Final Report

HYDROLOGY AND SEDIMENTOLOGY OF THE COLORADO RIVER IN GRAND CANYON

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by

Emmett M. Laursen
and
Elliot Silverston

Department of Civil Engineering
University of Arizona
Tucson, Arizona 85721

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or
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Introduction

A previous study (1) of the fluvial morphology of the Colorado River between Glen Canyon Dam and Lake Mead established that the capacity of the controlled river to transport beach-building bed material is about 13 million tons per year and that the tributaries in this reach only contribute about 3 million tons per year. The deficit of 10 million tons per year means that the river below Glen Canyon Dam is degrading progressively downstream. Some additional material, much finer than the beach material, will also continue to be transported and to contribute to the filling of Lake Mead, albeit at a much slower rate than before the closure of the river by Glen Canyon Dam, but will have little to do with the future of the beaches of the Colorado. Measurements by the Bureau of Reclamation (2) verify that the reach between Glen Canyon Dam and Lees Ferry has been degraded and stabilized with an armour bed of self-sorted riprap ranging from small cobble to large boulders.

This investigation focused on the beaches, which are primarily foun below the rapids, in an effort to explain their formation and predict th future.

Recreational activities in the Canyon are very dependent on the bea If the beaches were to disappear (or even to be greatly reduced in size) the coming years, the thousands who run the river every year would have more than a bit of a problem finding a camping spot each night. The dar of flash flooding means that the tributaries are a poor choice for sleep (Figure 1) the boulder masses at rapids are hardly inviting, (Figure 2) sheer rock walls are impossible (Figure 3) - some of the talus slopes m be a poor substitute for the beaches as campsites (Figure 4). The prob of campsites is not merely a matter of the amenities. The crowding of people and their wastes onto less space is a health problem.

Because the beaches are a somewhat different habitat from the rest of the Canyon, the amount of beach left after the degradation and erosi processes have reached equilibrium could make a difference in the ecolo along the River. The determination of whether the possible ecological changes are of any consequence would require a separate investigation.

The objectives in this investigation were several: (1) the estab ment of camera stations at a number of locations along the River which would permit a continuing surviellance of selected beaches, (2) a bet understanding of beach formation and destruction through a combination field measurements of the river bed configuration off the beaches, and qualitative laboratory experiments, and (3) a qualitative appraisal o natural armouring of beaches and the feasibility of enhancing this nat process.

Preliminary Study Above Lees Ferry

Several days were spent on the reach between Glen Canyon Dam and Lees Ferry. The immediate reasons were simply to check out the equipment that would be used during the trip down the Colorado River to Lake Mead and to learn how to pick out and establish camera stations. A more important reason in the long run is that what will happen below Lees Ferry has been happening above Lees Ferry.

A modest degree of proficiency was acquired in handling the measuring instruments. The characteristic behavior of the blinking neon light of the fathometer could be correlated with the observable bottom of the river. Large boulders could be detected by an erratic bouncing of the signal as it reflected off the top of boulders or the river bed between the boulders. The trace of the paper chart revealed the presence of sand dunes in the one limited area in which they were found.

It was quickly discovered that the thin, liquid epoxy glue worked much better and easier when sand was mixed with it, resulting in a paste that would stay in any space between the pebbles forming the camera station and the large boulder or parent rock which was the base of the station. The epoxy was thin enough to make a good contact with smooth rock or even penetrate porous rock; the mix was thick enough to stay in place and remained workable long enough to set several stations. On a second trip a few months later, it was observed that at some of these early stations the paste had run enough to be a little messy. However, the paste blended well enough with the rocks that the stations were hardly noticeable except under close inspection.

The 15-mile reach between Glen Canyon Dam and Lees Ferry has degraded and the bed is now armoured. There are deep pools and there are shallows; all seem to be armoured. In some deep pools there are very large rocks ten to twenty feet in size. The natural riprapping ranges down to perhaps an inch in diameter in some places. Out from Lee's old fort, one sizeable patch of sand dunes was found. This sand may be coming from the erosion of the beaches that are left, but it is more likely a result of the blow sand from the plateau above dropping into the canyon about a mile upstream. Figure 5 shows ripples on a small beach near the sand patch and the blow sand in the background.

