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Colorado River Ecosystem Sediment Augmentation Appraisal Engineering Report

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Colorado River Ecosystem Sediment Augmentation Appraisal Engineering Report

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Table of Contents

List of Tables

List of Figures

1.0 Introduction

Colorado River sediment loads, through the Colorado River ecosystem below Glen Canyon Dam are substantially less today compared to natural conditions (U.S. Department of the Interior, Bureau of Reclamation, 1995). This Colorado River ecosystem is defined by the Glen Canyon Dam Adaptive Management Program as the river corridor extending from the forebay of the dam downstream to river mile 278. The primary reason for the reduction in Grand Canyon sediment load is the reservoir sedimentation in Lake Powell. Essentially, the entire sediment load of the Colorado River, upstream from Glen Canyon Dam, is trapped within Lake Powell (U.S. Department of the Interior, Bureau of Reclamation, 1995).

Lake Powell is formed behind Glen Canyon Dam and is located on the Colorado River near the City of Page, in northern Arizona (see figures 1 and 2). Lake Powell backs up into southern Utah and has a total storage capacity of 27 million acre-feet (33 billion m^3), which is 2.3 times the mean annual flow of the Colorado River. Based on the last complete reservoir survey in 1986, sedimentation in Lake Powell had reduced the storage capacity by 868,000 acre-feet (1.07 billion m^3), which is 3.2 percent of the total storage capacity of 27 million acre feet (33 billion m^3) (Ferrari, 1988). Now, Colorado River tributaries below Glen Canyon Dam provide the only significant sediment source to the Grand Canyon.

Since the completion of Glen Canyon Dam in 1963, annual sediment loads to the Grand Canyon stream gage have decreased from 91 ± 4 million tons per year (83 ± 4 million Mg per year), of which approximately 35% was sand, to 15 million tons per year (14 ± 1 million Mg per year) (Topping et al, 2000a). Sediment can be classified by particle size and can include clay, silt, sand, gravel, and cobbles. This study is primarily concerned with sand and finer (silt and clay) sized sediments. The reduced sand loads and natural floods have reduced the number and size of sandbars in Glen, Marble, and Grand Canyons. The reduced fine sediment loads have resulted in less turbidity and less cover for native and endangered fish (U.S. Department of the Interior, Bureau of Reclamation 1995). The augmentation of sediment loads to the Colorado River ecosystem may reverse some of the sediment related impacts caused by operation of Glen Canyon Dam.

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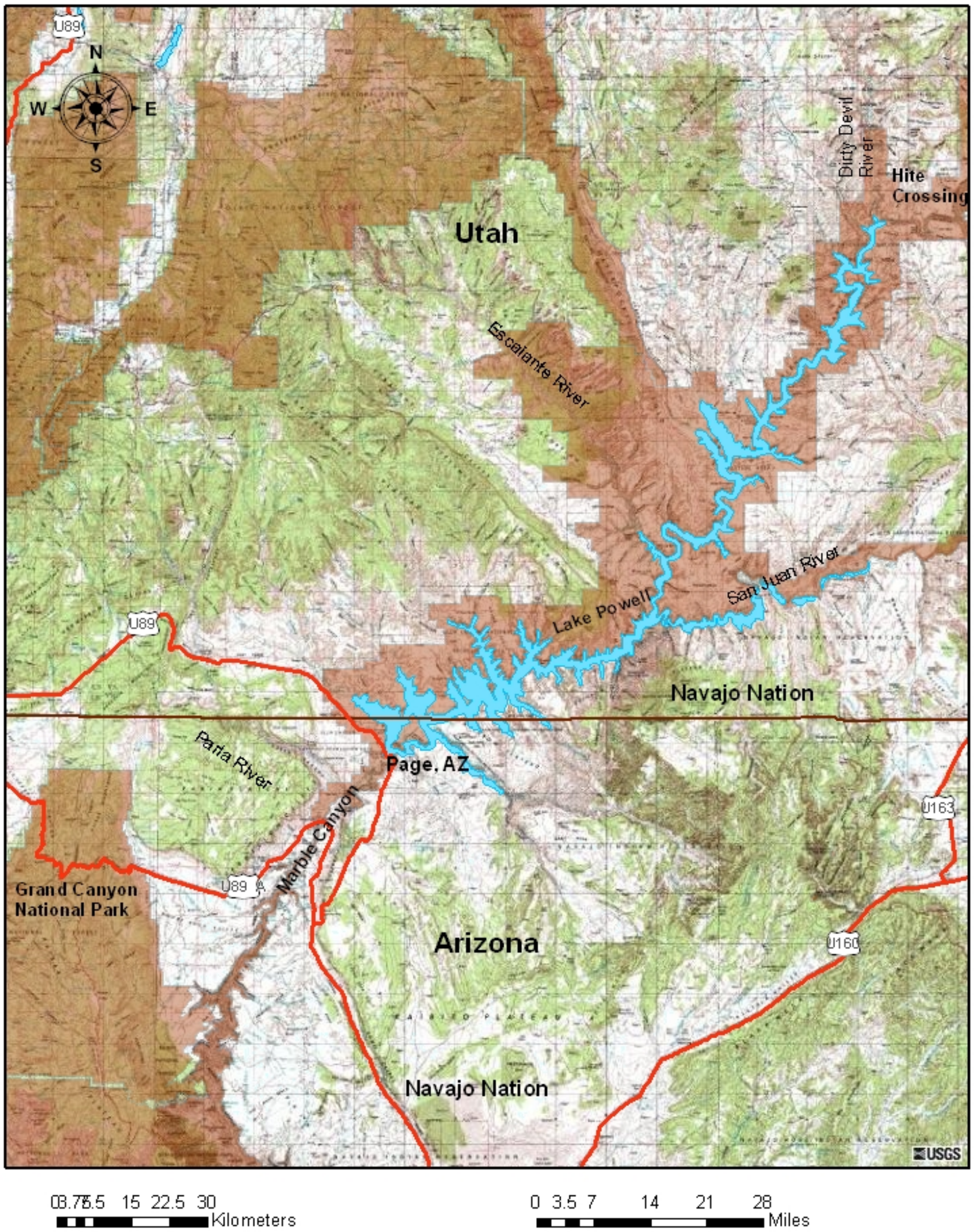

