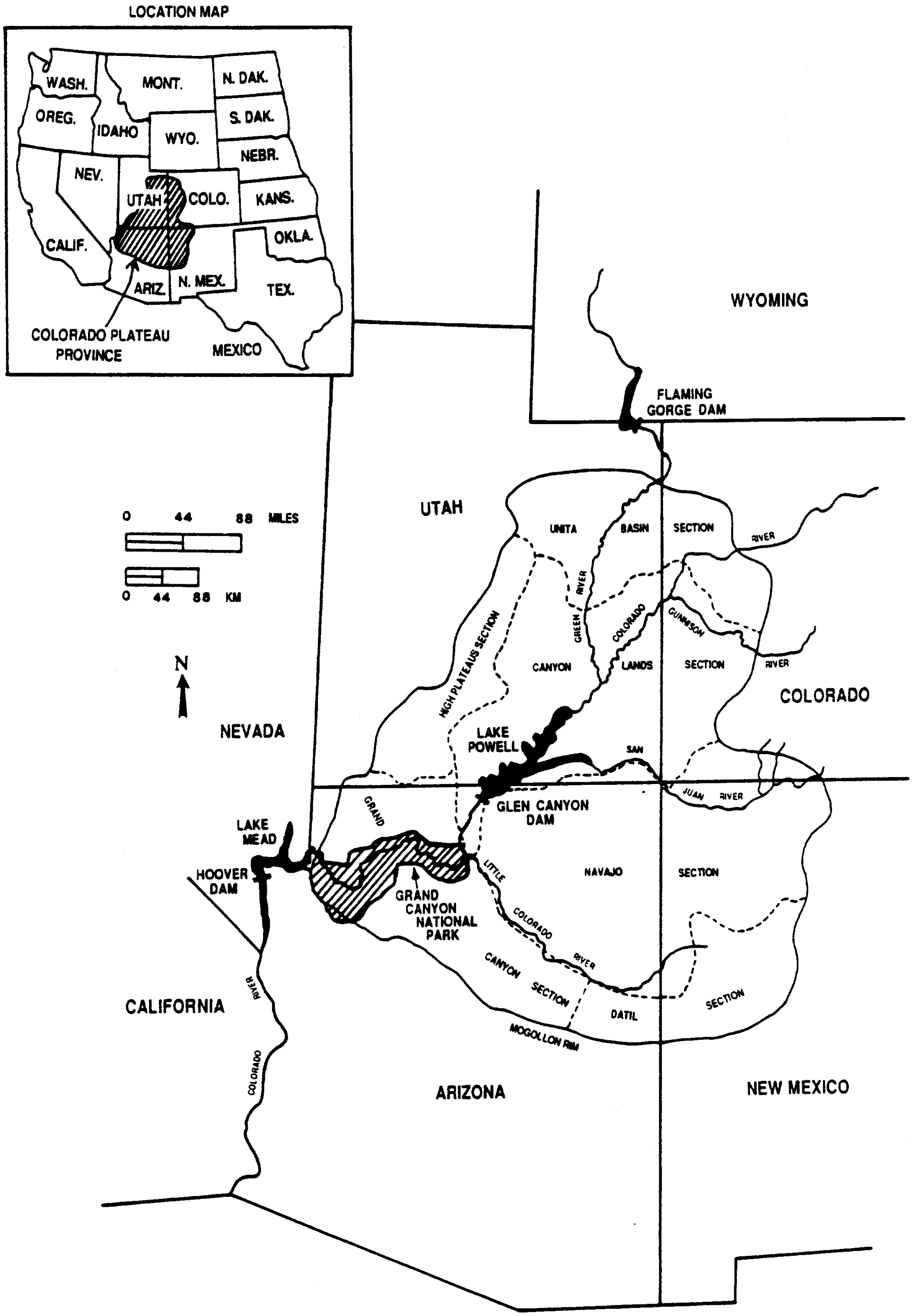

Figure 1.1. The location of the Colorado River and the Grand Canyon in the Colorado Plateau Province (Redrawn from U. S. Department of the Interior 1988).

are exposed in the walls of the Grand Canyon. The rock types range from the younger Permian Kaibab Limestone on the rim to the Precambrian Vishnu Group found in the inner gorge, which are the oldest rocks dating back some 2.5 billion years (Figure 1.2). The profile of the Grand Canyon resembles a staircase, with the steeper, more resistant sandstones, limestones, and schists alternating with the more gently sloped, less resistant shales. Two broad platforms, the Tonto Plateau and the Esplanade, parallel the Colorado River and occur where the softer shales from above have been eroded away. Debris flows are most commonly caused by slope failures in the Hermit Shale and Supai Group throughout the Grand Canyon (Webb et al. 1987). Other geologic formations that have a high potential for slope failures include the Kaibab Limestone, Toroweap Formation, Coconino Sandstone, Muav Limestone, and Bright Angel Shale. Longitudinal spacing of rapids may be related to the proximity of these rock units to the Colorado River (Webb et al. 1987).

There have been three theories proposed to explain the cutting of the Colorado River through the Kaibab Plateau and the formation of the Grand Canyon (Stevens 1983). The theory of antecedence, introduced by Powell, suggests the river was present prior to the uplift of the Plateau, and has since cut through it. The second theory, superposition, suggests that the river has cut and captured drainages

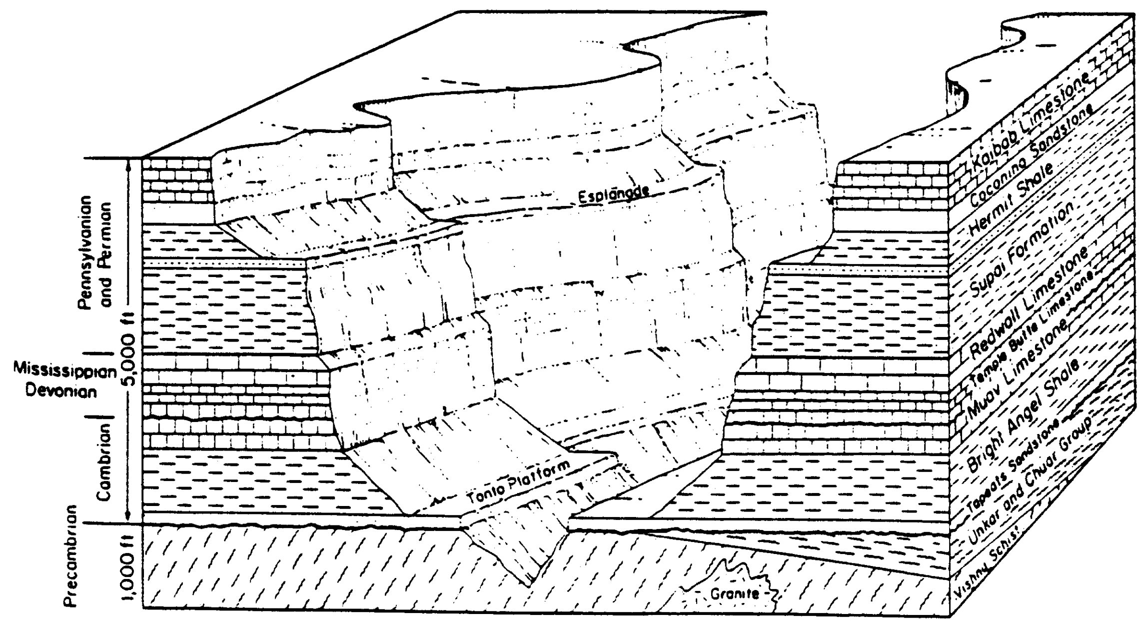

Figure 1.2. Geologic cross section of the Grand Canyon (From Hunt 1967).

through headward erosion both prior to and following the uplift of the Plateau. The third theory, anteposition, proposes that downcutting of the river was interrupted by a period of uplift, during which headward erosion occurred. Graf et al. (1987) reviewed various studies on the formation of the Colorado Plateau and the Grand Canyon and discussed the importance of research in the western Grand Canyon in estimating an earlier age of the Colorado River. Debate over the age and formation of the Grand Canyon still continues.

Climate. Climatic variations in the Grand Canyon are related to elevational differences between the canyon rims and the inner gorge. The change in climate from the inner gorge to the rims of the Grand Canyon is comparable to the change in climate that occurs when travelling from northern Mexico to central Canada (Hoffman 1987). Descending into the canyon, temperature generally increases and precipitation decreases.

Temperatures during the winter average a low of 36 °F (2.2 °C) and a high of 56 °F (13.3 °C) at Phantom Ranch and a low of 20 °F (-6.7 °C) and a high of 41 °F (5 °C) at Grand Canyon Village on the South Rim. Summer temperatures average a low of 78 °F (25.6 °C) and a high of 106 °F (41.1 °C) at Phantom Ranch and a low of 54 °F (12.2 °C) and a high of 85 °F (29.4 °C) at Grand Canyon Village (Whitney 1982).

The Grand Canyon, like other locations in Arizona, receives precipitation during two rainy seasons. Intense thunderstorms occur during the summer "monsoon" season and winter storms that move in from the Pacific Ocean provide another period of precipitation (Stevens 1983). The intense summer thunderstorms are responsible for many of the flash floods on tributaries of the Colorado River which supply debris to the rapids. Phantom Ranch receives 0.68 inches (1.73 cm) of precipitation in January and 0.87 inches (2.21 cm) in July with a mean annual precipitation of 8.39 inches (21.31 cm). Grand Canyon Village receives 1.35 inches (3.43 cm) in January and 1.5 inches (3.81 cm) in July with a mean annual of 14.46 inches (36.73 cm) (Whitney 1982).

Vegetation. Vegetation in the Grand Canyon is also affected by elevational differences. Related to the changes that occur in climatic variables, vegetation associations change descending into the canyon (Figure 1.3). The vertical zonation concept of plants and animals, called life zones, was first postulated by C. H. Merriam in 1889, to aid in explaining the changes in vegetation with changes in elevation. The rims of the Grand Canyon are in the Transition and Boreal Zones. The South Rim is dominated by the Pinyon-Juniper Woodland and extensive stands of Ponderosa Pine Forests while the North Rim is covered with Spruce-Fir and Pine-Fir Forests (Whitney 1982). Descending into the canyon, the Upper Sonoran Zone (located between

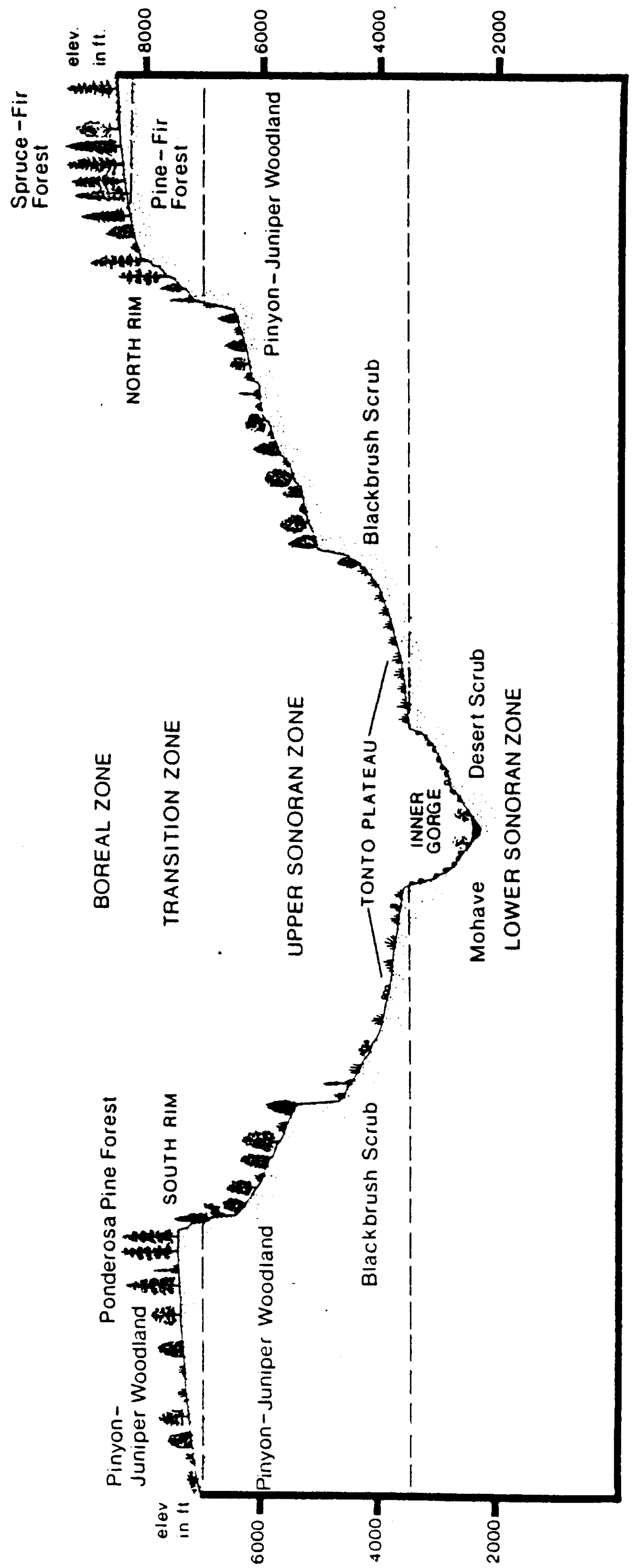

Figure 1.3. Life zones and plant communities of the Grand Canyon (From Whitney 1982).

3,500 to 7,000 feet (1,067 to 2,134 m)) is indicated by the Pinyon-Juniper Woodland and the Blackbrush Scrub. The Lower Sonoran Zone is located in the inner gorge below 3,500 feet (1,067 m) and is distinguish by the Mohave Desert Scrub. The sparse vegetation in this zone causes increased rates of erosion which leads to steeper slopes and increased slope instability. Webb et al. (1987) noted that "high relief combined with differential strength properties of the rocks leads to a high potential for slope failures." These slope failures are the main cause of debris flows which supply sediment to debris fans and influence rapids in the Colorado River.

Vegetation composition along the Colorado River has been dramatically altered by the reduction in the mean annual maximum discharge produced by the operations of Glen Canyon Dam. An increase in dense flood-plain vegetation has occurred along with the elimination of floods which previously scoured stream side vegetation during the pre-dam period (Dolan et al. 1977). This change in the flood regime has increased the number of exotic species such as tamarisk, arrow weed, coyote willow, and bermuda grass growing along the river´s edge. This new vegetation association has been designated the New High Water Zone (NHWZ) by researchers (Figure 1.4). Native species such as Cat-claw acacia and honey mesquite are found in the Old High Water Zone (OHWZ)

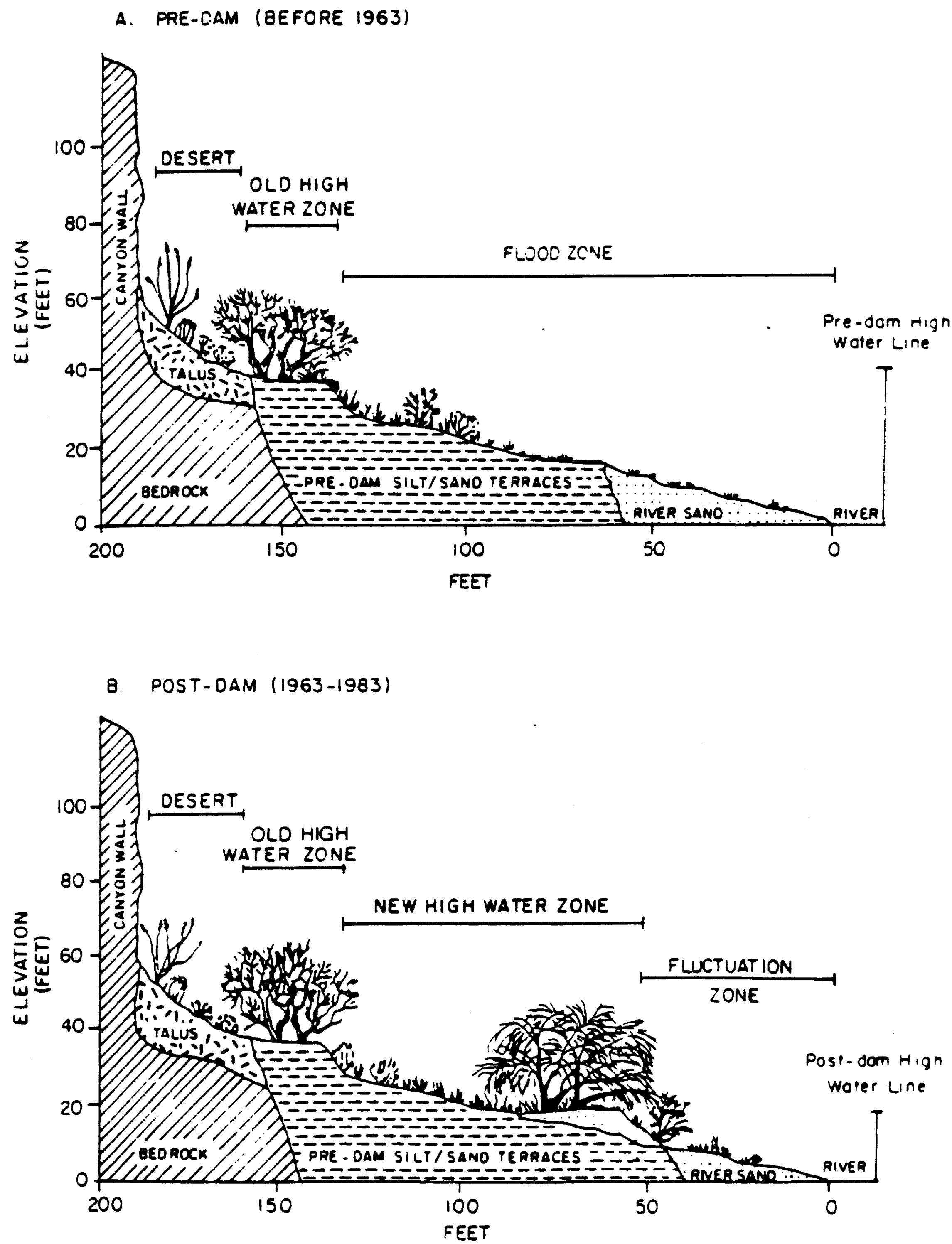

Figure 1.4. Changes in shoreline vegetation due to changes in the flow regime of the Colorado River (From U. S. Department of the Interior 1988, GCES Final Report, p. B-10)

and mark the maximum extent of the pre-dam mean annual maximum discharge.