This reach of the Colorado is rich in the variety of flow conditions. In some sections the river is narrow, in others it is wide. Although there are no rapids, there is fast water in some restricted sections that might almost be called riffles during low flow conditions. A gravel bar or deposit which might serve as a control at low water with a flow over it which is critical or slightly supercritical can be easily drowned out at a higher flow and merely be somewhat fast water. In the deep pool sections the velocity can be quite low, but it evidently has been sufficient to move the sand and fine gravel out of the reach, rather than to have filled in the deeps because of the low velocities of the controlled

Figure 5. Ripples formed at high water and exposed at low water

flow from the dam. The water surface elevation fluctuates about five feet between high and low water. There are sheer cliffs forming the side boundary of the river; there are talus slopes of mixed rock and residual soil forming banks; there are exposed sand beaches formed as sand bars during past floods; there are beaches armoured naturally with large gravel and cobbles or boulders, and there are beaches covered with salt cedar.

Although the bed of this reach seems to be completely degraded to an equilibrium condition; so completely that even a major increase in controlled flows will probably only cause some slight rearrangement, there still are beaches. An inventory of beaches before the closure of Glen Canyon Dam is not available and probably was not made. Some have probably disappeared; some remain as residual, naturally riprapped beaches (Figure 6). The remaining sand beaches appear to be eroding; some may eventually disappear, some may have enough cobbles mixed in to armour, others may be large enough so that as they diminish in size the flow which attacks them will finally be unable to erode them any more. The camera stations established at and above Lees Ferry should accumulate the evidence of what is happening to these beaches after the bed is completely degraded and sediment transport in the river has dropped to virtually zero. The lessons to be learned here should be applicable shortly to the river below Lees Ferry.

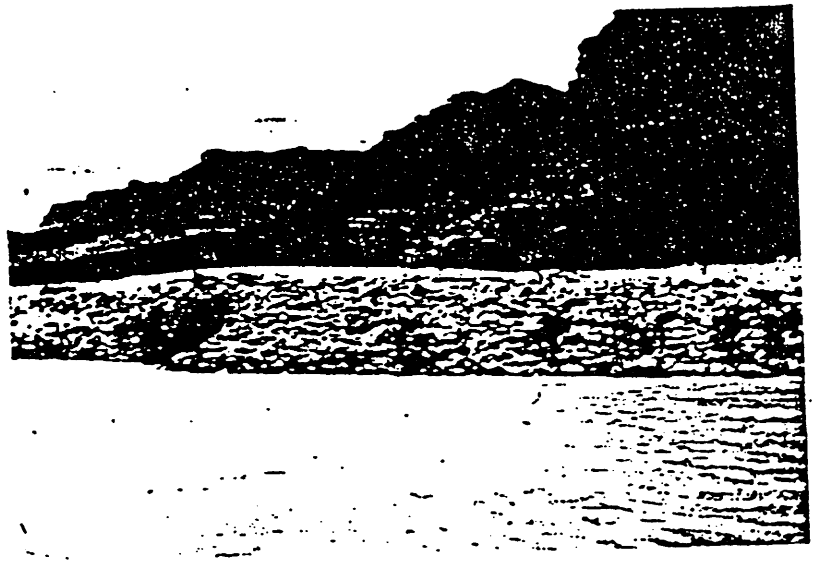

Figure 6. Naturally riprapped beach along the Colorado River

Camera Stations

A total of 47 Camera Stations were installed at 17 locations. Full details of those stations - maps, descriptions, photos of camera stations, photos taken from the camera stations - are included as a separately bound supplement which can be used independently of this report when retaking pictures in a monitoring program.