Figure 1. Location map of study area including Lake Powell, Colorado River, Paria River, Marble Canyon, Grand Canyon National Park, and the Navajo Nation.

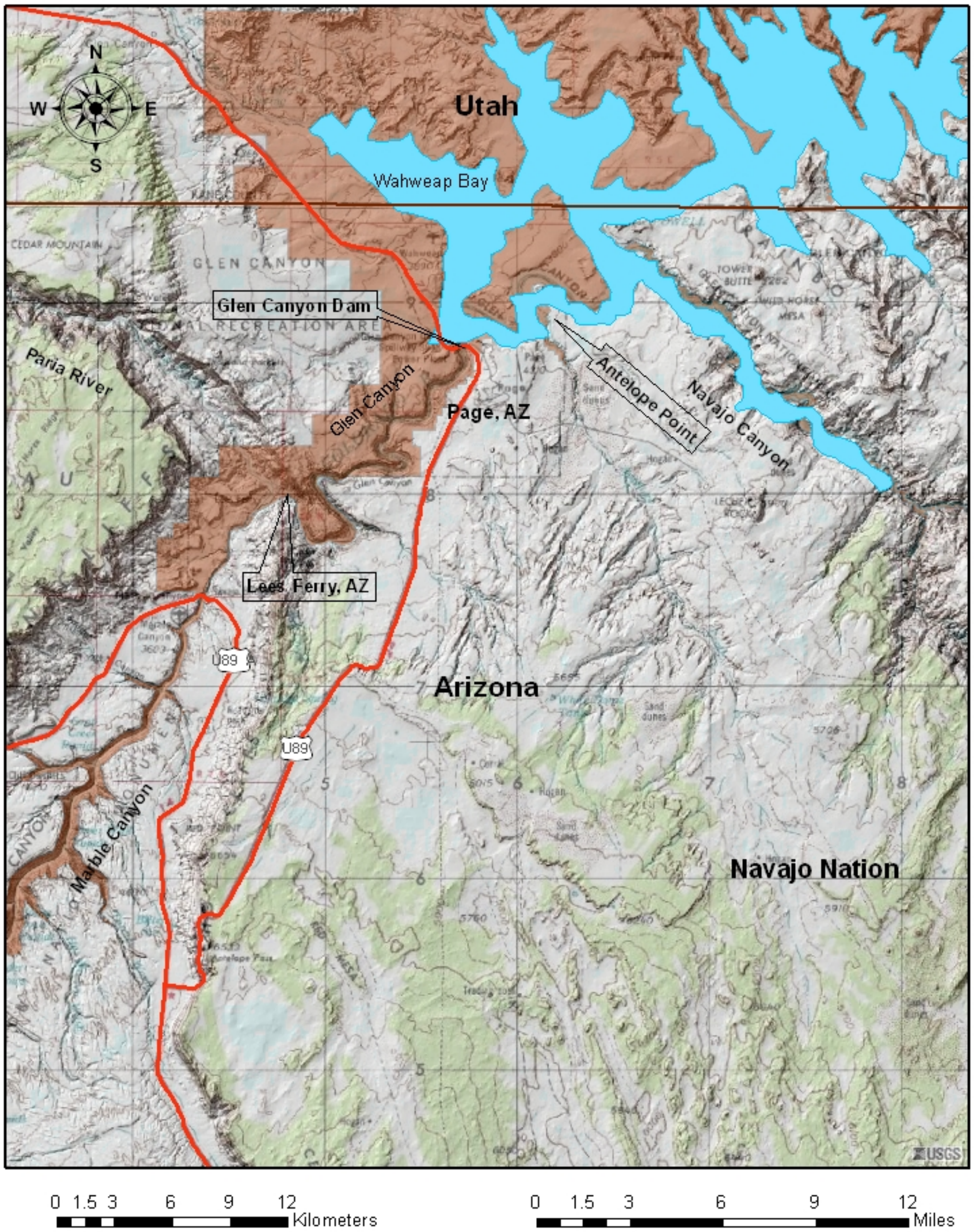

Figure 2. Close-up location map of Glen Canyon Dam, Lake Powell, Navajo Canyon, Antelope Point, City of Page, the Navajo Nation, Colorado River, Paria River, Lees Ferry, and Marble Canyon.

1.1 Study objectives

The objectives of this appraisal-level study are to investigate the engineering methods and requirements of sediment augmentation systems that would deliver sand, silt and clay to the Colorado River at alternative locations downstream from Glen Canyon dam. Alternative sediment sources, delivery methods, and points of delivery are evaluated and appraisal-level costs are compared. This appraisal-level study provides the necessary information to facilitate making decisions on whether or not to proceed with a detailed study and evaluation of any alternative. A detailed description of the physical and biological effects of sediment augmentation in Grand Canyon is beyond the scope of this investigation.

1.2 Sediment Augmentation Purposes

Grand Canyon sediment augmentation would have two primary purposes:

1. Seasonally increase the turbidity of the Colorado River to provide cover for native and endangered fish during the months of May through December. This is the period when young-of-the year humpback chub emerge from the Little Colorado River and then rear in the Colorado River (U.S. Department of the Interior, Bureau of Reclamation, 1995). These native fish evolved in a turbid environment and may use it for cover from potential predators.

2. Annually increase the sand supply to the Colorado River during beach-building flows to build larger sandbars, especially in Marble Canyon, through fluvial processes.

The Colorado River turbidity objective is to continuously achieve a minimum suspended-sediment concentration for silt and clay-size sediments (fine sediment) each year from May through December. Fine sediment would not have to be added during times when the turbidity of the Colorado River has increased during floods from the Paria River. The mean annual sediment load from the Paria River at Lees Ferry, Arizona was 3.3 ±0.7 million tons per year (3.0 ± 0.6 Mg/yr), of which about 50 percent was sand, for the period of sediment record (Topping et al, 2000a). During the period 1923 to 1986, two-thirds of the Paria River annual peak discharge occurred in the months of August, September, and October. About than 90 percent of the Paria River annual sediment load occurs during the period July through October (Andrews, 1991).