River Characteristics. The Colorado River in the Grand Canyon region extends 275 miles (443 km) from Lake Powell downstream to Lake Mead (Figure 1.1). Within this reach, there are 160 rapids (depending upon discharge level) that are well documented by the river surveys of the U. S. Geological Survey (Birdseye 1923) and by guides for river runners (Belknap 1969; Hamblin and Rigby 1968, 1969; Péwé 1968; Simmons and Gaskill 1969; Stevens 1983). The Colorado River has an average depth of 35 feet (11 m), reaches a maximum depth of 85 feet (26 m) at River Mile 135, and ranges in width from 76 feet (23 m) to 400 feet (122 m). The river descends 1,900 feet (580 m) over 275 miles (443 km) and has an average gradient of 8 feet/mile (1.6 m/km) (Stevens 1983).

Prior to the construction of Glen Canyon Dam, the mean annual maximum discharge recorded at the U. S. Geological Survey gaging site at Bright Angel Creek was 86,000 ft^3/s (2,434 m^3/s) and the average sediment load was 1,250 parts per million (PPM) (Table 1.1). During the post-dam period the mean annual maximum discharge decreased to 28,000 ft^3/s (784 m^3/s) and the average sediment load ~~decreased~~ to 350 PPM. This corresponds to roughly a three-fold decrease in both categories. The maximum discharges during the pre-dam period were 300,000 ft^3/s (8,400 m^3/s) in 1884 and 200,000

ft^3/s (5,600 m^3/s) in 1921 (Table 1.1). The post-dam maximum discharge of 92,600 ft^3/s (2,593 m^3/s) occurred in 1983 during a high spring snowmelt, shortly after Lake Powell was filled in 1980.

Table 1.1

Discharge rates and sediment load data for the Colorado River in the Grand Canyon

	Pre-Dam	Post-Dam
Median Discharge - ft^3/s	8,200	12,800
(m^3/s)	(230)	(358)
Mean Annual Maximum Discharge - ft^3/s	86,000	28,000
(m^3/s)	(2,434)	(784)
10-Year Recurrence Interval Flood - ft^3/s	122,000	40,000
(m^3/s)	(3,416)	(1,120)
Maximum Flood on Record - ft^3/s	200,000	92,600
(m^3/s)	(5,600)	(2,593)
Sediment Load - PPM	1,250	350

Source: Dolan et al. (1977), based on U. S. Geological Survey records, gaging station #9-4025, Colorado River Near Grand Canyon.

Study Sites. The Colorado River in the Grand Canyon was chosen as the study site because of the availability of high quality data from recent studies conducted on the impact of Glen Canyon Dam on resources of the Colorado River. Also a comparison of the effects of Glen Canyon Dam on rapid stability with the effects of Flaming Gorge Dam on rapid stability in the Green River (Graf 1979, 1980) could be made. I analyzed rapids along a 35 mile (56 km) reach of the Colorado River from its confluence with the Little Colorado River (River Mile 62) to Hermit Rapids (River Mile 95) (Figure 1.5). "River Mile" refers to the number of miles below Lee's Ferry that the rapid is located. The following rapids were examined; Lava Canyon, Tanner Canyon, Escalante, Nevills, Hance, Sockdolager, Grapevine, Bright Angel, Pipe Springs, Granite, and Hermit. These rapids were chosen because they are accessible from established hiking trails from the South Rim of the Grand Canyon.

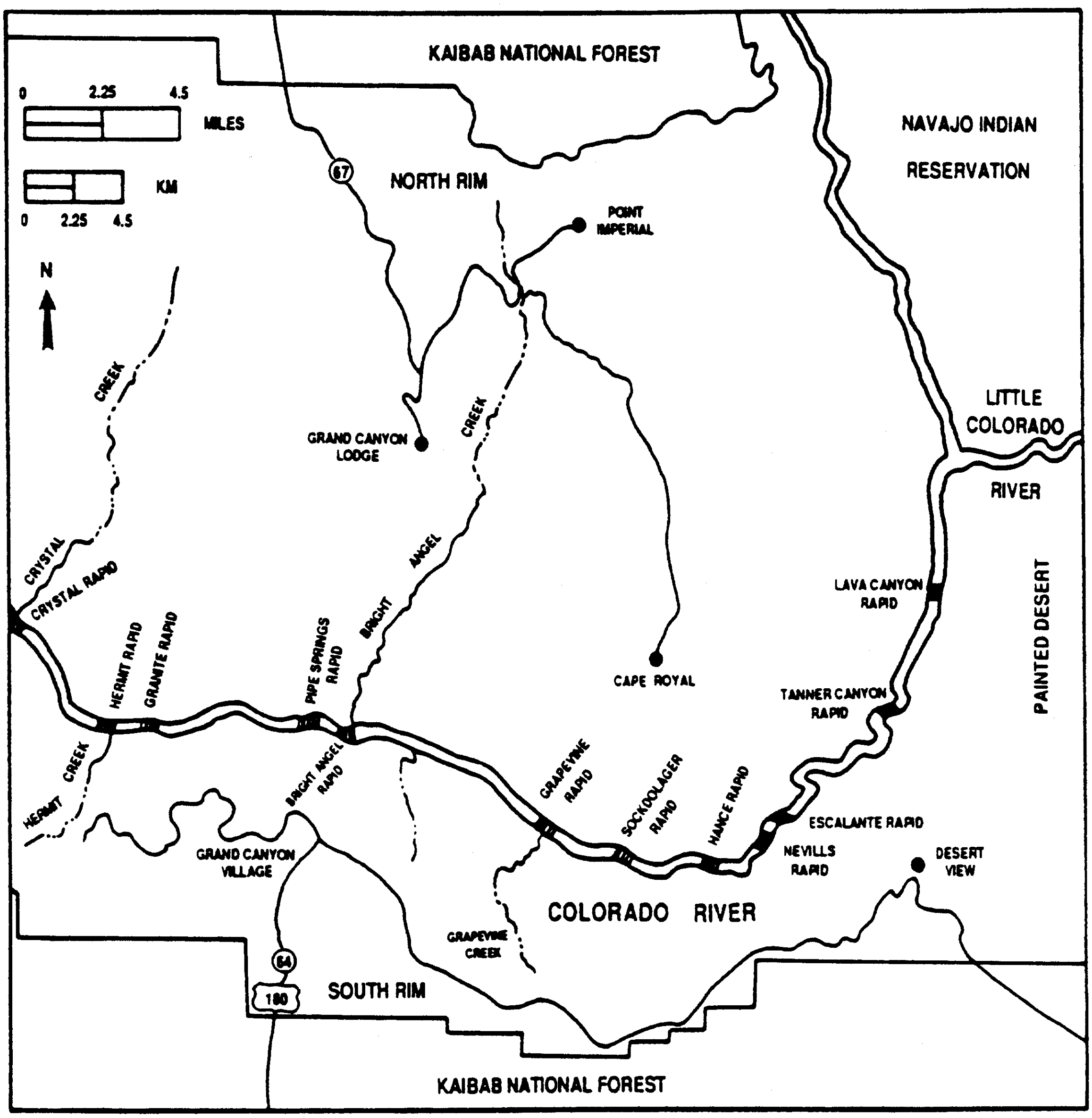

Figure 1.5. Location of the study rapids in Grand Canyon National Park (Redrawn from Hoffman 1987).

CHAPTER II. RESEARCH METHODOLOGY

Rapids

Rapids are significant geomorphic features in the Colorado River. They account for only 10% of the river's distance but nearly 50% of the 2,200 foot (671 m) drop in elevation between Lee's Ferry and Lake Mead (Leopold 1965). Rapid rating is related to the elevation drop or gradient of the river through the channel constriction (Table 2.1). In general, as elevation drop through the rapid increases, the rating or difficulty of the rapid tends to increase (Figure 2.1). Rapids increase in severity when channel gradient is increased by deposition of material during debris flows. Obstructions in the channel (large boulders) and channel discharge also influence the navigational difficulty of a rapid.

For the purpose of this study a rapid is considered to be an accumulation of boulders in the channel which break the water surface elevation at mean annual discharge and increases channel gradient and velocity. Rapids in the Grand Canyon occur primarily at channel constrictions caused by debris fans deposited by tributaries (Figures 2.2 and 2.3). During flash floods or debris flows, boulders a few

Table 2.1.

Characteristics of major rapids in the Colorado River from Lee´s Ferry to Diamond Creek

Rapid	River Mile	Rating	Vertical Drop (Feet)
Badger	7.8	7	15
Soap Creek	11.2	8	17
Sheer Wall	14.4	7	8
House Rock	17.0	7	10
Tanner Wash	24.5	8	9
Unkar	72.4	10	25
Nevills	75.2	6	15
Hance	76.5	10	30
Sockdolager	78.6	8	19
Grapevine	81.5	10	18
Horn Creek	90.0	10	10
Granite	93.5	9	17
Hermit	95.0	9	15
Boucher	96.2	6	13
Crystal	99.3	10	17
Walthenburg	112.0	6	15
Deubendorff	131.8	7	15
Upset	149.9	7	15
Lava Falls	179.2	10	37
Diamond Creek	225.6	5	25

Source: Hamblin and Rigby (1968, 1969)

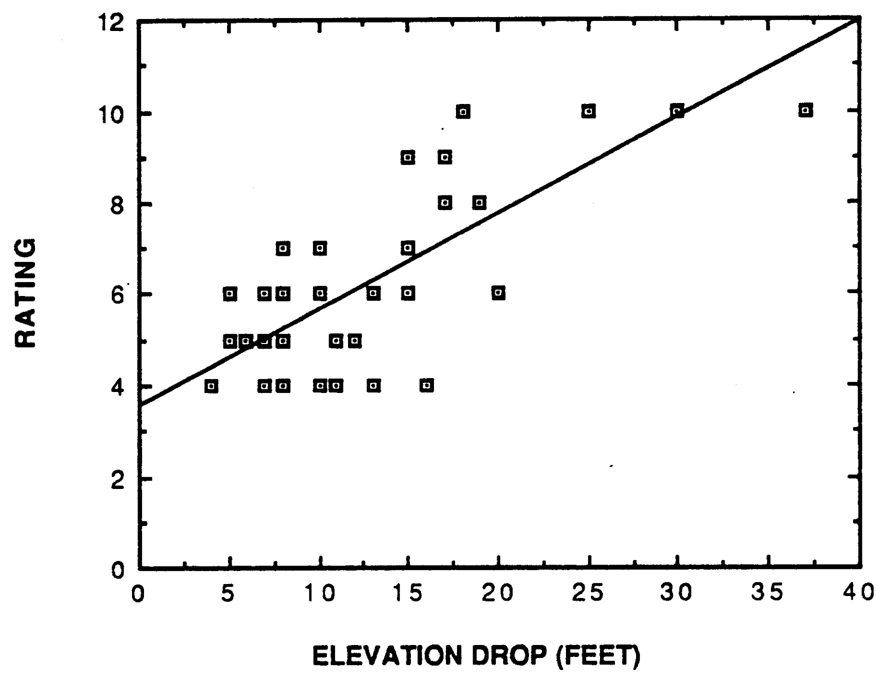

Figure 2.1. Relationship between drop in elevation and rating of rapids in the Grand Canyon (Data from Stevens 1983).

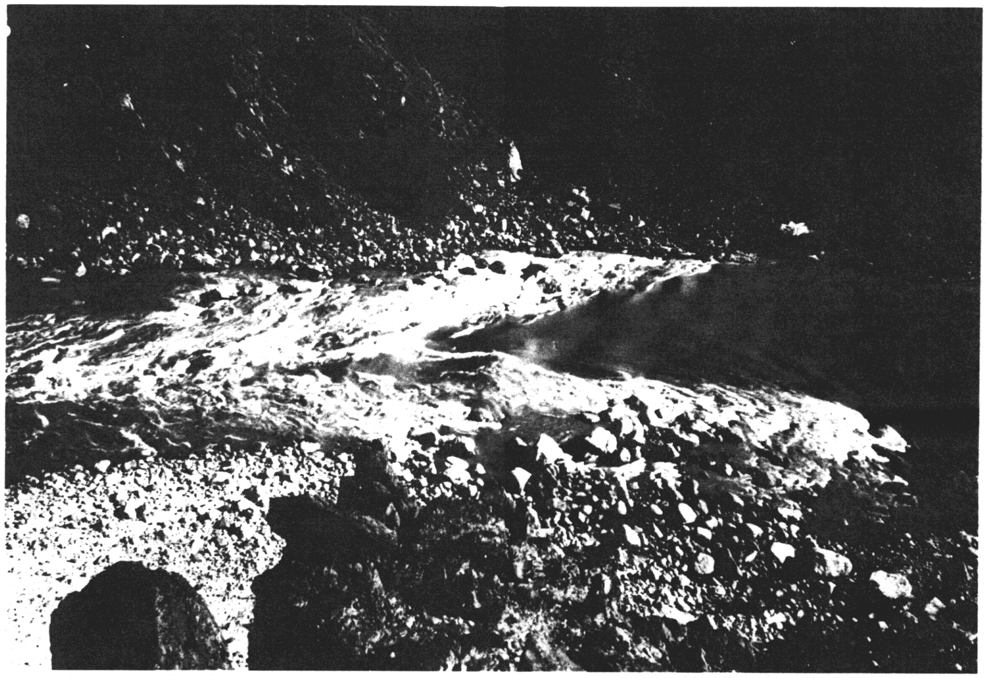

Figure 2.2. Granite Rapids, River Mile 93.5, channel constriction caused by debris fan.

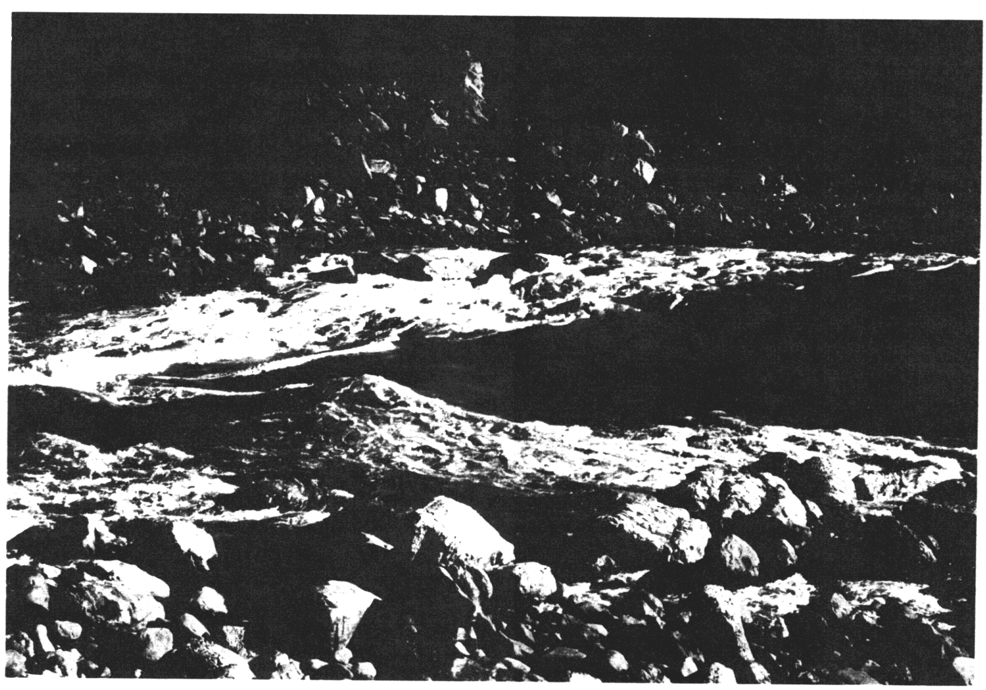

Figure 2.3. Granite Rapids, River Mile 93.5, close up of constriction and waves.

meters in diameter are capable of being transported and deposited on the debris fans causing a constriction in the channel and an increase in channel gradient. Webb et al. (1987, 1988) discussed the role which debris flows play in forming and maintaining rapids in the Grand Canyon. Kieffer (1985, 1987b) proposed a model for the formation and evolution of a rapid following the emplacement of a debris fan (Figure 2.4). The diagram shows the series of stages through which a rapid progresses following the emplacement of a new debris fan by a debris flow.