The camera stations were made by attaching pebbles to the flat top of a large boulder or a ledge of rock to fit a RICOH Model 500G 35mm camera with a 40mm lens. A very small clearance was left between the pebbles and the camera body so almost exactly the same picture should be taken over and over. Both of the cameras used will be made available for the continuing monitoring program to insure obtaining photos that can be directly compared. In taking the first set of photos the automatic setting on the camera was used. This proved to be a mistake because the beach sometimes was the brightest part of the picture, sometimes the darkest. The pictures should be taken with camera settings for the beach without regard for the rest of the picture. Therefore, some type of light meter should be used to get spot light readings when possible. There should always be enough detail in the rest of the picture to serve as reference points. Color slide film (Kodachrome 25) was used.

In choosing the vantage points for the camera stations an effort was made to ignore the water line between the beach and the river becau it is dependent on the rate of flow which cannot be matched from one picture taking to another. Nevertheless, the waterline is in the photo because it is this part of the beach which is of greatest interest. Parts of the beach which are out of the water at low flow can be submerged at high flow; careful interpretation will be necessary in order not to be mislead by such seeming changes between successive photos. Insofar as possible photos should be taken at low water, however, this will often be impracticable if the phototaking is an "extra" undertaking during a routine patrol or a research trip for some other purpose.

In locating the camera stations an attempt was made to either outline a cross-sectional profile of the beach or to include large rocks (too large to be likely to be moved). If the beach erodes, the profile should move back from the river or down, and the sand line on the large rock should be lowered. These are the changes that can be looked for in successive photos. In the beginning qualitative changes will be sufficient evidence of what is happening. Is the beach eroding or not? If it is eroding, is it eroding a lot or just a little bit? If more quantitative values are necessary in the future, measurement of the distance between rocks, or of rock dimensions, or photos with sticks of known dimensions, strategically placed, should suffice. Figures 7, 8 and 9 show a boulder and a ledge chosen for stations, the pebbles glued on to form stations, and the photos taken from these stations.

General Observations Of The River

In the few days available on the river it was not possible to observe in the leisurely way one might have wished, but it was possible to obtain some general notions of the river behavior which are important to the question of what is happening to the beaches. Fathometer surveys were taken of the river opposite a number of beaches. Typically, the river was deep just downstream of the rapids, indicating a scour hole created by the high velocity jet issuing from the rapids. The scour hole was 40 to 50 feet deep measured from the water surface where the depth of flow downstream was only 15 to 20 feet deep. The shape of the scour hole and the river bed configuration downstream was completely in agreement with preliminary laboratory experiments conducted before the river trip and the qualitative experiments conducted afterwards. The inescapable conclusion is that the beach is cast up because of the flow pattern out of the hole that is scoured out below the rapids; the hole that is scoured and the beach that is built are two complementary features of a pool-rapid river such as the Colorado. All natural rivers, however, are the agents whereby the weathered fragments of the mountains are transported to the sea. If this natural supply of sediment being transported is interrupted, the scour hole will remain and may even be enlarged, but the depositional feature-the beach-may disappear.

On a geological time scale, equilibrium is never reached by a river as it moves the mountain to the sea. On our time scale of years (even hundreds of years), a river will be in a sort of equilibrium based on a weighted average flow but fluctuating about that equilibrium during periods of high and low water. Always in a river transporting sediment, there will be local scour or desposition if locally the supply of sediment to an area is not exactly equal to the capacity to transport sediment in that area. Therefore, there can be observable local effects on the Colorado River through the Grand Canyon which are due to the controlled, but fluctuating, flow out of Glen Canyon Dam. Changes in that controlled flow can result in local scour and deposition, and aggradation and degradation in the pools. And, it is important to remember, these effects can persist as they move downstream even if the controlled flow is again changed. However, any such changes will tend towards a temporary equilibrium state of a balance of supply and capacity and should not give rise to drastic changes in the beaches.