Rapid Stability

Two primary forces act upon flowing water in a channel; gravity, which acts in a downslope direction to move water, and friction, which opposes downslope motion. According to Knighton (1984), it is the relationship between gravity and friction that determines the capability of flowing water to erode and transport sediment. Techniques used to estimate sediment transport rates compare the force of flowing water to the resistance of particles to the flow. The ratio of force to resistance functions as a threshold, with sediment transport occurring when force is greater than resistance. In the present study, I calculated rapid stability for two different particle sizes found on the debris fans. The first analysis is for the largest boulders (d_{max}) which are often 10 to 15 feet (3 to 4.6 meters) in diameter. These boulders are significant since they occupy a large section

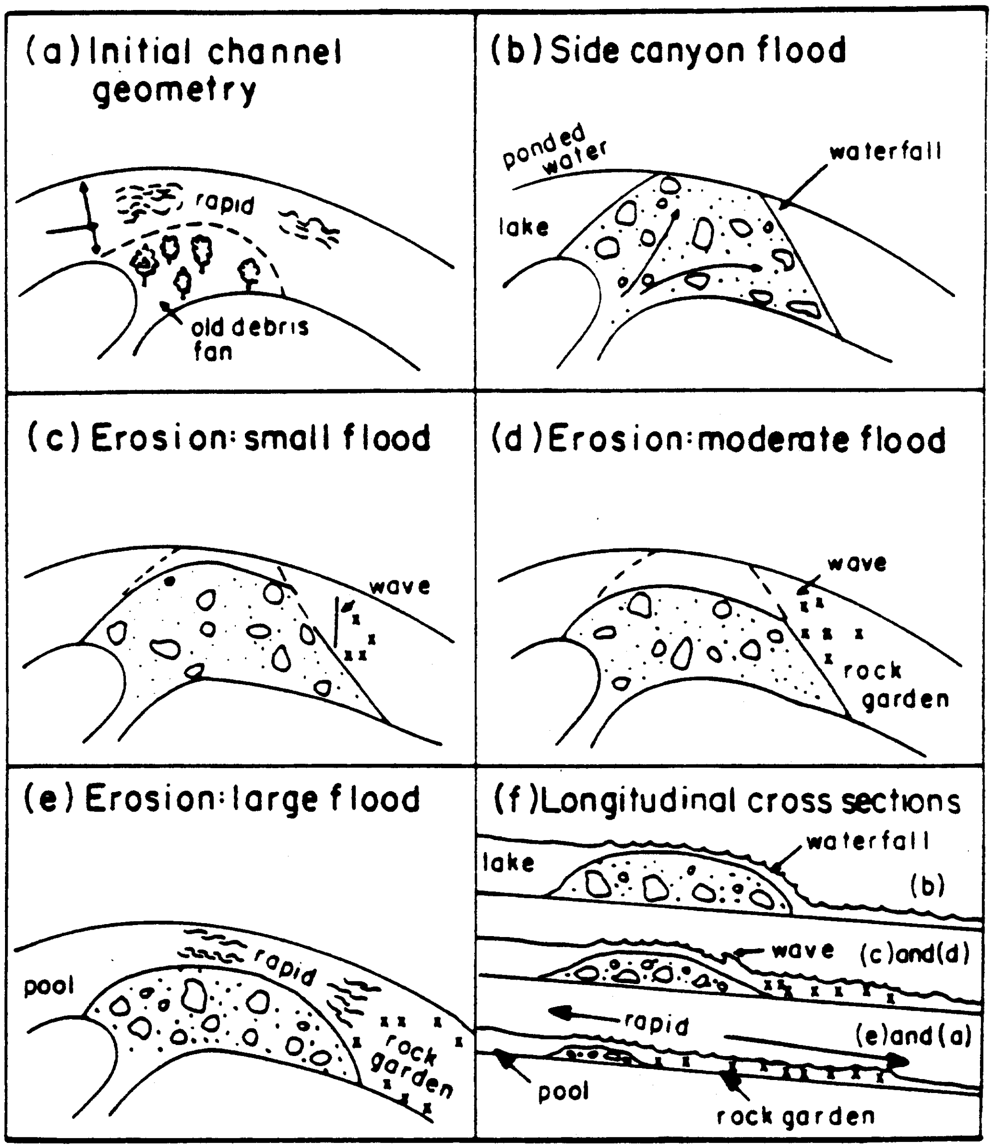

Figure 2.4. Formation and evolution of a rapid following the emplacement of a debris fan by a debris flow (From Kieffer 1987b).

of the channel and influence flow dynamics of the rapids. The second analysis is for the mean particle size (d_{50}) found on the debris fans. These boulders are typically 1.5 to 3 feet (0.5 to 1.0 meters) in diameter and are more likely to be transported during floods.

Analysis of the Largest Boulders

Calculation of rapid stability for the largest boulder at each rapid was determined by using a force/resistance stability ratio (Figure 2.5). This technique estimates values of the resistance of the largest boulder on the debris fan, the force of flowing water acting upon the boulder, and a ratio of force to resistance to determine rapid stability. When force exceeds resistance (f/r ratio greater than 1.0), the boulder is capable of being transported, and the rapid is considered unstable. However, if resistance is greater than the force (f/r ratio less than 1.0), the boulder is immobile, and the rapid is considered stable.

The equations used to determine force, resistance, and rapid stability, reproduced from Graf (1980), are outlined in Figure 2.5. The following variables are necessary to determine force and resistance; discharge values (Q), channel roughness (Manning's "n" value), channel width (W), channel gradient (S), boulder density (Y_s), boulder dimensions (height (d_1), width (d_2), and length (d_3)), acceleration of gravity (g), density of water (Y_f), and a

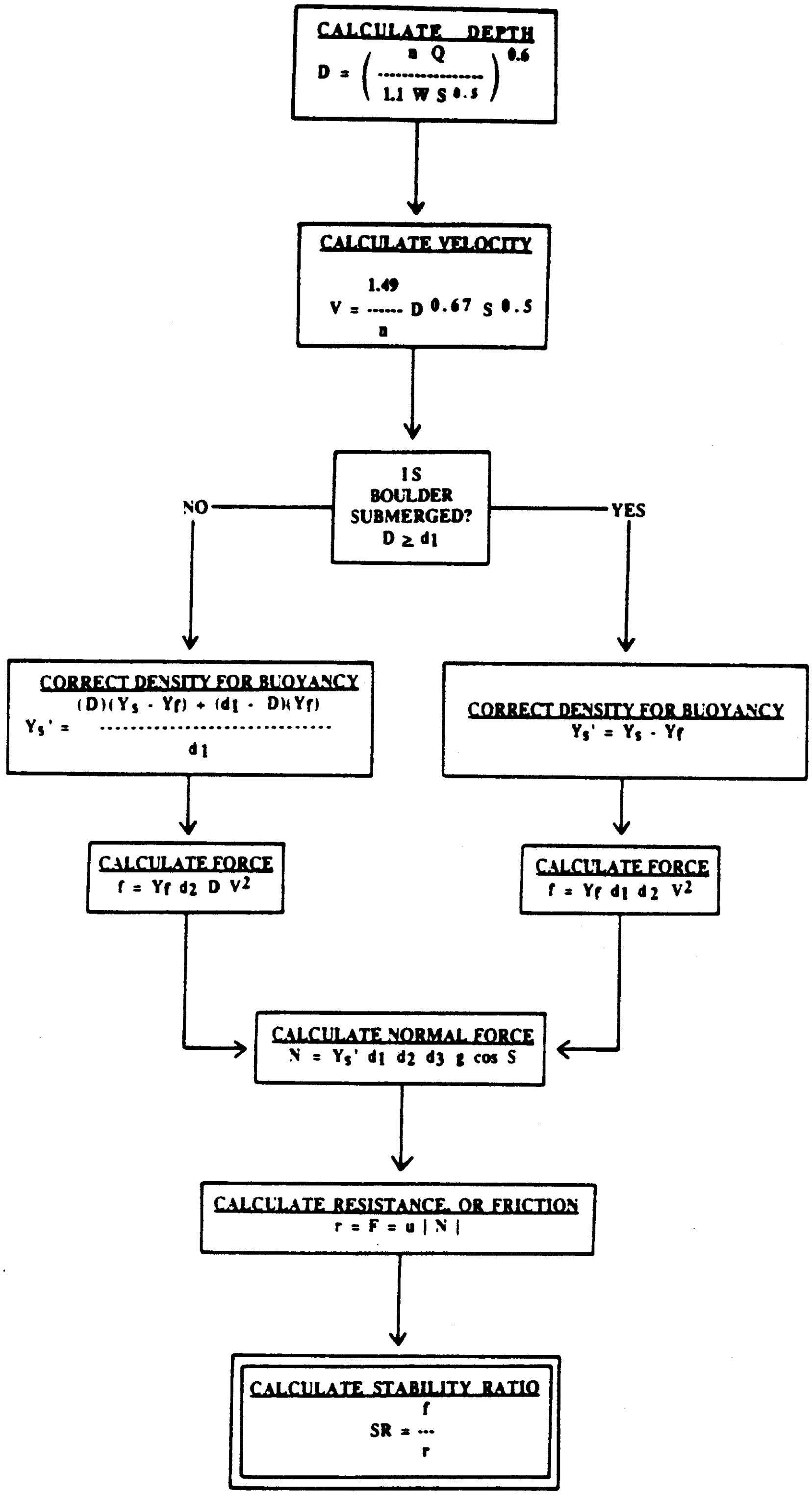

Figure 2.5. Flowchart used to calculate the f/r stability ratio (From Graf 1980).

coefficient of friction (u). Channel depth (D) and velocity (V) were calculated using a form of the Manning equation and measured in feet and feet per second. Next, the density of the boulder was corrected for effects of buoyancy (Y_s') related to the relationship between depth of flow and boulder height. The force of flowing water exerted on the boulder (f) was calculated as the product of the density of the water, the upstream submerged cross sectional area of the boulder, and the velocity of flow. Resistance of the boulder to the force of flowing water (r) was calculated as the product of the normal force of the boulder on the channel bed and the friction of the boulder resting upon the surface. Rapid stability or the stability ratio (SR) was then determined by the ratio of the force of flowing water to the resistance of the boulder to the flow.

Analysis of Mean Particle Size

Rapid stability was also determined for the mean particle size (d_{50}) found on the debris fans. These boulders, which were measured along their "b" or intermediate axis, ranged in size from 10 to 60 inches (250 to 1,524 mm). A more detailed discussion of the sampling procedure used to calculate the mean particle size is found in the "Data Collection" section. Comparison of tractive force and critical tractive force was used to determine mobility of these particles. Tractive force, similar to shear stress, is the friction exerted on the bed of a channel by flowing water. When this value is compared to critical tractive force, which is the force required to move a particle of a given size, an erosion threshold can be determined. When tractive force is greater than critical tractive force, the particle is capable of being transported, and the rapid is considered unstable. When tractive force is less than critical tractive force, the particle is immobile, and the rapid is considered stable.

Equations 2.1 and 2.2 were used to determine tractive force (TF) and critical tractive force (CTF).

$$\text{(2.1)} \qquad TF = \gamma R S$$

$$\text{(2.2)} \qquad CTF = 0.06\ g\ (Y_s - Y_f)\ d_{50}$$

Data needed for input include the specific weight of water (γ), the hydraulic radius (R) of the channel (D or channel depth is substituted for this value), channel slope (S), acceleration of gravity (g), density of the particle (Y_s), density of water (Y_f), and the mean particle size (d_{50}). Tractive force and critical tractive force were computed for each rapid for various discharge levels and then compared to determine rapid stability.

Data Collection

Channel Discharge (Q). The flow history of the Colorado River in the Grand Canyon can be separated into three phases (U. S. Department of the Interior 1988); Phase I, the pre-dam period prior to 1963, Phase II, the filling period, which occurred during the filling of Lake Powell from 1963 to 1980, and Phase III, the post-filling period, 1980 to the present. In this study, these phases are referred to as the pre-dam, filling, and post-filling periods respectively. Since the filling of Lake Powell in 1980, there is a greater probability of discharges greater than 31,500 ft^3/s (892 m^3/s) (the maximum discharge for power generation) occurring since the flood storage capacity of the reservoir has decreased. An increase in the mean annual maximum discharge during the post-filling period has occurred due to this decrease in storage capacity as well as changes in climatic controls (Figure 2.6). During the filling period discharges above the capacity of the penstocks of Glen Canyon Dam (31,500 ft^3/s or 892 m^3/s) occurred during four of eighteen years. However, during the post-filling period discharges above this level occurred during four of six years for which data were available.

The discharge (Q) values used in the analysis of rapid stability are the pre-dam mean annual maximum discharge, 86,000 ft^3/s (2,434 m^3/s), the filling period mean annual maximum discharge, 25,000 ft^3/s (708 m^3/s), and the post-filling period mean annual maximum discharge, 36,000 ft^3/s (1,020 m^3/s) (U. S. Geological Survey 1960-86). Analysis using the post-filling period mean annual maximum discharge was included to determine possible changes in rapid stability as a result of dam operations.

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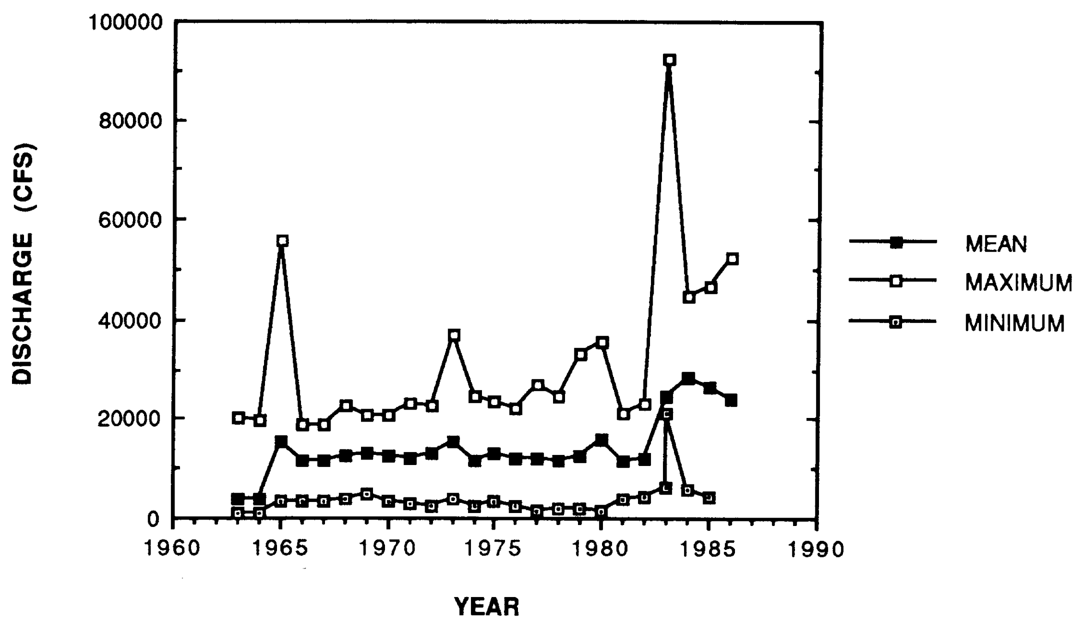


Figure 2.6. Change in annual channel discharge values for the Colorado River in the Grand Canyon (Based on data from U. S. Geological Survey gaging station #9-4025, Colorado River near Grand Canyon).

The discharge values were derived from data for U. S. Geological Survey gaging station #9-4025, Colorado River near Grand Canyon, Arizona. It is located 0.25 miles (0.40 km) upstream of Bright Angel Creek on the right bank of the Colorado River.

Channel Roughness (n). Channel roughness or Manning's "n" value is a dimensionless value designed to describe channel roughness. It ranges from 0.00 to 0.10 depending upon the nature of the boundary through which water is flowing (Table 2.2). Factors affecting Manning's roughness coefficient include surface roughness (size and shape of the grains) and channel vegetation. In general, fine grains result in a low "n" value while coarse grains result in a high "n" value (Chow 1959). Vegetation type, density, distribution, and height also influence the "n" value although not to a great extent at the rapids in the Grand Canyon. The roughness coefficient was estimated in the field using guides to estimating roughness values in natural channels (Barnes 1947; Chow 1959). These guides are particularly useful as they provide photographs of various rivers with different particle sizes and calculated "n" values that can be compared to the river which is being investigated. In the guides, rivers with boulders similar to those found on the debris fans had "n" values from 0.051 to 0.079. Since the boulders on the debris fans were on the

Table 2.2

Manning Roughness Coefficients for various surface boundaries

Surface Boundary	Manning Roughness, (n)
Smooth concrete	0.012
Vitrified clay	0.015
Shot concrete, untrowled, and earth channels in best condition	0.017
Straight unlined earth canals in fair condition - some growth	0.020
Alluvial channels, sand bed, no vegetation	
1. Lower regime	
Ripples	0.017-0.028
Dunes	0.018-0.035
2. Washed-out dunes or transition	0.014-0.024
3. Upper regime	
Plane bed	0.011-0.015
Standing waves	0.012-0.016
Antidunes	0.012-0.020
Winding natural streams and canals in poor condition - considerable moss growth	0.035
Mountain streams with no vegetation	
1. Bottom: gravels, cobbles, and few boulders	0.030-0.050
2. Bottom: cobbles with large boulders	0.040-0.070
Major Streams (flood stage width > 100 ft	
1. Regular section with no boulders or brush	0.025-0.060
2. Irregular and rough section	0.035-0.100

Sources: Chow (1959); Dunne and Leopold (1978) higher end of this scale, an "n" value of 0.08 was chosen and held constant for all rapids.

Channel Width (W). Channel width was measured for the three discharge values listed above. Width was measured in the field using a Brunton compass and triangulation. Width values for the present high water line and the pre-dam mean annual maximum discharge channel cross section were measured at each rapid. The pre-dam mean annual maximum discharge channel cross section is easily distinguished by the marked change in vegetation type that occurs along the channel sides between the OHWZ and the NHWZ (Figure 1.4). Channel width was also measured from aerial photographs taken at the three study discharge levels (Appendix III). The field calculations of channel width for the pre-dam mean annual maximum discharge were supported by width calculations from False Color Infrared aerial photographs (Appendix III) which showed the Old High Water Zone vegetation as a distinct band of red along the side of the channel.