The drastic and irreversible changes can be expected when the general degradation to a clear-water flow (or almost a clear-water flow) regime reaches first one beach and then another. The equilibrium state is then that configuration of bed and beach such that the fluid-flow stresses on the boundary material are no longer able to move the sand, gravel, or cobble that remains. Since the beach sand is easily moved, the boundary stresses must be very low if any sandy beach remains. Therefore, the flow velocities near the beach at high water must be very low. The beaches are thus obviously in danger of being slowly washed away, never to be replaced until Lake Powell is filled with sediment and the sediment-transporting regime is re-established.

Some fathometer surveys were repeated in the morning at a different rate of flow than when taken the evening before. The measurements were not able to detect a cyclic daily change in response to the fluctuations in the flow throughout a typical day. However, the anticipated response, which would have been of interest in regard to the ability to predict what is happening in the river, is not crucial to predicting the future of the beaches. Perhaps the limited measurements made were too crude, perhaps the changes over a day are too small to measure.

The important observation was that the field measurements agreed with the laboratory observations; that the flow patterns and the sediment movement observable in the laboratory seemed to be duplicated in the field; that the casting up, or building, of beaches and the wearing away of beaches observed in the laboratory were in all probability processes that occur in the field over a much longer period of time.

The measurements made of the velocity "at" the beach, (Figure 10) were somewhat disappointing. In general the velocities observed were quite small, one foot per second or less by a sand beach, three feet per second at the most by a riprapped beach. It was not possible to remain at a location for a day and measure the highest velocity during the

Figure 10. Taking a velocity measurement near a beach

day. And, of course, even this would not have been sufficient becau the configuration of the beach can be a function of past, higher flo It is more than a bit difficult to interpret these low velocities. the case of sand beaches, ripples and sediment transport could be ob served, (Figure 5) implying that the limiting beach configuration of transport (critical tractive force) would involve considerably more beach erosion. On the other hand, the low velocities near riprappe beaches implies that they were formed by considerably higher flows with higher velocities. Both of these interpretations could be per ly valid, but much more time and study in the laboratory and in the field would be necessary to prove the point. Whether such an inves ment of time and effort is justifiable is questionable.

At many rapids and many beaches, it could be observed that the flow boundary had been naturally armoured with riprap - and that o this riprap was only a few inches in diameter. Examples are shown Figure 11. Considerable time and effort would be needed to expand simple observation to decide just what size is needed to armour a face for a given flow in a given rapid geometry. On the other han there is no reason to doubt that physically manageable cobbles and small boulders should in most instances be quite sufficient to protect the beaches against the flows likely to be released from Glen Canyon Dam.

Qualitative Laboratory Experiments

The rapids formed in the small laboratory flume could only be suggestive of real Colorado River rapids. They seemed to be typical in their action. The rapids constricted the flow, there was a critical control and supercritical flow down the face of the rapids. This high velocity, supercritical jet dug a scour hole below the rapids. The jet in the scour hole spread laterally in a 180° fan with some of the flow coming out laterally. The lateral flow carried with it a bed load which moved outward and upward and was deposited as an underwater bar. When the flow rate and the water surface elevation was decreased, this bar (or deposit) was above water and had formed a typical Colorado River beach below a rapids (Figure 12).

As long as sediment was supplied to the head of the flume above the rapids, the bar or beach was stable once it had been formed. The supply of sediment to the beach and the capacity to move sediment along and off the beach was balanced. When the supply ceased, the capacity to transport was no longer balanced by the supply and the beach started to erode. The erosion continued for a time with essentially the same flow pattern as with a sediment supply, but when the beach eroded too much, the main flow would separate from the boundary (the beach) and an eddy would be interposed between the main flow and the beach. The eddy would move sediment upstream along the beach and off the beach into the main flow from whence it would be moved on downstream. The erosion of the beach seemed to go on and on forever, although the rate of erosion got slower and slower. This geometric, assympotic progressi is the usual form of clear-water scour phenomena.

During the active phase of scour hole formation and beach building a greater supply of sediment would result in a shallower scour hole and more rapid beach building. If the rapid contained a large rock, the flow could go over the rock during high flow and be diverted during lo flow - not completely, but more or less. A steep rapid could result i a short scour hole; a flat rapid in a long scour hole. A small, intens eddy could form directly at the end of rapid before the geometry of th scour hole induced the spread of the jet into a fan shape; a strategically placed rock could cause enough lateral flow to break up this edd Different rocks placed differently resulted in different bed and beach configurations but all were very similar and qualitatively alike (Figure 13).

These qualitative laboratory experiments were sufficient to establish that the scour hole and beach found in nature are natural complementary features. It would be surprising to find one without the oth

In the real river there is a wider variation in size of sediment than used in the model. The sediment used for these experiments was the beach material from the Colorado River. The bed material contains coarser material but this coarser material would not be as able to "climb" the bank and become part of the beach. A small fraction of the bed material and a large fraction of the suspended load would be finer than the sediment used in the experiments, but this fine material would not tend to be deposited. The slack water area, in which the bar that ultimately becomes the beach is deposited, is very limited and the fine material does not have enough opportunity to fall out of suspension to any great extent. (The small fraction of fine material in the natural bed material was mostly removed for the experiments in order to be able to see what was going on. The fine material that remained tended not to deposit but instead cycle as suspended load through the recirculatory system). Thus the beach material is a self-sorted fraction of the total sediment being carried by the river, but a fraction that is easily transported even by moderate and low flows.

Occasionally a rock used to form the mass of model rapid would be dislodged. If dislodged, such a rock would be moved a considerable distance. A boulder on top of a sand bed is much easier to move than a boulder in among other boulders of the same general size. This is possibly one reason cobbles and boulders are found in the sand of the beaches, why there can be material in the beach that can armour the face of the beach.

Expectations As To Sediment Transport And Pool Degradation

Earlier work (1) established that the capacity of the controlled river for transporting the normal basic bed material sediment load was about 13 million tons per year and that the tributaries below Glen Canyon supplied only about 3 million tons per year to the river. The size range of the normal beach material is a portion of the size range of this normal, basic bed-material sediment load. The coarser fraction of this sediment load is transported as bed load and the even finer sands, silts and clays that can be temporarily added to the sediment load tend to stay in suspension and if deposited on the beach are easily washed away or blown away.

Because capacity for transport is greater than the supply of sediment, degradation, starting at Glen Canyon Dam, is to be expected and has occured. Surveys of degradation between the Dam and Lees Ferry by the Bureau of Reclamation (2) found that the river bed from the Dam to Lees Ferry is now armoured and that the 8,000 acre feet scoured from the bed was removed mostly in the first years after closure and practically no sediment load has passed Lees Ferry in the last few years. Because the capacity for transport would decrease as the bed became progressively more armoured, the calculated capacity for sediment transport of basic bed material and the measured degradation between Glen Canyon Dam and Lees Ferry are in excellent agreement.

In this 15-mile reach, the river is almost entirely armoured with either residual large rock or self-sorted cobbles and boulders that could not be transported out of the reach by the controlled flows released from Glen Canyon Dam. What little sand transport is still going on is probably mostly derived from the continued erosion of beaches. Some sediment is also supplied from the small tributaries in the reach when they occasionally run and from blow sand from the plat above. ~~Moss~~ Algae growing on the bed of the stream is indicative of little or no sediment being transported.

If the bed material in the pool reaches was only sand of a size readily moved by the flow, and if the sediment supply to the head of the first pool was determined by the normal sediment-transporting capacity of the flow, there would be scour and fill occuring with every change in river flow. For every discharge in every pool there is some bed configuration which is the equilibrium condition attained after a long period of constant flow. This equilibrium condition is dependent on the geometry of the rapids, the geometry (including roughness) of the pool reach, the particular discharge, and the sediment supply to the first pool from the river upstream. As shown by Silverston (3) the behavior of the bed in a downstream pool can seem to be quite erratic as it reacts to variable sediment supply due to the scour and fill in upstream pools.