Channel Gradient or Slope (S). Channel gradient at each rapid was measured in the field as well as from aerial photography. Channel gradient is calculated as the change in elevation over the distance of a measured channel reach. The change in elevation was measured from the head of the rapid where the channel is first constricted by the debris fan to the foot of the rapid where the last waves caused by the constriction occur (Figures 2.2 and 2.3). Elevational changes were measured over 90 foot (27.4 m) intervals using a telescopic aledaide and a stadia rod. Vertical height values are read off of a stadia rod using a telescopic aledaide which is an instrument similar to a telescope. This measures the elevation difference between point A and point B, the 90 foot (27.4 m) interval. Measurements were conducted along the present high water line. The total elevational change divided by the total horizontal distance of the rapid resulted in the channel gradient. Field calculations were verified with channel gradient values calculated from data for elevation drop from river runners guides (Hamblin and Rigby 1968, 1969; Stevens 1983) and rapid length measurements from aerial photographs (Appendix III). The two different techniques used to calculate gradient resulted in similar values and an average value was used for the final analysis (Table 2.3).

Boulder Dimensions (d_1, d_2, d_3). Boulder dimensions of height (d_1 or the a-axis), width (d_2 or the b-axis), and length (d_3 or the c-axis) were measured for the largest boulder on the debris fan of each rapid. There were three or four boulders on each debris fan that were considerably larger than the rest. These boulders are geomorphically significant since they occupy a large portion of the channel, influence channel flow, and are obstacles to river runners. They also effect the mobility of surrounding particles and may cause a localized accumulation of material

Table 2.3

Slope measurements for rapids in the Colorado River in the Grand Canyon

Rapid Name	Aerial Photography	Field Calculation	Average Slope
Lava Canyon	0.0071	0.0091	0.0081
Tanner Canyon	0.0285	0.0333	0.0309
Escalante	0.0117	0.0107	0.0112
Nevills	0.0233	0.0220	0.0227
Hance	0.0339	0.0441	0.0390
Sockdolager	0.0367	0.0264	0.0316
Grapevine	0.0272	0.0225	0.0249
Bright Angel	0.0222	0.0250	0.0236
Pipe Springs	0.0155	0.0136	0.0146
Granite	0.0262	0.0304	0.0283
Hermit	0.0210	0.0221	0.0216

which otherwise would not have occurred. The boulder that was closest to the middle of the channel and most accessible was chosen for analysis. By choosing the largest boulder on the debris fan, maximum values of force of flow for the main channel, boulder resistance, and rapid stability were calculated.

Boulder Density (Y_s). Density of the boulders was calculated by determining rock type in the field and then using *A Field Guide and Introduction to the Geology and*

Chemistry of Rocks and Minerals (Sorrell and Sandstrom 1973) to determine the density of the boulder. Geologic formations that were sources for the debris include the Kaibab Limestone, Toroweap Limestone, Coconino Sandstone, Redwall Limestone, Muav Limestone, Tapeats Sandstone, Bass Limestone, and Zoroaster Granite (Figure 1.2).

Mean Particle Size (d_{50}). Mean particle size of the boulders on the debris fans was measured for the "b" or intermediate axis of 50 boulders. The boulders ranged in size from 10 - 60 inches (250 - 1,524 mm). Measurements were taken every 15 feet (4.6 m) along a survey tape that was stretched across the daily high water line. The daily high water level is indicated by the marking of silt and mud on the boulders. This type of grid sampling (Kellerhals and Bray 1971) measures particles under the survey tape at regularly spaced sampling points. The boulder which was located directly below the survey tape was measured. If two sampling points fell on the same particle, the particle was counted twice. The mean of this sample (d_{50}) was calculated and used in the analysis of rapid stability using the mean particle size.

Constants (Y_f, u, g). Three variables were assumed to be constant during the study; Y_f, the density of the water, u, a coefficient of friction, and g, the acceleration of gravity. The density of water was assumed to be 1.15 gm/cm^3, a value for sediment-laden flood water. This value was chosen since the Colorado River in the study area often carries a suspended sediment load brought into the river by the Little Colorado River. The coefficient of friction, u, is a value which estimates the friction between the particle and the channel bottom and is related to the nature of the particle surface. The coefficient of friction value was held constant at 0.65 and based on values used in similar studies (Graf 1979, 1980). The acceleration of gravity, g, was assumed to be 9.81 m/s^2.

CHAPTER III. RESULTS

Introduction

The largest boulder (d_{max}) and the mean particle size (d_{50}) were used to calculate rapid stability for each rapid in the study area. The f/r stability ratio, which compares the force of flowing water (f) to the resistance of the largest boulder (r), indicates rapid stability when it is less than 1.0. For the mean particle size, ratios of tractive force to critical tractive force (TF/CTF) with values less than 1.0 also indicate rapid stability. The following chapter presents results for the at-a-site situation (which examines the effect of the change in discharge on the stability of an individual rapid) and for the downstream situation (which analyzes the change in rapid stability for the entire study reach). The chapter also addresses the effects of Glen Canyon Dam on rapid stability.

Analysis of the Largest Boulder

At-a-site. Values of force, resistance and the f/r stability ratio were calculated for individual rapids in the study area (Table 3.1). Plots of stability ratios for the largest boulders (f/r) and depth of flow (Figures 3.1 and 3.2) were used to determine rapid stability. The symbols

Table 3.1

Force/Resistance stability ratio data for rapids in the Grand Canyon

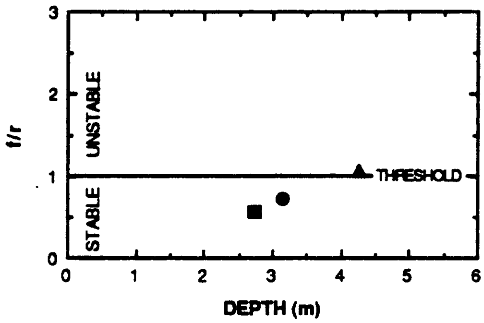
Rapid	Q (m^3/s)	D (m)	V (m/s)	f (N)	r (N)	f/r
Lava Canyon	708	2.74	3.29	85.71	152.84	0.561
Lava Canyon	1,020	3.15	3.61	111.23	155.72	0.714
Lava Canyon	2,434	4.24	4.42	165.99	155.72	1.066
Tanner Canyon	784	1.42	4.14	62.78	104.74	0.599
Tanner Canyon	1,020	1.64	4.55	87.68	107.86	0.813
Tanner Canyon	2,434	2.56	6.14	200.06	113.80	1.758
Escalante	784	2.61	3.75	105.61	151.05	0.699
Escalante	1,020	2.77	3.91	122.07	153.31	0.796
Escalante	2,434	4.16	5.12	223.40	155.71	1.435
Nevills	708	1.92	4.35	207.10	497.52	0.416
Nevills	1,020	2.15	4.69	269.55	497.52	0.542
Nevills	2,434	3.38	6.34	538.24	497.52	1.082
Hance	708	1.48	4.77	119.90	342.11	0.350
Hance	1,020	1.74	5.33	175.99	351.70	0.500
Hance	2,434	2.85	7.42	539.86	388.58	1.389
Sockdolager	708	2.05	5.36	199.15	240.02	0.830
Sockdolager	1,020	2.32	5.82	235.38	240.02	0.981
Sockdolager	2,434	3.49	7.65	405.82	240.02	1.691
Grapevine	708	2.49	5.42	267.23	317.74	0.841
Grapevine	1,020	2.83	5.90	317.50	317.74	0.999
Grapevine	2,434	4.23	7.72	542.94	317.74	1.709

Continued on next page

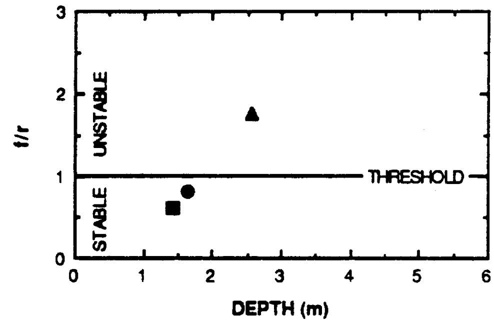
Table 3.1 -- Continued

Rapid	Q (m^3/s)	D (m)	V (m/s)	f (N)	r (N)	f/r
Bright Angel	708	2.38	5.11	364.61	598.69	0.609
Bright Angel	1,020	2.47	5.25	385.20	598.69	0.643
Bright Angel	2,434	3.36	6.44	580.44	598.69	0.970
Pipe Springs	708	2.74	4.42	61.01	73.65	0.828
Pipe Springs	1,020	3.27	4.97	77.10	73.65	1.047
Pipe Springs	2,434	4.45	6.12	116.54	73.65	1.582
Granite	708	1.99	4.96	456.30	777.60	0.587
Granite	1,020	2.34	5.54	578.77	780.94	0.741
Granite	2,434	3.82	7.69	1113.73	780.94	1.426
Hermit	708	2.33	4.29	219.47	247.92	0.885
Hermit	1,020	2.68	5.30	304.23	247.92	1.227
Hermit	2,434	4.28	7.25	598.70	247.92	2.415

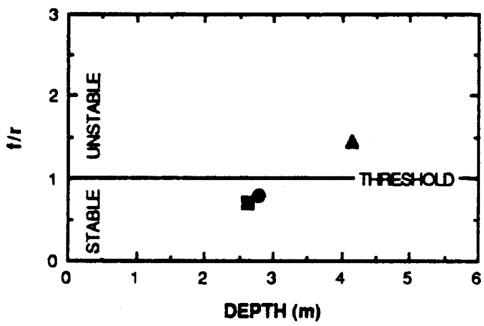
used on the graphs, ■, ●, ▲, correspond to the depths of flow for the filling period, post-filling period, and pre-dam discharges of 25,000 ft^3/s (708 m^3/s), 36,000 ft^3/s (1,020 m^3/s) and 86,000 ft^3/s (2,434 m^3/s) respectively. A f/r stability ratio less than 1.0 for any given discharge value plots below the threshold line indicating rapid stability. However, a f/r stability ratio greater than 1.0 plots above the threshold line indicating rapid instability.



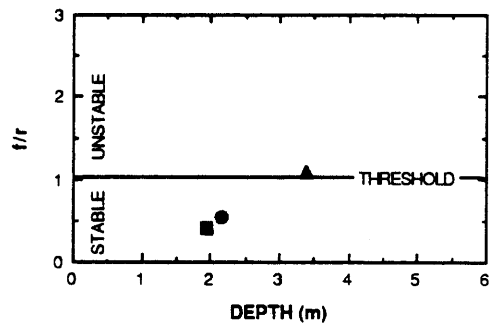
a. Lava Canyon Rapids Mile 65.4



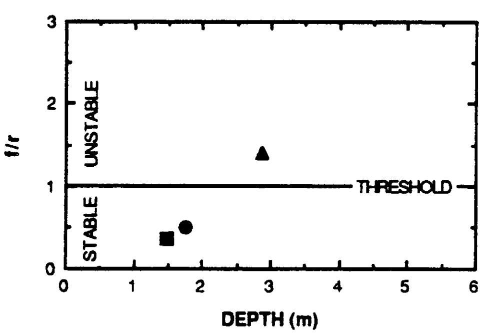
b. Tanner Canyon Rapids Mile 68.5



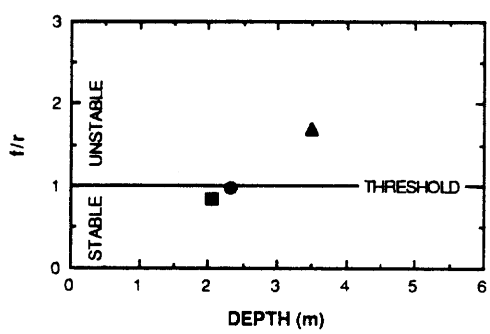
c. Escalante Rapids Mile 74.5



d. Nevills Rapids Mile 75.0

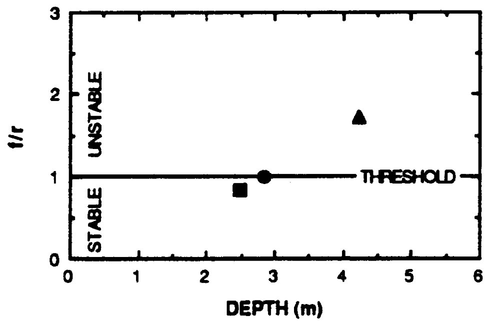


e. Hance Rapids Mile 75.6

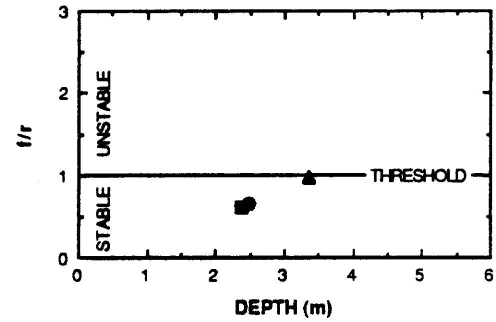


f. Sockdolager Rapids Mile 78.6

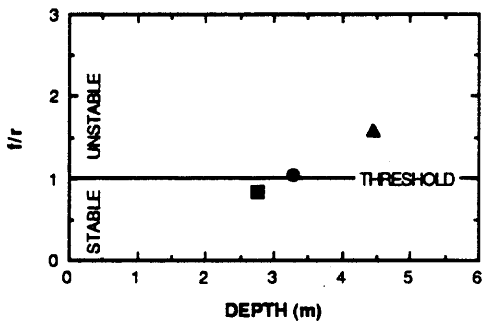
Figure 3.1. Force/Resistance stability ratios for the three study period discharges from Lava Canyon Rapids to Sockdolager Rapids. Values less than 1.0 indicate rapid stability. Values greater than 1.0 indicate rapid instability. ■ = filling period, ● = post-filling period, and ▲ = pre-dam period.



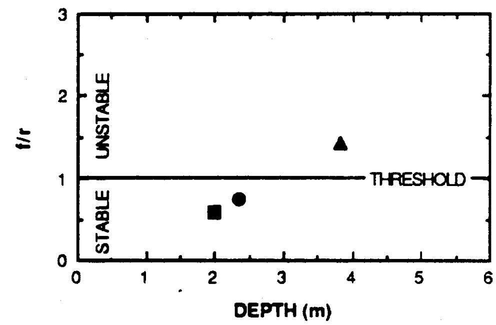
a) Grapevine Rapids Mile 81.5



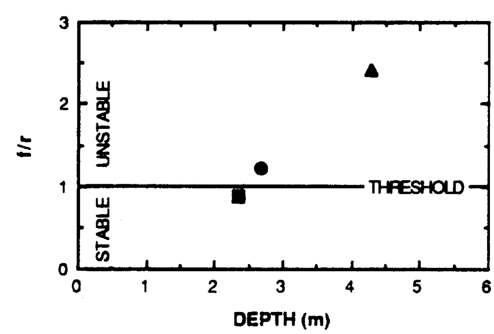
b) Bright Angel Rapids Mile 87.5



c) Pipe Springs Rapids Mile 89.0



d) Granite Rapids Mile 93.5



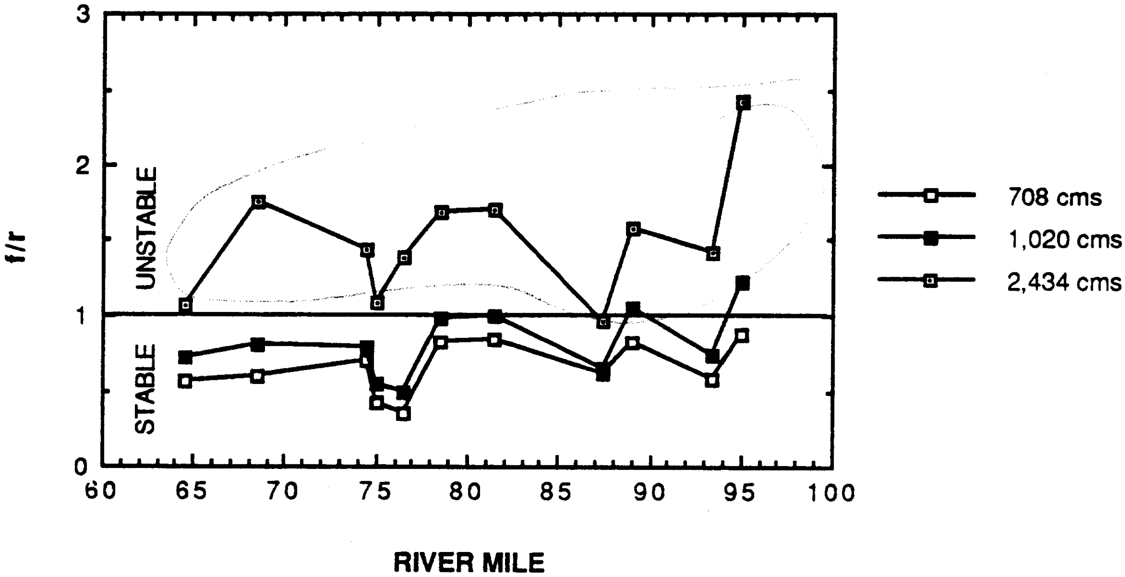
e) Hermit Rapids Mile 95.0

Figure 3.2. Force/Resistance stability ratios for the three study period discharges from Grapevine Rapids to Hermit Rapids. Values less than 1.0 indicate rapid stability. Values greater than 1.0 indicate rapid instability. ■ = filling period, ● = post-filling period, and ▲ = pre-dam period.

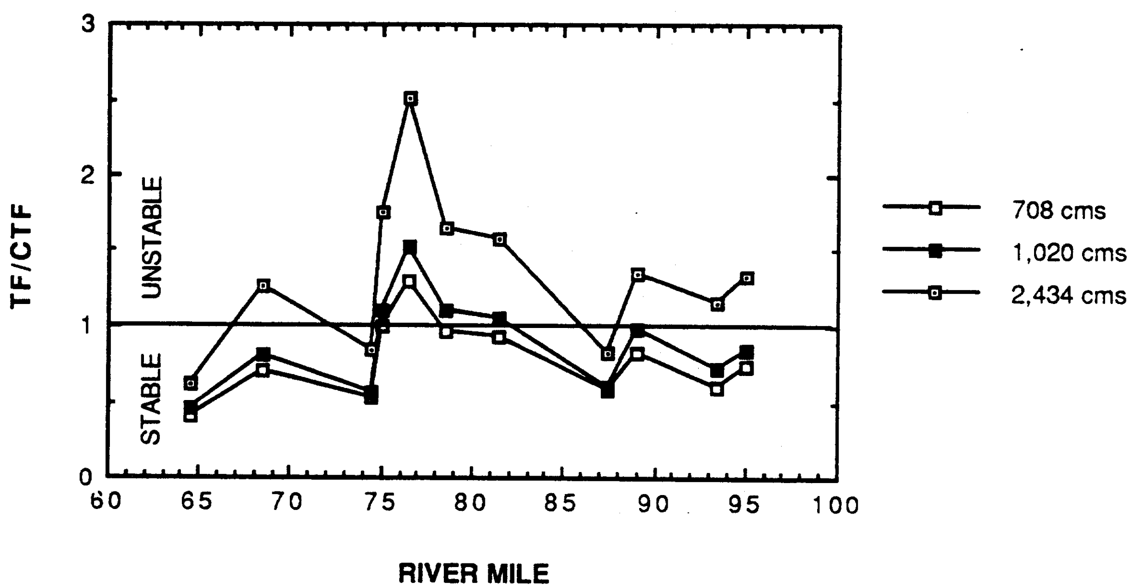
Hance Rapids (Figure 3.1 (e)) is representative of the eight rapids that were unstable during the pre-dam period and stable during the filling and post-filling periods. Hance Rapids had a f/r ratio of 0.350 for the filling period and 0.500 for the post-filling period. However, during the pre-dam period the rapid had a f/r ratio of 1.389, well above the threshold indicating rapid instability. Thus, the rapid crossed over the threshold and changed from being an unstable geomorphic feature to a stable one. Lava Canyon, Tanner Canyon, Nevills, Escalante, Sockdolager, Grapevine, and Granite Rapids also exhibit this same temporal pattern of rapid stability.

Pipe Springs and Hermit Rapids (Figure 3.2 (c) and (e)) experienced instability during the pre-dam period, stability during the filling period, and instability during the post-filling period. Only Bright Angel Rapids (Figure 3.2 (b)), remained stable during all three periods.

Downstream. Values of force, resistance, and the f/r ratio were also examined for the entire length of the study reach. Values of f/r plotted for each rapid indicates rapid stability or instability (Figure 3.3 (a)). "River Mile" refers to the number of miles the rapid is located downstream from Lee´s Ferry. The total number and percentage of rapids that were stable and unstable at the three discharge levels were also calculated (Table 3.2).



a) f/r stability ratio analysis



b) TF/CTF stability ratio analysis

Figure 3.3. Downstream rapid stability for rapids in the Grand Canyon.

Table 3.2

Rapid stability using the largest boulders on the debris fans of rapids in the Grand Canyon

Discharge (m^3/s)	Stable (Total)	Stable (%)	Unstable (Total)	Unstable (%)
708	11	100.0	0	0.0
1,020	9	81.8	2	18.2
2,434	1	9.1	10	90.9

During the pre-dam period, only one of the eleven rapids (9.1%) had a f/r ratio less than 1.0 indicating rapid stability. However, during the filling period, all eleven rapids (100%) had f/r ratios less than 1.0. An increase of 90.9% in rapid stability occurred from the pre-dam period to the filling period. During the post-filling period, when the mean annual maximum discharge increased to 36,000 ft^3/s (1,020 m^3/s), Pipe Springs and Hermit Rapids became unstable while Sockdolager (f/r = 0.981) and Grapevine Rapids (f/r = 0.999) bordered on instability. Thus, during the post-filling period, nine or 81.8% of the rapids were stable, which corresponds to a 18.2% decrease in the stability of the rapids from the filling period to the post-filling period. Overall, a 72.7% increase in rapid stability occurred from the pre-dam period to the post-filling period due to the decrease in discharge resulting from the operations of Glen Canyon Dam.

Analysis of the Mean Particle Size

At-a-site. Values of tractive force, critical tractive force, and the TF/CTF stability ratio were calculated for each rapid (Table 3.3). Plots of the TF/CTF stability ratios and depth of flow (Figures 3.4 and 3.5) were used to determine rapid stability. If the TF/CTF ratio for a rapid is less than 1.0 for any given discharge level, it plots below the threshold line indicating rapid stability. However, if the ratio is greater than 1.0, it plots above the threshold line and indicates rapid instability.

Hermit Rapids (Figure 3.5 (e) is representative of the four rapids that were unstable during the pre-dam period and stable during the filling and post-filling periods. Hermit Rapids had a TF/CTF ratio of 0.731 for the filling period and 0.840 for the post-filling period. However, during the pre-dam period, Hermit Rapids had a TF/CTF ratio of 1.341 which plotted above the threshold line indicating rapid instability. Tanner Canyon, Pipe Springs and Granite Rapids were also stable during both the filling and post-filling period but unstable during the pre-dam period.

Nevills, Sockdolager and Grapevine (Figures 3.4 (d) and (f) and Figure 3.5 (a)) changed from an unstable condition during the pre-dam period to a stable condition during the filling period and returned to an unstable condition during the post-filling period. In three cases, Lava Canyon,

Table 3.3

Tractive Force/Critical Tractive Force stability ratio data for rapids in the Grand Canyon

Rapid	Q (m^3/s)	D (m)	V (m/s)	TF	CTF	TF/CTF
Lava Canyon	708	2.74	3.29	217.58	551.40	0.395
Lava Canyon	1,020	3.15	3.61	250.06	551.40	0.454
Lava Canyon	2,434	4.24	4.42	337.13	551.40	0.611
Tanner Canyon	784	1.42	4.14	429.65	611.55	0.703
Tanner Canyon	1,020	1.64	4.55	495.59	611.55	0.810
Tanner Canyon	2,434	2.56	6.14	774.90	611.55	1.267
Escalante	784	2.61	3.75	286.40	541.37	0.529
Escalante	1,020	2.77	3.91	304.68	541.37	0.563
Escalante	2,434	4.16	5.12	456.84	541.37	0.844
Nevills	708	1.92	4.35	428.16	430.74	0.994
Nevills	1,020	2.15	4.69	479.20	430.74	1.113
Nevills	2,434	3.38	6.34	751.98	430.74	1.746
Hance	708	1.48	4.77	564.45	435.65	1.296
Hance	1,020	1.74	5.33	665.04	435.65	1.527
Hance	2,434	2.85	7.42	1090.31	435.65	2.503
Sockdolager	708	2.05	5.36	635.55	655.47	0.970
Sockdolager	1,020	2.32	5.82	719.97	655.47	1.098
Sockdolager	2,434	3.49	7.65	1081.10	655.47	1.649
Grapevine	708	2.49	5.42	608.22	655.47	0.928
Grapevine	1,020	2.83	5.90	691.71	655.47	1.055
Grapevine	2,434	4.23	7.72	1032.30	655.47	1.575

Continued on next page

Table 3.3 -- Continued

Rapid	Q (m^3/s)	D (m)	V (m/s)	TF	CTF	TF/CTF
Bright Angel	708	2.38	5.11	549.60	947.92	0.580
Bright Angel	1,020	2.47	5.25	572.60	947.92	0.604
Bright Angel	2,434	3.36	6.44	777.57	598.69	0.820
Pipe Springs	708	2.74	4.42	392.70	473.34	0.830
Pipe Springs	1,020	3.27	4.97	467.61	473.34	0.988
Pipe Springs	2,434	4.45	6.12	636.49	476.34	1.345
Granite	708	1.99	4.96	551.34	911.40	0.605
Granite	1,020	2.34	5.54	650.23	911.40	0.713
Granite	2,434	3.82	7.69	1059.77	911.40	1.163
Hermit	708	2.33	4.29	494.10	676.20	0.731
Hermit	1,020	2.68	5.30	568.11	676.20	0.840
Hermit	2,434	4.28	7.25	906.91	676.20	1.341

Escalante, and Bright Angel Rapids (Figure 3.4 (a) and (c) and Figure 3.5 (b)), the rapids were stable during all three discharge periods. Only one rapid, Hance Rapids (Figure 3.4 (e)), was unstable during all three discharge periods.

Downstream. Values for tractive force, critical tractive force, and the TF/CTF stability ratio were examined for the entire group of rapids in the downstream direction. Values of the TF/CTF stability ratio for each rapid indicated whether the rapid was stable or unstable. (Figure 3.3 (b)). Rapids with a TF/CTF ratio less than 1.0 were

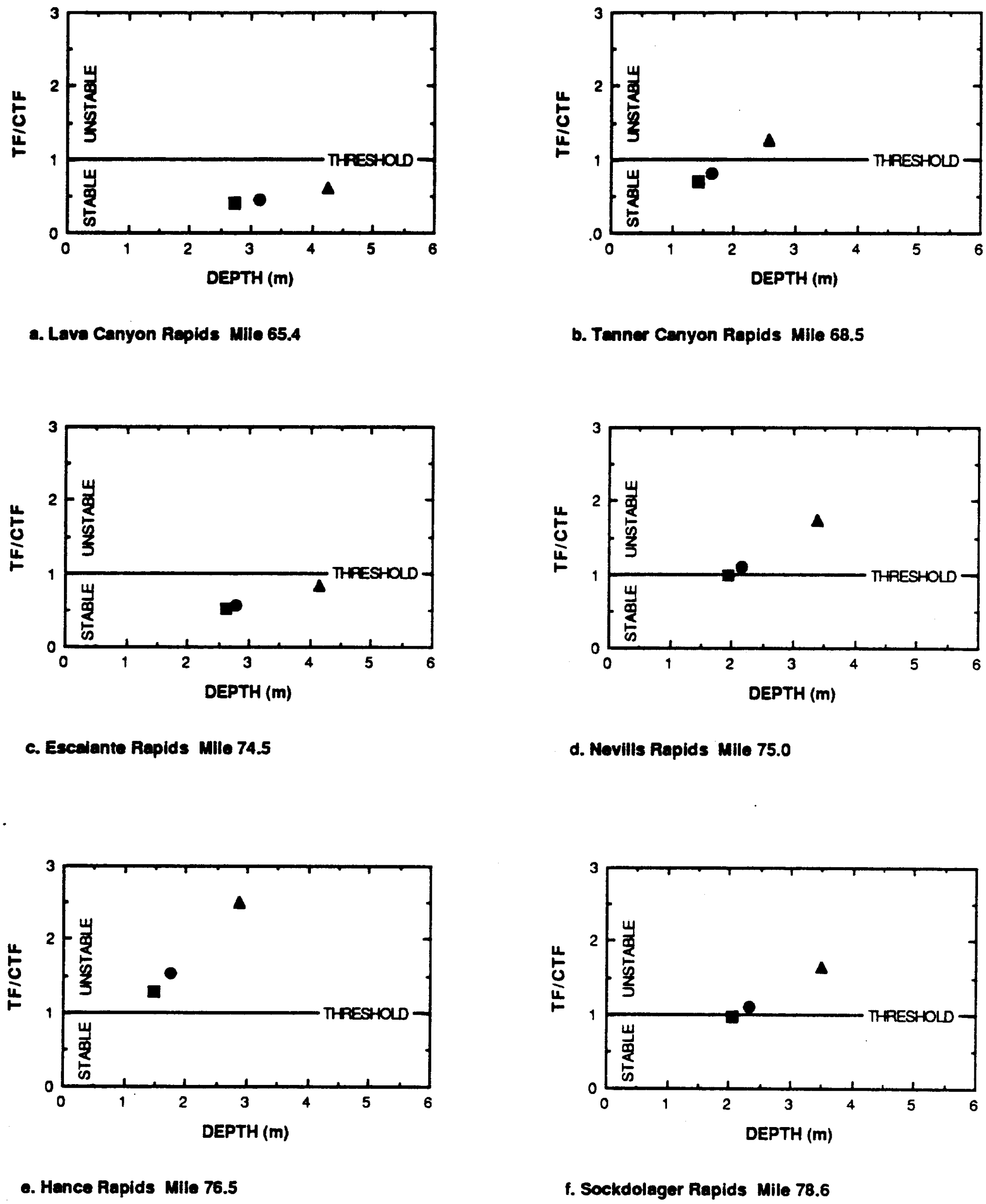


Figure 3.4. Tractive Force/Critical Tractive Force stability ratios for the three study period discharges from Lava Canyon Rapids to Sockdolager Rapids. Values less than 1.0 indicate rapid stability. Values greater than 1.0 indicate rapid instability. ■ = filling period, ● = post-filling period, and ▲ = pre-dam period.

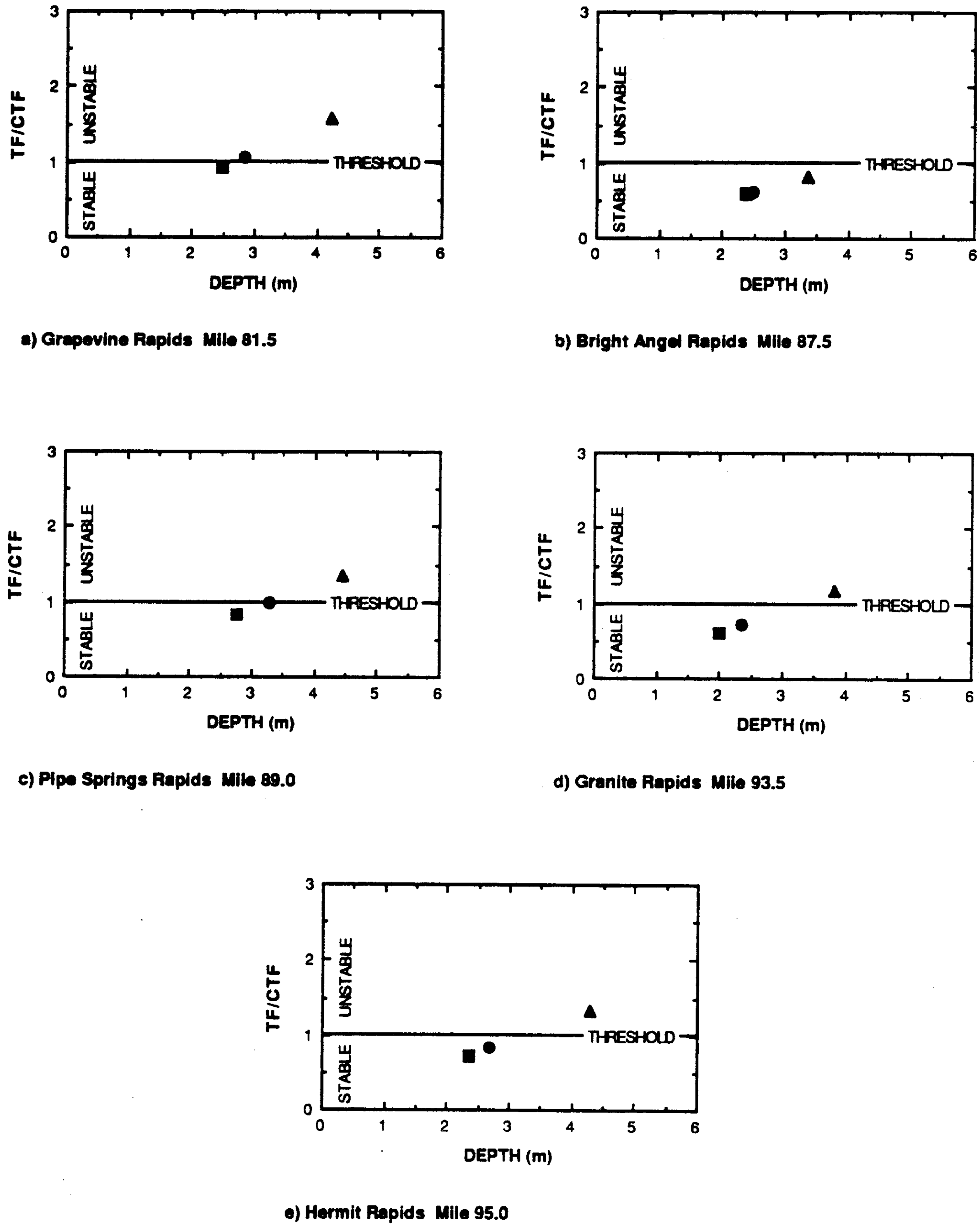


Figure 3.5. Tractive Force/Critical Tractive Force stability ratios for the three study period discharges from Grapevine Rapids to Hermit Rapids. Values less than 1.0 indicate rapid stability. Values greater than 1.0 indicate rapid instability. ■ = filling period, ● = post-filling period, and ▲ = pre-dam period.

considered stable and plotted below the threshold line while rapids with a TF/CTF ratio greater than 1.0 plotted above the line and were considered unstable. The total number and percentage of rapids that were stable and unstable at the three discharge levels were also calculated (Table 3.4).