If the bed material in the pool reaches was still only sand, but now the sediment supply to the first pool goes to zero, each pool in turn will be degraded to a depth such that the velocity of flow and the boundary shear are no longer able to move the sand grains. The greater depth of flow means also a lesser velocity, less head loss, and a smaller slope to the water surface. A little more degradation then occurs, equal to the difference in slopes times the distance upstream from the rapids. If, after equilibrium has been established, the discharge increases, degradation will again occur in the same pattern with time until a new equilibrium is attained. If, then, the dis charge decreases, nothing will happen because there is no supply from above to cause aggradation.

If the bed material in the pool reaches is sand with some boulder that cannot be moved out by the flows now occuring, the degradation ma not be as great as with a simple sand bed. That is to say, if the boulders left behind as the sand bed is scoured out form an armour lay protecting the sand underneath, the amount of degradation will depend how many boulders there are in the bed material. If there are only a few, the degradation can be as much as would be expected with sand alo with the boulders still not forming a protective riprap layer. If the are many boulders the amount of degradation may be quite small. If an armour or riprap layer forms of boulders so large that none of the flo occuring can move them, an increase in discharge will not result in an more degradation. If the boulders are of a size such that some of the can be moved by some flows, some added degradation can take place. An if the pool reach is not uniform from section to section boulders ca[n] be moved downstream and deposited in a deeper pool.

With the controlled flows there should not be much rearrangemen[t] unless some extreme event occurs.

Expectations In Regard To The Future Of The Beaches

Until the general degradation of the river reaches a particular beach, there is a strong tendency for stability of that beach. The flow along the beach is supplied with sediment being transported by the river and the capacity for transport and the sediment supply tend to be in balance. This tendency for stability is merely a tendency and it can be offset by the difference between the prevailing flow pattern and the flow pattern in the past uncontrolled floods which cast up the beach long ago. The large beaches are formed below a rap (Figure 14). With the moderate flows of the controlled releases the direction of the high velocity jet issuing from the rapids (or constriction) can be enough different to cause a steady erosion of a bea towards a new equilibrium of capacity and supply. Such a difference in flow pattern could also cause beach building or a combination of beach building and erosion. Changes in the controlled high and low flow can also cause some erosion and building of particular beaches. As a general rule, however, it would not be expected that these chang in the beach would be major unless the change in flow patterns are major. Some minor changes are to be anticipated since a large boulde becomes relatively smaller in a large flood; it may deflect a large part of a small flow, but only a small part of a large flow.

There may be some tendency towards erosion wearing away the beac at moderate and low flows (Figure 15). Scour and fill often tend to be cyclic; points in a stream which scour during high flow fill durin low flow and vice versa. Since the beaches are cast up in floods, the possibility of erosion during low flows should not be entirely discour However, because low flows have low capacities for transport, the scou or fill processes during low water tends to be slow.

The change in the river which will cause a major change in a beac is the reduction of sediment transport when the degradation comes to that particular beach. Presently the sediment transport in the river is mostly supplied by degradation of the bed and banks in the upstream reaches. Tributaries are supplying perhaps a quarter of the total sediment load of beach-building size and this supply is mostly on a intermittent basis when there is a flood on a tributary. The tendency for stability of the beaches is the balance of sediment supply and capacit to transport sediment. When the sediment supply is reduced to a fract of what it was (or to zero at the extreme), the capacity to transport remains what it was, and the fluid forces pick up and move the beach se ments at the boundary of the flow. The beach erodes. For a time the flow pattern changes slightly with the retreating boundary and erosion continues. With further erosion, the flow may no longer be able to follow the boundary and the main flow may break away or separate from the boundary. An eddy is formed then between the boundary and the flow. The eddy continues to erode the boundary supplying the main flow with the eroded material which is then swept on downstream. In the eddy, the velocity at the boundary is upstream but this has no effect on its ability to erode the beach. As the beach retreats, the eddy becomes larger and eventually the boundary shear in the eddy may no longer be able to move the beach material. Whatever beach is left may be permanent-unless the controlled high flows are increased for some reason sometime in the future.