Table 3.4

Rapid stability for the mean particle size on the debris fans of rapids in the Grand Canyon

Discharge (m^3/s)	Stable (Total)	Stable (%)	Unstable (Total)	Unstable (%)
708	10	90.9	1	9.1
1,020	7	64.6	4	35.4
2,434	3	27.3	8	72.7

During the pre-dam period, eight of the eleven rapids in the study area had TF/CTF ratios greater than 1.0 indicating rapid instability. Three rapids, Lava Canyon, Escalante, and Bright Angel Rapids, had TF/CTF ratios less than 1.0 indicating rapid stability. Therefore, 27.3% of the rapids in the study area were stable during the pre-dam period. During the filling period ten of the eleven rapids, or 90.9% were stable with only Hance Rapids (TF/CTF = 1.296) being unstable. This results in a 63.6% increase in the stability of rapids in the study area from the pre-dam period to the filling period. During the post-filling period, when the mean annual maximum discharge increased to 36,000 ft³/s (1,020 m³/s), seven or 64.6% of the rapids were stable and four or 35.4% were unstable. Therefore, a 26.3% decrease in the stability of rapids occurred from the filling period to the post-filling period. Overall, when considering the mean particle size (d_{50}), a 37.3% increase in the stability of rapids occurred from the pre-dam period to the post-filling period due to the decrease in discharge from Glen Canyon Dam.

Comparison of the f/r and TF/CTF Stability Techniques

Rapid stability was based upon the immobility of boulders on the debris fans. In general, as particle size increases, the discharge needed to initiate particle movement also increases. From this relationship it would be expected that the largest boulders on the debris fans would be more stable than the mean particle size boulders during any given discharge event. Two techniques were used to determine rapid stability; the f/r stability ratio which determined rapid stability by the immobility of the largest boulders (d_{max}) on the debris fan and the TF/CTF stability ratio which determined rapid stability by the immobility of the mean particle size (d_{50}) boulders on the debris fan. Differences in particle mobility can be discerned from these two techniques.

Comparison of the results of the two techniques indicate that the largest boulders were indeed more stable than the mean particle size during the three discharge values used in the analysis (Table 3.5).

Table 3.5

Comparison of the Force/Resistance and Tractive Force/Critical Tractive Force stability ratio techniques used to determine rapid stability

	f/r Stability Ratio		TF/CTF Stability Ratio	
Discharge (m^3/s)	Stable (Total)	Stable (%)	Stable (Total)	Stable (%)
708	11	100.0	10	90.9
1,020	9	81.8	7	64.6
2,434	1	9.1	3	27.3

This is important for two reasons. First, the largest boulders influence flow dynamic at the rapids and cause rapids that are obstacles to river runners. Second, the largest boulders also influence the mobility of surrounding particles. This may cause localized accumulation of smaller boulders that would normally be unstable.

CHAPTER IV. DISCUSSION

Interpretation of Results

The construction of Glen Canyon Dam has dramatically altered the natural environment of the Colorado River in the Grand Canyon. The main effects, a reduced discharge, a reduced sediment load, and a change in water temperature, have caused a series of complex responses throughout the river system. The full extent of these effects are now just beginning to be recognized and the resulting problems need to be addressed. The change in the flow regime of the Colorado River has affected several resources in the Grand Canyon, including white-water rapids.

The decrease in the mean annual maximum discharge from 86,000 ft^3/s (2,400 m^3/s) to 28,000 ft^3/s (790 m^3/s) due to the operations of Glen Canyon Dam has reduced the competence of the Colorado River to remove the larger boulders that accumulate on the debris fans of rapids. Tributary processes have not been affected by the dam and large quantities of material are still deposited on the debris fans during debris flows (Webb et al. 1987). With a reduction in the competence of the main stream and a continuing supply of material from the tributaries, the rapids will increase in navigational difficulty and severity with time.

The findings of this study support the hypothesis that an increase in the stability of the rapids as geomorphic features has occurred since the closure of Glen Canyon Dam. Calculations of rapid stability using the largest boulders and the mean particle size resulted in increases in rapid stability of 72.7% and 37.3%, respectively, from the pre-dam period to the post-filling period. As long as main stream processes are controlled by Glen Canyon Dam, further increases in the stability and severity of rapids can be expected.

Relationship to Previous Research

Research conducted by Webb et al. (1987, 1988) on the history of debris flows in tributaries of the Colorado River in the Grand Canyon and the effects of the 1984 debris flow in Monument Creek at Granite Rapids provide a better understanding of the role that debris flows play in supplying sediment to rapids. Debris flows are the dominant process by which boulders are transported to the rapids. The present study has shown an increase in rapid stability due to the reduced competence of the Colorado River resulting from the reduction in discharge due to the operations of Glen Canyon Dam. Rapid stability was based on the immobility of the largest boulders on the debris fans. Boulder dimensions were assumed constant for the three discharge periods used in the analysis and the study disregarded the input of new material from debris flows. However, the relatively frequent occurrence of debris flows in tributaries (Webb et al. 1987, 1988) will further increase the stability and severity of the rapids in the Grand Canyon unless discharges sufficient enough to move the boulders occur on the main stream.

Research on the hydraulics and configuration of rapids in the Grand Canyon by Kieffer (1985, 1987b) discussed the effects of Glen Canyon Dam on the transportation of boulders and erosion of debris fans. According to Kieffer (1987b) "The rapids will become steeper, rockier, and narrower, unless discharges adequate to remove the debris are permitted through the Canyon." Examination of the effects of the 1983 flood discharges of 92,000 ft^3/s (2,604 m^3/s) on the Crystal Rapids debris fan (Kieffer 1985) demonstrated that discharges of this magnitude are capable of eroding material being deposited on debris fans by debris flows. Results of the present research have shown a 90.9% increase in rapid stability from the pre-dam period to the filling period due to the reduction of the mean annual maximum discharge from 86,000 ft^3/s (2,434 m^3/s) to 25,000 ft^3/s (708 m^3/s). An increase in the mean annual maximum discharge during the post-filling period to 36,000 ft^3/s (1,020 m^3/s) resulted in a 18.2% decrease in rapid stability. The results of the present research as well as the work done by Kieffer (1985, 1987b) indicate that pre-dam magnitude floods may be desirable to remove the accumulating debris being deposited on the debris fans by debris flows, thus decreasing the severity of the rapids in the Grand Canyon. Further studies on the effects of flood discharges on erosion of debris fans should be conducted if discharges of pre-dam period magnitude occur in the future.

The results of this study can be compared with the results of Graf's research (1979, 1980) on the effects of Flaming Gorge Dam on the stability of rapids in the Green River in Lodore, Whirlpool, and Split Mountain Canyons. Prior to the completion of Flaming Gorge Dam in 1962, 62% of the rapids in the Green River study area were stable. During the post-dam period, 93% of the rapids were stable. This corresponds to a 31% increase in the stability of rapids, as measured by the immobility of the largest boulder at each rapid. Prior to the completion of Glen Canyon Dam, only 9.1% of the rapids in the Grand Canyon study area were considered stable. However, during the post-filling period, 81.8% of the rapids were stable, resulting in a 72.7% increase the stability of rapids following the closure of the Glen Canyon Dam.

Comparison of these results should take into account several differences. First, the discharge values used for the two studies were of different magnitudes. The discharges used in the Flaming Gorge Dam study were 18,000

ft^3/s (510 m^3/s), the maximum flood of record during the pre-dam period and 6,000 ft^3/s (170 m^3/s), the maximum probable flood for the post-dam period. The discharges used in this study were 86,000 ft^3/s (2,434 m^3/s) for the pre-dam period, 25,000 ft^3/s (708 m^3/s) for the filling period, and 36,000 ft^3/s (1,020 m^3/s) for the post-filling period. These values are four to five times greater than those in the previous study. Since calculations of depth, velocity and force use channel discharge (Figure 2.5), increasing discharge values would result in higher stability ratios. Calculations of the force/resistance stability ratio for the Colorado River in the Grand Canyon for 5,000 ft^3/s (142 m^3/s) and 18,500 ft^3/s (524 m^3/s), discharges similar to those used in the Flaming Gorge Dam study, are shown in Figure 4.1. All of the rapids are stable during the 5,000 ft^3/s discharge and only one rapid is unstable during the 18,500 ft^3/s discharge. This corresponds to only a 10% increase in the stability of rapids at these discharge values. Differences in other variables used to calculate rapid stability such as channel width, channel slope, and boulder dimensions also need to be considered when comparing results.

Another major factor is the number of rapids examined in each study. Graf's research calculated stability ratios for 57 rapids, 13 in Split Mountain Canyon, 12 in Whirlpool Canyon, and 32 in Lodore Canyon. This study was limited to

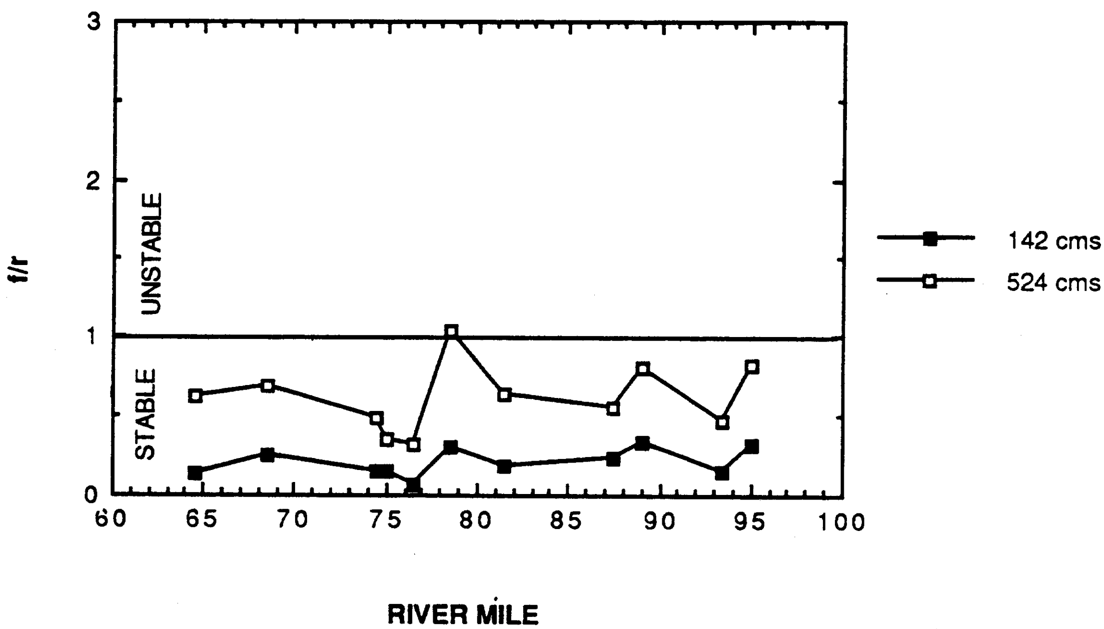


Figure 4.1. Downstream force/resistance stability ratios for rapids in the Grand Canyon at 5,000 ft^3/s (142 m^3/s) and 18,500 ft^3/s (524 m^3/s).

only 11 rapids located in the Grand Canyon. A larger sample may have resulted in a greater number of stable or unstable rapids during the three study periods which could have resulted in a different percentage increase in the stability of rapids. Also, the 31% increase in rapid stability for Flaming Gorge Dam was based on the results of all 57 rapids. If the stability ratios for the three individually canyons were examined, increases in rapid stability would change to 15.4%, 33.4% and 40.6% (Table 4.1).

Table 4.1

Comparison of rapid stability for the Green River in Split Mountain, Whirlpool, and Lodore Canyons and the Colorado River in the Grand Canyon

Canyon Name	Discharge (m^3/s)	Stable (Total)	Stable (%)	Increase in Stability (%)
Split Mountain	170	13	100.0	15.4
Split Mountain	510	11	84.6	
Whirlpool	170	9	75.0	33.4
Whirlpool	510	5	41.6	
Lodore	170	31	96.9	40.6
Lodore	510	18	56.3	
Grand Canyon	1,020	9	81.8	73.7
Grand Canyon	2,434	1	9.1	

This is due in part to the nature and source of debris that form the rapids in each of the canyons. Rapids in Split

Mountain Canyon are mainly formed by deposition of material from mass movements from canyon walls. These events supply boulders to the rapids that are too large to be moved by flows in the main channel. This is indicated by the number of stable rapids during the pre-dam period, 84.6%. The effect of Flaming Gorge Dam in this case was mainly to make the rapids more stable. In Whirlpool Canyon, rapids are formed by deposition of debris from tributaries. During the pre-dam period, approximately 40% of the rapids were stable in this canyon. The dam had a major affect on the mobility of the boulders on the debris fans and increased rapid stability by 33.4%. The introduction of Flaming Gorge Dam significantly affected the rapids of the Canyon of Lodore (Graf 1980). Rapids in this canyon were formed by a combination of debris deposited from mass movements and from flood discharges on major tributaries. Rapids along this reach of the river experienced the highest increase in stability; from 56% in the pre-dam period to 97% in the post-dam.

As mentioned earlier, rapids in the Grand Canyon (especially the study area) are caused predominately by the deposition of boulders by debris flows in tributaries. The results of this study showed that only one (9.1%) rapid in the study area was stable during the pre-dam period. This value increased to 100% during the post-dam period which corresponds to a 90.9% increase in rapid stability. Since most of the rapids in the study area were unstable during the pre-dam period, similar to Whirlpool Canyon and the Canyon of Lodore, the introduction of Glen Canyon Dam had a significant impact upon rapid stability in the Grand Canyon.

Implications for Glen Canyon Dam Operations

The results of this research indicate an increase in the stability of rapids in the Grand Canyon due to the reduced competence of the Colorado River during the post-dam period. Research by Webb et al. (1987, 1988) on the magnitude and frequency of debris flows in tributaries of the Colorado River showed that sediment supply to the rapids has not been affected by the introduction of the dam on the main stream. Kieffer (1985) concluded that the debris flow in Crystal Creek in 1966 constricted Crystal Rapids to 25% of the upstream channel width between 1966 and 1983. The flood discharges of 96,000 ft^3/s (2,717 m^3/s) in 1983 caused erosion of the Crystal Rapids debris fan and widened the constriction to a value of 40%, which is closer to the 50% value for channel constrictions found at more mature rapids. Thus, a discharge of pre-dam magnitude was capable of transporting boulders that were deposited by a debris flow during the post-dam period. These studies indicate that the rapids will become progressively more severe due to the continuing deposition of coarse material from debris flows. Discharges of pre-dam mean annual maximum discharge magnitude or greater may be required to remove this accumulating material.

The implications of these results on the operations of Glen Canyon Dam are that discharges of pre-dam magnitude are capable of transporting boulders deposited by debris flows during the post-dam period. Periodic releases similar to the pre-dam mean annual maximum discharge may be desirable to erode portions of the debris fan thus decreasing the severity of the rapid. However, the operations of Glen Canyon Dam affect several downstream resources, all of which must be considered when changes in dam operations are considered including flood discharges and daily fluctuations. These critical resources as defined by the U. S. Department of the Interior (1988) are the Humpback Chub, common native fish, Rainbow Trout, camping beaches, riparian vegetation and wildlife, white-water boating, and trout fishing. Modification to dam operations is complicated by the fact that some of these resources benefit more from lower discharges while others benefit more from higher discharges. Pre-dam magnitude discharges that may be desirable to erode the increasing accumulation of material on the debris fans may have detrimental affects on camping beaches, riparian vegetation and wildlife, as well as lost power revenues.

As is evident, operating the dam to benefit the greatest number of downstream resources is a highly complex task. The Glen Canyon Environmental Studies developed five modified operating strategies designed to benefit specific critical resources (U. S. Department of the Interior 1988). For each scenario, effects of the modified operation on the targeted resource and on the other critical resources were outlined and compared to current operations. Releases to benefit these critical resources are further complicated by the requirements for water storage and by operations to benefit power production.

Problems with the Present Research

The results of this study must be viewed with certain reservations. First, the limited number of rapids examined in the study area may have biased and influenced the estimations of rapid stability. However, the study area comprised two different reaches, the wider section from Lava Canyon Rapids to Hance Rapids and the narrower "Inner Gorge" section from Sockdolager Rapids to Hermit Rapids. The rapids had a variety of slopes ranging from 0.0081 to 0.0390. Significant differences in rapid stability for the two sections were not observed.

The study did not consider the effects of packing on rapid stability or the force of saltating smaller boulder on the larger boulders on the debris fans. The effects of packing of surrounding particles on the resistance of the largest boulder is not considered due to the turbulent nature of the flow at rapids which often made measurements difficult. Usually the largest boulders were considerably larger than those surrounding it so that the effects of packing were considered negligible. Also, the force imparted by small saltating boulders on the larger boulders was not considered. This process probably occurs, although it would difficult to observe and measure given the nature of flow at the rapids.

The final problem concerns the possibility of measurement error in the calculation of the force/resistance and tractive force/critical tractive force stability ratios which in turn might have led to errors in estimates of rapid stability. The use of the Manning equation in calculating values for channel depth and velocity may also introduce some error but the problem of error is inherent in any study involving the collection of field data and use of equations containing constants. Measurement of variables needed for the sediment transport equations is compounded by the turbulent nature of rapids which make precise measurements difficult. Because of this factor and the lack of adequate techniques for calculating sediment transport for particles as large as those found on the debris fans of rapids, these results must be considered an estimate of rapid stability upon which future studies can build.

Values of channel discharge, boulder density, water density, and boulder dimensions were assumed to be without error since individual values of force and resistance were calculated for these particular values. Field measurements of channel slope and channel width were verified utilizing measurements obtained from aerial photographs and topographic maps. The effects of a 5% error in measuring these variables can be assessed however, using a low and high estimate for these values in the calculation of the stability ratios. Stability ratios were calculated using low and high estimates of channel slope and width as well as a low and high value for channel roughness and the coefficient of friction (Tables 4.2 and 4.3).

Table 4.2

Results of the force/resistance stability ratio using a ± 5% error factor

Period	-5%	Actual Values	+5%
	Stable (%)	Stable (%)	Stable (%)
Pre-dam	0.0	9.1	27.3
Filling	90.9	100.0	100.0
Post-Filling	63.6	81.8	90.9
% Increase	63.6	72.7	63.6
% Change	-9.1	----	-9.1

Two important factors can be inferred from these calculations. First, analysis using a ± 5% error factor revealed changes in rapid stability of 9.1% from 72.7% to 63.6% for each case. Given the limited sample size, this error, which corresponds to a change in only one rapid, seems acceptable. Second, the low estimates used for variables in the equation resulted in a lower percentage of stable rapids while the high estimates resulted in a higher percentage of stable rapids. Changes in channel slope, width, and roughness along with the change in the coefficient of friction resulted in different channel depth and velocity values which in turn affect the values of the force/resistance stability ratio.

Table 4.3

Results of the tractive force/critical tractive force stability ratio using a ± 5% error factor

Period	-5%	Actual Values	+5%
	Stable (%)	Stable (%)	Stable (%)
Pre-dam	27.3	27.3	27.3
Filling	90.9	90.9	72.7
Post-Filling	63.6	63.6	54.5
% Increase	36.3	36.3	27.2
% Change	0.0	----	-9.1

Similar changes resulted from the use of low and high estimates for the tractive force/critical tractive force stability ratios. Calculations using a +5% error factor displayed a 9.1% change in the stability of rapids while calculations using a -5% error factor showed no change. Lower estimates of the variables used to calculate tractive force and critical tractive force resulted in a higher percentage of stable rapids for each period. Conversely, higher estimates resulted in a lower percentage of stable rapids. This is directly related to the change in channel slope and depth which are used in the calculation of tractive force.

Uncertainty regarding measurement error and the validity of sediment transport equations for large boulders resulted in the analysis using a $\pm 5\%$ error factor. The results of this analysis provided a high degree of confidence in the results of this study.

CHAPTER V. CONCLUSIONS

Research Question and Answers

This study addressed the following research question; What effect has Glen Canyon Dam had upon the stability of rapids in the Grand Canyon? This question was answered using two different techniques, one that calculated rapid stability as measured by the immobility of the largest boulder on the debris fan and another which calculated rapid stability as measured by the immobility of the mean particle size (d_{50}) on the debris fan. When examining the largest boulders on the debris fans, rapid stability increased by 72.7% from the pre-dam period to the post-filling period due to the effects of Glen Canyon Dam. When considering the mean particle size, an increase of 37.3% in rapid stability occurred over the same time period. These measures of increased stability are explained by declines in tractive force and shear stress related to declines in flood flows.

Significance of the Study

The closure of Glen Canyon Dam has had significant effects both upstream and downstream on the Colorado River. The major effects downstream include a reduction in discharge, a reduced sediment load, and a change in water temperature. These changes have caused a series of complex changes throughout the entire Grand Canyon region. The results of this research provide information on the effects of Glen Canyon Dam on the stability of rapids in the Grand Canyon. They also provide information on the complex changes that occur in river systems due to dam construction. It will be of value to resource managers in policy implications for the Colorado River and the Grand Canyon. The Bureau of Reclamation is currently entering the second phase of the Glen Canyon Environmental Studies; the agency will continue to monitor the effects of Glen Canyon Dam on several downstream resources. The results of this study will be of value to these studies since an increase in rapid stability and severity will have a tremendous impact upon the white-water rafting resource in the Grand Canyon. Lastly, the results of this study provide river recreationists with information on the increase in the stability and severity of rapids which will be useful for safer navigation.

The Need for Further Research

The results of this research provide the basis for further, more detailed monitoring of the stability of rapids in the Grand Canyon. Future research should focus on documenting the effects of debris flows in tributaries on the configuration of debris fans and the hydraulics of the rapids. The role of debris flows in supplying debris fans with coarse material that the main stream is incapable of moving is important to the understanding of rapid stability. Webb et al. (1988) investigated the effects of the 1984 debris flow in Monument Creek on Granite Rapids. Further studies should be conducted when debris flows occur in the future. Detailed photography and mapping of the configuration of boulders at the rapids should be undertaken so that precise location of the boulders can be made. Kieffer (1987a) produced a series of ten hydraulic maps of rapids in the Grand Canyon which showed the standing wave structures as well as the location of boulders on the debris fans. Similar maps should be made for any rapids that experience debris flows in the future.

Additional research on the effects of flood discharges on transportation of boulders and erosion of debris fans should be conducted if discharges similar to the floods of 1983 occur again. Techniques for estimating sediment transport when large particles are involved are limited. Studies that help understand the processes involved in the transportation of boulders will be of great value.

Operation of Glen Canyon Dam and management of the Colorado River and the Grand Canyon are complex due to the vast resources that are affected by changes in the river system. Debris flows in tributaries are the dominant process that supply sediment to debris fans that form rapids in the Grand Canyon. In its present flow regime, the

Colorado River is incapable of eroding most of the material deposited by debris flows. The rapids will become steeper, rockier, and more difficult to navigate in the future unless discharges capable of eroding the debris fans are released through the dam. Calculation of a discharge threshold above which this erosion will occur as well as a better understanding of the effects of these flood discharges on other canyon resources are fundamental to the management policies of this controlled river environment created by Glen Canyon Dam.

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APPENDIX 1

RAPID.CAL: COMPUTER PROGRAM TO CALCULATE RAPID STABILITY

```
list
10   REM  This program is designed to calculate the values of the force of
20   REM  flowing water, the resistance of boulders, and the force/resistance
30   REM  stability ratio that will be used to determine the effects of Glen
40   REM  Canyon Dam on the stability of rapids in the Colorado River in Grand
50   REM  Canyon National Park, Arizona.  It also calculates values of
60   REM  tractive force and critical tractive force for the mean particle
70   REM  size boulder on the debris fan.
80   REM  The program requires the following input: channel roughness, n,
90   REM  channel discharge, Q, channel width, w, channel slope, S, boulder
100  REM  height, width, and depth, d1, d2, d3, boulder density, YS, and mean
110  REM  particle size, d50.
120  REM  The program produces the following output: channel depth, D, channel
130  REM  velocity, V, density of the boulder corrected for buoyancy, Ys',
140  REM  force of flowing water, f, normal force of the boulder on the channel,
150  REM  N, resistance of the boulder to flow, r, and the stability ratio, SR.
160  REM  It also produces values of tractive force, TF, critical tractive
170  REM  force, CTF, and a ratio of tractive force to critical tractive
180  REM  force, TF/CTF.
190  OPEN "DATA2.FIL" FOR INPUT AS #1
200  OPEN "WP.FIL" FOR OUTPUT AS #2
210     FOR J=1 TO 33
220     INPUT #1, A$, N, Q, W, S, D1, D2, D3, YS, D50
230     IF A$ = "quit", GOTO 830
240     YF=1.15
250     SWW = 9807
260     G=9.8
270     U = .65
280     D=((N*Q)/(1.1*W*(S^.5)))^.6
290     V=(1.49/N)*(D^.67)*(S^.5)
300     IF D>=D1 THEN 350
310     IF D<D1 THEN 320
320     YSC=(D*(YS-YF)+(D1-D)*YF)/D1
330     F=YF*D2*D*(V^2)
340     GOTO 380
350     YSC=YS-YF
360     F=YF*D1*D2*(V^2)
370     GOTO 380
380     N1=YSC*D1*D2*D3*G*COS(S)
390     R=U*ABS(N1)
400     SR=F/R
410     TF = SWW*D*S
420    CTF = .06*G*(YS-YF)*D50
430     BA = D1*D2*D3
440     PRINT #2, "THIS RUN IS FOR "A$ " RAPID AT"; Q "CMS."
450     PRINT #2,
460 PRINT #2, USING "Channel Width Value (m)                W       #######.### ";W
470 PRINT #2, USING "Channel Slope Value,                   S       #######.### ";S
480 PRINT #2, USING "Channel Depth Value (m),               D       #######.### ";D
490 PRINT #2, USING "Channel Velocity Value (m/sec),        V       #######.### ";V
500 PRINT #2, USING "Boulder Height (m),                    d1      #######.### ";D1
510 PRINT #2, USING "Boulder Width (m),                     d2      #######.### ";D2
520 PRINT #2, USING "Boulder Length (m),                    d3      #######.### ";D3
530 PRINT #2, USING "Boulder Density (gm/cm3)               Ys      #######.### ";YS
540 PRINT #2, USING "Boulder Density Corrected              Ys'     #######.### ";YSC
550 PRINT #2, "     for Buoyancy (gm/cm3)"
560 PRINT #2, USING "Force of Flowing Water Value (N), f            #######.### ";F
570 PRINT #2, USING "Normal Force of Boulder (N)            N       #######.### ";N1
580 PRINT #2, USING "Boulder Resistance Value, (N)          r       #######.### ";R
590 PRINT #2, USING "Force/Resistance Value,                SR           ##.### ";SR
600 PRINT #2,
```

```
600 PRINT #2,
610 IF SR < 1! THEN 630
620 IF SR > 1! THEN 650
630 PRINT #2, "                                    LARGEST BOULDER IS STABLE"
640 GOTO 670
650 PRINT #2, "                                  LARGEST BOULDER IS UNSTABLE"
660 GOTO 670
670 PRINT #2,
680 PRINT #2, USING "Mean Particle Size (mm),        d50       #######.### ";D50
690 PRINT #2, USING "Tractive Force,                  TF       #######.### ";TF
700 PRINT #2, USING "Critical Tractive Force,        CTF       #######.### ";CTF
710 PRINT #2, USING "TF/CTF Value,                TF/CTF       #######.### ";TF/CTF
720 PRINT #2,
730 IF TF/CTF >1! THEN 750
740 IF TF/CTF <1! THEN 770
750 PRINT #2, "                                    MEAN PARTICLE IS UNSTABLE"
760 GOTO 780
770 PRINT #2, "                                     MEAN PARTICLE IS STABLE"
780 PRINT #2,
790 PRINT #2,
800 NEXT J
810 CLOSE #1
820 CLOSE #2
830 END
```

APPENDIX 2

RESULTS OF THE FORCE/RESISTANCE STABILITY RATIO CALCULATIONS

THIS RUN IS FOR LAVA CANYON RAPID AT 708 CMS.

Channel Width Value (m)	W	106.700
Channel Slope Value,	S	0.008
Channel Depth Value (m),	D	2.739
Channel Velocity Value (m/sec),	V	3.293
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.521
Force of Flowing Water Value (N),	f	85.708
Normal Force of Boulder (N)	N	235.141
Boulder Resistance Value, (N)	r	152.842
Force/Resistance Value,	SR	0.561

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	605.000
Tractive Force,	TF	217.578
Critical Tractive Force,	CTF	551.397
TF/CTF Value,	TF/CTF	0.395

MEAN PARTICLE IS STABLE

THIS RUN IS FOR LAVA CANYON RAPID AT 1020 CMS.

Channel Width Value (m)	W	121.900
Channel Slope Value,	S	0.008
Channel Depth Value (m),	D	3.148
Channel Velocity Value (m/sec),	V	3.614
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	111.233
Normal Force of Boulder (N)	N	239.563
Boulder Resistance Value, (N)	r	155.716
Force/Resistance Value,	SR	0.714

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	605.000
Tractive Force,	TF	250.064
Critical Tractive Force,	CTF	551.397
TF/CTF Value,	TF/CTF	0.454

MEAN PARTICLE IS STABLE

THIS RUN IS FOR LAVA CANYON RAPID AT 2434 CMS.

Channel Width Value (m)	W	176.800
Channel Slope Value,	S	0.008
Channel Depth Value (m),	D	4.244
Channel Velocity Value (m/sec),	V	4.415
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	165.993
Normal Force of Boulder (N)	N	239.563
Boulder Resistance Value, (N)	r	155.716
Force/Resistance Value,	SR	1.066

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	605.000
Tractive Force,	TF	337.130
Critical Tractive Force,	CTF	551.397
TF/CTF Value,	TF/CTF	0.611

MEAN PARTICLE IS STABLE

THIS RUN IS FOR TANNER CANYON RAPID AT 708 CMS.

Channel Width Value (m)	W	163.700
Channel Slope Value,	S	0.031
Channel Depth Value (m),	D	1.418
Channel Velocity Value (m/sec),	V	4.137
Boulder Height (m),	d1	2.050
Boulder Width (m),	d2	2.250
Boulder Length (m),	d3	2.500
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.427
Force of Flowing Water Value (N),	f	62.781
Normal Force of Boulder (N)	N	161.143
Boulder Resistance Value, (N)	r	104.743
Force/Resistance Value,	SR	0.599

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	671.000
Tractive Force,	TF	429.651
Critical Tractive Force,	CTF	611.549
TF/CTF Value,	TF/CTF	0.703

MEAN PARTICLE IS STABLE

THIS RUN IS FOR TANNER CANYON RAPID AT 1020 CMS.

Channel Width Value (m)	W	185.900
Channel Slope Value,	S	0.031
Channel Depth Value (m),	D	1.635
Channel Velocity Value (m/sec),	V	4.552
Boulder Height (m),	d1	2.050
Boulder Width (m),	d2	2.250
Boulder Length (m),	d3	2.500
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.469
Force of Flowing Water Value (N),	f	87.682
Normal Force of Boulder (N)	N	165.938
Boulder Resistance Value, (N)	r	107.860
Force/Resistance Value,	SR	0.813

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	671.000
Tractive Force,	TF	495.585
Critical Tractive Force,	CTF	611.549
TF/CTF Value,	TF/CTF	0.810

MEAN PARTICLE IS STABLE

THIS RUN IS FOR TANNER CANYON RAPID AT 2434 CMS.

Channel Width Value (m)	W	210.600
Channel Slope Value,	S	0.031
Channel Depth Value (m),	D	2.557
Channel Velocity Value (m/sec),	V	6.141
Boulder Height (m),	d1	2.050
Boulder Width (m),	d2	2.250
Boulder Length (m),	d3	2.500
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	200.063
Normal Force of Boulder (N)	N	175.076
Boulder Resistance Value, (N)	r	113.799
Force/Resistance Value,	SR	1.758

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	671.000
Tractive Force,	TF	774.895
Critical Tractive Force,	CTF	611.549
TF/CTF Value,	TF/CTF	1.267

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR ESCALANTE RAPID AT 708 CMS.

Channel Width Value (m)	W	98.500
Channel Slope Value,	S	0.011
Channel Depth Value (m),	D	2.607
Channel Velocity Value (m/sec),	V	3.746
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.504
Force of Flowing Water Value (N),	f	105.613
Normal Force of Boulder (N)	N	232.376
Boulder Resistance Value, (N)	r	151.045
Force/Resistance Value,	SR	0.699

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	594.000
Tractive Force,	TF	286.395
Critical Tractive Force,	CTF	541.372
TF/CTF Value,	TF/CTF	0.529

MEAN PARTICLE IS STABLE

THIS RUN IS FOR ESCALANTE RAPID AT 1020 CMS.

Channel Width Value (m)	W	128.000
Channel Slope Value,	S	0.011
Channel Depth Value (m),	D	2.774
Channel Velocity Value (m/sec),	V	3.905
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.526
Force of Flowing Water Value (N),	f	122.069
Normal Force of Boulder (N)	N	235.865
Boulder Resistance Value, (N)	r	153.312
Force/Resistance Value,	SR	0.796

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	594.000
Tractive Force,	TF	304.678
Critical Tractive Force,	CTF	541.372
TF/CTF Value,	TF/CTF	0.563

MEAN PARTICLE IS STABLE

THIS RUN IS FOR ESCALANTE RAPID AT 2434 CMS.

Channel Width Value (m)	W	155.500
Channel Slope Value,	S	0.011
Channel Depth Value (m),	D	4.159
Channel Velocity Value (m/sec),	V	5.122
Boulder Height (m),	d1	2.950
Boulder Width (m),	d2	2.510
Boulder Length (m),	d3	2.130
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	223.395
Normal Force of Boulder (N)	N	239.555
Boulder Resistance Value, (N)	r	155.711
Force/Resistance Value,	SR	1.435

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	594.000
Tractive Force,	TF	456.837
Critical Tractive Force,	CTF	541.372
TF/CTF Value,	TF/CTF	0.844

MEAN PARTICLE IS STABLE

THIS RUN IS FOR NEVILLS RAPID AT 708 CMS.

Channel Width Value (m)	W	114.900
Channel Slope Value,	S	0.023
Channel Depth Value (m),	D	1.923
Channel Velocity Value (m/sec),	V	4.349
Boulder Height (m),	d1	2.350
Boulder Width (m),	d2	4.950
Boulder Length (m),	d3	5.840
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	207.096
Normal Force of Boulder (N)	N	765.417
Boulder Resistance Value, (N)	r	497.521
Force/Resistance Value,	SR	0.416

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	428.155
Critical Tractive Force,	CTF	430.739
TF/CTF Value,	TF/CTF	0.994

MEAN PARTICLE IS STABLE

THIS RUN IS FOR NEVILLS RAPID AT 1020 CMS.

Channel Width Value (m)	W	137.200
Channel Slope Value,	S	0.023
Channel Depth Value (m),	D	2.153
Channel Velocity Value (m/sec),	V	4.690
Boulder Height (m),	d1	2.350
Boulder Width (m),	d2	4.950
Boulder Length (m),	d3	5.840
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	269.553
Normal Force of Boulder (N)	N	765.417
Boulder Resistance Value, (N)	r	497.521
Force/Resistance Value,	SR	0.542

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	479.204
Critical Tractive Force,	CTF	430.739
TF/CTF Value,	TF/CTF	1.113

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR NEVILLS RAPID AT 2434 CMS.