If there is a sufficient percentage of rocks and cobbles and boulders in a beach, it can gradually and naturally riprap itself because the flow may not be able to move such material and it remain to become the surface of the beach, (Figure 16). Such a riprap armour can be observed may places along the river. The natural process could be enhanced artificially by adding more cobbles of the right size; the result should appear perfectly natural.

How long will all this take? When will the beaches be gone - or almost gone? The experience above Lees Ferry gives an answer of sorts. The degradation will proceed downstream at about the rate of one mile per year. In some reaches the armouring will happen quickly because there is a lot of coarse material in the bed; in some reaches the downstream rate of progress will slow because the bed is mostly sand. The beaches will take longer to go and some beach will probably always remain. The rate at which the river is being cleaned out is not fast. If a program to save the beaches is decided upon, it would not need to be a crash program all along the river. On the other hand, each year that nothing is done means that the beaches in another mile or two of the river are jeopardized.

Expectations As To The Future Of The Rapids

The rapids of the Colorado River are there because unusual storms on tributaries resulted in floods of sufficient magnitude to bring down boulders, large and small, in such a quantity as to create rock dams across the river which subsequent river floods have not been able to wash away. Rock falls, residual boulders and exposed bedrock can contribute to these rock dams which can be built up through a series of events. There are boulder masses which merely constrict the river without creating a rapids; whether because the mass was never large enough to create a dam or because the river has been able to wear it away is difficult, if not impossible, to say. A small rock dam may only create a riffle rather than a rapids; the difference being one of degree from a scientific viewpoint, but of considerable consequence from a practical viewpoint. Running the rapids is a large part of the fun of a Colorado River boat trip (Figure 17).

The essential hydraulic characteristic of rapids is that the cor striction of the flow by the rise in the river bed and the pinching of the walls results in a critical control, i.e., the flow goes thro critical (minimum energy for a given discharge) with subcritical, tr quil, low velocity flow in the pool above, critical depth and veloci at the crest, and supercritical, high velocity flow on the steep roc downstream slope of the boulder mass. At the toe of the rapids, the transition back to the tranquil flow condition in the next pool take place either by jet dispersion in a deep hole downstream of the rapi or among a jumble of large rocks downstream of the toe.

A well-shaped, concrete weir or dam results in a flow pattern wherein these characteristics are simply and clearly illustrated; su critical flow upstream accelerating to the critical control at the crest and on to supercritical flow down the face of the dam and fina a transition to subcritical flow at the toe.

These same characteristics in the same order are found in the f pattern over the boulder mass that forms a rapids; however, the flov now three dimensional and not at all smooth and simple. Each boulde especially the large ones, is a geometric boundary element that the flow must go over and around. In going over a boulder the flow mus uphill and will slow down, only to speed up again when past the top In going around a boulder the flow may be constricted and increase velocity, or it may be deflected past a low-velocity, deadwater cup it may go into a superelevated curve. At different flow rates the surface will be higher or lower in respect to the boulders and the patterns can change dramatically. The boulder mass will not be sym rical right and left, but will be roughly a flat V (or U) shape. S times there will be two channels separated by a boulder island whic may or may not be covered at high flows. At low flow rates, only t bottom of the V is covered with water. At higher flow rates, the c and the velocity over the bottom of the V is greater, and the sides the V becomes covered with water. The dynamic fluid forces on the boulders in the bottom of the V increase from some modest value to larger value; the forces on the boulders on the sides of the V incr from zero when they are out of the flow to some moderate value. Ir eral at low flow rates the forces on any boulder are smaller than a high flow rates; however, because the flow pattern can switch arour with changes in flow rates, for a few special boulders the opposite may be possible.