Channel Width Value (m)	W	154.500
Channel Slope Value,	S	0.023
Channel Depth Value (m),	D	3.378
Channel Velocity Value (m/sec),	V	6.343
Boulder Height (m),	d1	2.350
Boulder Width (m),	d2	4.950
Boulder Length (m),	d3	5.840
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	538.238
Normal Force of Boulder (N)	N	765.417
Boulder Resistance Value, (N)	r	497.521
Force/Resistance Value,	SR	1.082

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	751.983
Critical Tractive Force,	CTF	430.739
TF/CTF Value,	TF/CTF	1.746

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR HANCE RAPID AT 708 CMS.

Channel Width Value (m)	W	136.300
Channel Slope Value,	S	0.039
Channel Depth Value (m),	D	1.476
Channel Velocity Value (m/sec),	V	4.774
Boulder Height (m),	d1	2.750
Boulder Width (m),	d2	3.100
Boulder Length (m),	d3	4.620
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.365
Force of Flowing Water Value (N),	f	119.902
Normal Force of Boulder (N)	N	526.328
Boulder Resistance Value, (N)	r	342.113
Force/Resistance Value,	SR	0.350

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	478.000
Tractive Force,	TF	564.446
Critical Tractive Force,	CTF	435.649
TF/CTF Value,	TF/CTF	1.296

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR HANCE RAPID AT 1020 CMS.

Channel Width Value (m)	W	149.400
Channel Slope Value,	S	0.039
Channel Depth Value (m),	D	1.739
Channel Velocity Value (m/sec),	V	5.328
Boulder Height (m),	d1	2.750
Boulder Width (m),	d2	3.100
Boulder Length (m),	d3	4.620
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.403
Force of Flowing Water Value (N),	f	175.994
Normal Force of Boulder (N)	N	541.083
Boulder Resistance Value, (N)	r	351.704
Force/Resistance Value,	SR	0.500

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	478.000
Tractive Force,	TF	665.043
Critical Tractive Force,	CTF	435.649
TF/CTF Value,	TF/CTF	1.527

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR HANCE RAPID AT 2434 CMS.

Channel Width Value (m)	W	156.400
Channel Slope Value,	S	0.039
Channel Depth Value (m),	D	2.851
Channel Velocity Value (m/sec),	V	7.421
Boulder Height (m),	d1	2.750
Boulder Width (m),	d2	3.100
Boulder Length (m),	d3	4.620
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	539.860
Normal Force of Boulder (N)	N	597.811
Boulder Resistance Value, (N)	r	388.577
Force/Resistance Value,	SR	1.389

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	478.000
Tractive Force,	TF	1090.310
Critical Tractive Force,	CTF	435.649
TF/CTF Value,	TF/CTF	2.503

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR SOCKDOLAGER RAPID AT 708 CMS.

Channel Width Value (m)	W	87.500
Channel Slope Value,	S	0.032
Channel Depth Value (m),	D	2.051
Channel Velocity Value (m/sec),	V	5.357
Boulder Height (m),	d1	1.780
Boulder Width (m),	d2	3.390
Boulder Length (m),	d3	3.570
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	199.150
Normal Force of Boulder (N)	N	369.263
Boulder Resistance Value, (N)	r	240.021
Force/Resistance Value,	SR	0.830

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	635.551
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	0.970

MEAN PARTICLE IS STABLE

THIS RUN IS FOR SOCKDOLAGER RAPID AT 1020 CMS.

Channel Width Value (m)	W	102.400
Channel Slope Value,	S	0.032
Channel Depth Value (m),	D	2.323
Channel Velocity Value (m/sec),	V	5.824
Boulder Height (m),	d1	1.780
Boulder Width (m),	d2	3.390
Boulder Length (m),	d3	3.570
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	235.375
Normal Force of Boulder (N)	N	369.263
Boulder Resistance Value, (N)	r	240.021
Force/Resistance Value,	SR	0.981

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	719.972
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	1.098

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR SOCKDOLAGER RAPID AT 2434 CMS.

Channel Width Value (m)	W	124.100
Channel Slope Value,	S	0.032
Channel Depth Value (m),	D	3.489
Channel Velocity Value (m/sec),	V	7.647
Boulder Height (m),	d1	1.780
Boulder Width (m),	d2	3.390
Boulder Length (m),	d3	3.570
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	405.823
Normal Force of Boulder (N)	N	369.263
Boulder Resistance Value, (N)	r	240.021
Force/Resistance Value,	SR	1.691

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	1081.097
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	1.649

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR GRAPEVINE RAPID AT 708 CMS.

Channel Width Value (m)	W	71.300
Channel Slope Value,	S	0.025
Channel Depth Value (m),	D	2.491
Channel Velocity Value (m/sec),	V	5.417
Boulder Height (m),	d1	2.400
Boulder Width (m),	d2	3.300
Boulder Length (m),	d3	3.600
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	267.233
Normal Force of Boulder (N)	N	488.829
Boulder Resistance Value, (N)	r	317.739
Force/Resistance Value,	SR	0.841

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	608.219
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	0.928

MEAN PARTICLE IS STABLE

THIS RUN IS FOR GRAPEVINE RAPID AT 1020 CMS.

Channel Width Value (m)	W	82.900
Channel Slope Value,	S	0.025
Channel Depth Value (m),	D	2.833
Channel Velocity Value (m/sec),	V	5.904
Boulder Height (m),	d1	2.400
Boulder Width (m),	d2	3.300
Boulder Length (m),	d3	3.600
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	317.500
Normal Force of Boulder (N)	N	488.829
Boulder Resistance Value, (N)	r	317.739
Force/Resistance Value,	SR	0.999

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	691.706
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	1.055

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR GRAPEVINE RAPID AT 2434 CMS.

Channel Width Value (m)	W	101.500
Channel Slope Value,	S	0.025
Channel Depth Value (m),	D	4.227
Channel Velocity Value (m/sec),	V	7.721
Boulder Height (m),	d1	2.400
Boulder Width (m),	d2	3.300
Boulder Length (m),	d3	3.600
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	542.938
Normal Force of Boulder (N)	N	488.829
Boulder Resistance Value, (N)	r	317.739
Force/Resistance Value,	SR	1.709

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	637.000
Tractive Force,	TF	1032.302
Critical Tractive Force,	CTF	655.473
TF/CTF Value,	TF/CTF	1.575

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR BRIGHT ANGEL RAPID AT 708 CMS.

Channel Width Value (m)	W	79.300
Channel Slope Value,	S	0.024
Channel Depth Value (m),	D	2.375
Channel Velocity Value (m/sec),	V	5.107
Boulder Height (m),	d1	2.060
Boulder Width (m),	d2	5.900
Boulder Length (m),	d3	4.420
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	364.608
Normal Force of Boulder (N)	N	921.053
Boulder Resistance Value, (N)	r	598.685
Force/Resistance Value,	SR	0.609

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	921.200
Tractive Force,	TF	549.603
Critical Tractive Force,	CTF	947.915
TF/CTF Value,	TF/CTF	0.580

MEAN PARTICLE IS STABLE

THIS RUN IS FOR BRIGHT ANGEL RAPID AT 1020 CMS.

Channel Width Value (m)	W	106.700
Channel Slope Value,	S	0.024
Channel Depth Value (m),	D	2.474
Channel Velocity Value (m/sec),	V	5.250
Boulder Height (m),	d1	2.060
Boulder Width (m),	d2	5.900
Boulder Length (m),	d3	4.420
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	385.200
Normal Force of Boulder (N)	N	921.053
Boulder Resistance Value, (N)	r	598.685
Force/Resistance Value,	SR	0.643

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	921.200
Tractive Force,	TF	572.604
Critical Tractive Force,	CTF	947.915
TF/CTF Value,	TF/CTF	0.604

MEAN PARTICLE IS STABLE

THIS RUN IS FOR BRIGHT ANGEL RAPID AT 2434 CMS.

Channel Width Value (m)	W	152.900
Channel Slope Value,	S	0.024
Channel Depth Value (m),	D	3.360
Channel Velocity Value (m/sec),	V	6.444
Boulder Height (m),	d1	2.060
Boulder Width (m),	d2	5.900
Boulder Length (m),	d3	4.420
Boulder Density (gm/cm3)	Ys	2.900
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.750
Force of Flowing Water Value (N),	f	580.435
Normal Force of Boulder (N)	N	921.053
Boulder Resistance Value, (N)	r	598.685
Force/Resistance Value,	SR	0.970

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	921.200
Tractive Force,	TF	777.572
Critical Tractive Force,	CTF	947.915
TF/CTF Value,	TF/CTF	0.820

MEAN PARTICLE IS STABLE

THIS RUN IS FOR PIPE SPRINGS RAPID AT 708 CMS.

Channel Width Value (m)	W	79.300
Channel Slope Value,	S	0.015
Channel Depth Value (m),	D	2.743
Channel Velocity Value (m/sec),	V	4.424
Boulder Height (m),	d1	1.120
Boulder Width (m),	d2	2.420
Boulder Length (m),	d3	3.710
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	61.013
Normal Force of Boulder (N)	N	113.314
Boulder Resistance Value, (N)	r	73.654
Force/Resistance Value,	SR	0.828

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	700.000
Tractive Force,	TF	392.697
Critical Tractive Force,	CTF	473.340
TF/CTF Value,	TF/CTF	0.830

MEAN PARTICLE IS STABLE

THIS RUN IS FOR PIPE SPRINGS RAPID AT 1020 CMS.

Channel Width Value (m)	W	85.400
Channel Slope Value,	S	0.015
Channel Depth Value (m),	D	3.266
Channel Velocity Value (m/sec),	V	4.973
Boulder Height (m),	d1	1.120
Boulder Width (m),	d2	2.420
Boulder Length (m),	d3	3.710
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	77.096
Normal Force of Boulder (N)	N	113.314
Boulder Resistance Value, (N)	r	73.654
Force/Resistance Value,	SR	1.047

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	700.000
Tractive Force,	TF	467.613
Critical Tractive Force,	CTF	473.340
TF/CTF Value,	TF/CTF	0.988

MEAN PARTICLE IS STABLE

THIS RUN IS FOR PIPE SPRINGS RAPID AT 2434 CMS.

Channel Width Value (m)	W	121.900
Channel Slope Value,	S	0.015
Channel Depth Value (m),	D	4.445
Channel Velocity Value (m/sec),	V	6.115
Boulder Height (m),	d1	1.120
Boulder Width (m),	d2	2.420
Boulder Length (m),	d3	3.710
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	116.538
Normal Force of Boulder (N)	N	113.314
Boulder Resistance Value, (N)	r	73.654
Force/Resistance Value,	SR	1.582

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	700.000
Tractive Force,	TF	636.490
Critical Tractive Force,	CTF	473.340
TF/CTF Value,	TF/CTF	1.345

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR GRANITE RAPID AT 708 CMS.

Channel Width Value (m)	W	97.500
Channel Slope Value,	S	0.028
Channel Depth Value (m),	D	1.987
Channel Velocity Value (m/sec),	V	4.963
Boulder Height (m),	d1	2.020
Boulder Width (m),	d2	8.110
Boulder Length (m),	d3	4.830
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.543
Force of Flowing Water Value (N),	f	456.300
Normal Force of Boulder (N)	N	1196.309
Boulder Resistance Value, (N)	r	777.601
Force/Resistance Value,	SR	0.587

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	551.344
Critical Tractive Force,	CTF	911.400
TF/CTF Value,	TF/CTF	0.605

MEAN PARTICLE IS STABLE

THIS RUN IS FOR GRANITE RAPID AT 1020 CMS.

Channel Width Value (m)	W	106.700
Channel Slope Value,	S	0.028
Channel Depth Value (m),	D	2.343
Channel Velocity Value (m/sec),	V	5.543
Boulder Height (m),	d1	2.020
Boulder Width (m),	d2	8.110
Boulder Length (m),	d3	4.830
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	578.770
Normal Force of Boulder (N)	N	1201.443
Boulder Resistance Value, (N)	r	780.938
Force/Resistance Value,	SR	0.741

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	650.229
Critical Tractive Force,	CTF	911.400
TF/CTF Value,	TF/CTF	0.713

MEAN PARTICLE IS STABLE

THIS RUN IS FOR GRANITE RAPID AT 2434 CMS.

Channel Width Value (m)	W	112.800
Channel Slope Value,	S	0.028
Channel Depth Value (m),	D	3.818
Channel Velocity Value (m/sec),	V	7.689
Boulder Height (m),	d1	2.020
Boulder Width (m),	d2	8.110
Boulder Length (m),	d3	4.830
Boulder Density (gm/cm3)	Ys	2.700
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.550
Force of Flowing Water Value (N),	f	1113.732
Normal Force of Boulder (N)	N	1201.443
Boulder Resistance Value, (N)	r	780.938
Force/Resistance Value,	SR	1.426

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	1059.771
Critical Tractive Force,	CTF	911.400
TF/CTF Value,	TF/CTF	1.163

MEAN PARTICLE IS UNSTABLE

THIS RUN IS FOR HERMIT RAPID AT 708 CMS.

Channel Width Value (m)	W	85.400
Channel Slope Value,	S	0.022
Channel Depth Value (m),	D	2.333
Channel Velocity Value (m/sec),	V	4.828
Boulder Height (m),	d1	2.820
Boulder Width (m),	d2	3.510
Boulder Length (m),	d3	3.420
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	219.466
Normal Force of Boulder (N)	N	381.421
Boulder Resistance Value, (N)	r	247.924
Force/Resistance Value,	SR	0.885

LARGEST BOULDER IS STABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	494.103
Critical Tractive Force,	CTF	676.200
TF/CTF Value,	TF/CTF	0.731

MEAN PARTICLE IS STABLE

THIS RUN IS FOR HERMIT RAPID AT 1020 CMS.

Channel Width Value (m)	W	97.500
Channel Slope Value,	S	0.022
Channel Depth Value (m),	D	2.682
Channel Velocity Value (m/sec),	V	5.301
Boulder Height (m),	d1	2.820
Boulder Width (m),	d2	3.510
Boulder Length (m),	d3	3.420
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	304.228
Normal Force of Boulder (N)	N	381.421
Boulder Resistance Value, (N)	r	247.924
Force/Resistance Value,	SR	1.227

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	568.106
Critical Tractive Force,	CTF	676.200
TF/CTF Value,	TF/CTF	0.840

MEAN PARTICLE IS STABLE

THIS RUN IS FOR HERMIT RAPID AT 2434 CMS.

Channel Width Value (m)	W	106.700
Channel Slope Value,	S	0.022
Channel Depth Value (m),	D	4.281
Channel Velocity Value (m/sec),	V	7.252
Boulder Height (m),	d1	2.820
Boulder Width (m),	d2	3.510
Boulder Length (m),	d3	3.420
Boulder Density (gm/cm3)	Ys	2.300
Boulder Density Corrected for Buoyancy (gm/cm3)	Ys´	1.150
Force of Flowing Water Value (N),	f	598.704
Normal Force of Boulder (N)	N	381.421
Boulder Resistance Value, (N)	r	247.924
Force/Resistance Value,	SR	2.415

LARGEST BOULDER IS UNSTABLE

Mean Particle Size (mm),	d50	1000.000
Tractive Force,	TF	906.914
Critical Tractive Force,	CTF	676.200
TF/CTF Value,	TF/CTF	1.341

MEAN PARTICLE IS UNSTABLE

APPENDIX 3

LIST OF AERIAL PHOTOGRAPHY OF THE GRAND CANYON

LIST OF AERIAL PHOTOGRAPHY OF THE GRAND CANYON

DATE	TYPE	SCALE	CFS	LOCATION
3-2-63	B&W	?	5,600	GCES
5-14-65*	B&W	1:12,000	25,000	GCES
5-18-65	B&W	?	10,000	GCES
6-2-65	B&W	?	25,000	GCES
6-11-65	B&W	?	40,000	GCES
9-1968	COLOR	1:36,000	?	DRM
6-16-73*	B&W	1:7,200	6,400-9,800	GCES, DRM, USGS
9-12-78*	B&W	1:24,000	18,500	DRM
8-8-79	COLOR	1:4,800	22,000	GCES
7-11-80*	FCIR	1:4,000	25,000	GCES
10-22-84*	B&W	1:3,000	5,000	GCES
6-7-85*	FCIR	1:4,800	36,000	GCES
6-12-86	B&W	?	30,000	GCES
5-28-88*	FCIR	1:4,800	?	GCES

Location:

GCES Dave Wagner, Bureau of Reclamation, Salt Lake City, Utah.

DRM Division of Resources Management, Grand Canyon National Park.

USGS U. S. Geological Survey, Tucson, Arizona

* Aerial Photograph sets used for measurements.

BIOGRAPHICAL SKETCH

Stephen Edward Lee was born in Dorchester, Massachusetts on July 21, 1963. He received his elementary and secondary education in the Weymouth Public School System and graduate from Weymouth North High School in May 1981. In September 1981, he entered the Department of Geography at Plymouth State College. In the Fall of 1984, he spent a semester abroad studying in Arundel, England. In May 1986, he graduated with a Bachelor of Science degree in Geography and was awarded the John Ozog Memorial Scholarship in Geography. In August 1986, he entered the Graduate College at Arizona State University. From September 1986 to May 1989, he served as a Graduate Teaching Assistant in the Department of Geography while studying for his Master of Arts degree in Geography specializing in fluvial geomorphology. He is a member of the Association of American Geographers, Arizona-Nevada Academy of Sciences, and the Grand Canyon Natural History Association.