In the past a few, or many, boulders, large and small, were a to the rapids on infrequent occasions. These added boulders were upon by the dynamic fluid forces of the flow and either resisted t forces and stayed in place or were moved to a new position where t were able to resist the fluid forces. At the extreme, this new po would be in the downstream pool beyond the toe of the rapids. Bef closure and regulation by Glen Canyon Dam, the flood flow each yea quite large and occasionally was very, very large. These large, a very large, flows were unable to remove the boulder masses that fo rapids, but were certainly able to dislodge and transport many of th smaller boulders in the bottom of the V and high up on the sides of V. Since the number of very large boulders added to the rapids is ably small, and the small boulders could be swept out in the large it is likely that only rare events caused much change in a rapids. with the large floods controlled, the ability of the flow to sweep added boulders is less. Some boulders added to the sides of the V making the V a little steeper and concentrating the flow in the bot of the V. Some boulders in the bottom of the V stay between the ve large boulders tending to make the geometry less severe. The tend in general, therefore, should be to make the rapids easier to run; water being higher for a given flow and the deep holes in the bound geometry somewhat filled. The geometries of rapids are so complex ever, that the general tendency will not necessarily be fulfilled rapids. It is quite possible that in the absence of very large flo flows, there will be a tendency to build up a shallows at the toe rapids composed of boulders too big for the controlled high flows move farther on into the next pool.

As the degradation of the river bed in the pools, which start the closure of Glen Canyon Dam, moves on downstream the depth of f the pools will increase until a self-sorted armour or riprap layer tects the bed (unless the bed is already controlled by rock in the The greater depth implies less velocity and, therefore, less energ The water surface slope should, therefore, be less and the tailwate vation at the toe of the rapids lower. If the rock, or armour, la the toe of the rapids is high, the depth of flow in this area may small. There is, then, a second tendency for there to be a shallow boulders at the toe of the rapids in the future more than in the p

If there are not enough boulders to armour the bed at the toe rapids (an unlikely situation), then degradation at the head of the could conceivably undermine the toe of the rapids causing a rearra ment of the boulder mass that could then be either harder or easie run than before.

Summary Of Findings And Recommendations For Further Study

The observations made in this investigation confirm that the River below Glen Canyon is degrading and the beaches are being los though it may be one or two hundred years before this process has course all the way to Lake Mead, in the next five, ten, or fifteen a substantial portion of the most important part of the river wil changed - and it will not be possible to reverse the action and re the river to today's state or previous states. Indeed, it is prob not possible to have extensive sand beaches on the Colorado River Lake Powell is full of sediment and no longer serves as an enormou efficient sand trap. But this would be a long time to wait.

The camera stati. s which were established shoul be used in a monitoring program. Photos could be taken several times a year during routine patrols or research trips. It should only take a few minutes to find the stations and take the pictures. A comparison of past and new photos should be revealing as to what is happening and how fast it is happening. If interpretation of these photos indicate, more stations at other beaches could be easily established.

Nothing can be done about the degradation of the bed of the river. Fortunately, it probalby doesn't matter if the bed of the river does degrade and is eventually composed of cobbles and boulders. In the reach between Glen Canyon Dam and Lees Ferry, at least, the change seems to be for the better rather than for the worse. Below Lees Ferry fine suspended material is contributed by the Paria and the Little Colorado as well as other smaller tributaries and this portion of the river may never be comparable to the reach above Lees Ferry for fishing but neither should it become worse than it is.

The beaches are a different story; they are needed as campsites for river runners (Figure 18). They are disappearing although not as fast as the bed is degrading. In fact, there is reason to believe that the major attack on the beaches follows the degradation of the bed. That is, as long as there is a sediment supply to the beach it has a tendency to be stable. When the degradation has reached a particular beach, the supply goes to zero (or close thereto) and the destruction of the beach begins in earnest.

If manpower can somehow be made available, pilot studies involving beach riprapping should be considered. Some preliminary effort to find out how to riprap a beach so it looks natural, how to move the necessary rock with little or no equipment, and where to place the rock so it will stay, would be a worthwhile investment before embarking upon a major undertaking to save the beaches.

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