The minimum suspended-sediment concentration (for fine sediment) in the Colorado River that would benefit native and endangered fish has yet to be determined by fishery scientists, but is believed to be between 100 and 1,000 ppm. A concentration of 500 ppm is assumed for this study. At this concentration, the Colorado River would transport 3.8 million tons (3.4 million Mg) of fine sediment per year over the 8-month period from May through December.

The sand objective is to annually deliver one million tons (0.9 million Mg) of sand to the Colorado River that would be available for transport in the river up to one month prior to the release of beach-building flows from Glen Canyon Dam. The sand augmentation would increase the potential for sandbar deposition throughout Marble Canyon. In order to prevent the augmented sand from being transported past Marble Canyon prior to beach-building flow, the sand would have to be accumulated and stored in or near the river channel during the months prior to the release of the beach-building flow.

Together, these objectives would require that the Grand Canyon annually receive 3.8 million tons (3.4 million Mg) of silt and clay (over the period May through December) and 1 million tons (0.9 million Mg) of sand prior to the beach/habitat-building flow. The total annual sediment supply requirement would be 4.8 million tons (4.3 million Mg). A portion of this sediment load could come from the Paria River, but sediment augmentation would still be required in most years to meet these two objectives.

1.3 Previous Investigations

Sediment augmentation to the Colorado River below Glen Canyon Dam was considered as part of the "Operation of Glen Canyon Dam Environmental Impact Statement" (U.S. Department of the Interior, Bureau of Reclamation, 1995). Sediment augmentation was included as part of the Run-of-the-River Alternative that was considered, but eliminated from detailed study. The environmental impact statement (EIS) concluded that sediment augmentation would require data collection, research and analysis, a separate EIS on alternative augmentations systems, and that a sediment augmentation system would take a decade or more to implement. Therefore, the EIS focused on dam operation alternatives that could be implemented right away. The EIS concluded that sediment augmentation could be considered at a later time.

2.0 Alternative Sediment Augmentation Systems

A reasonable range of alternative sediment augmentation alternatives was formulated and evaluated for technical feasibility and cost. Attempts were made to make each alternative as viable as possible. However, some options were eliminated from additional consideration. Attempts were also made to formulate alternatives in a way that eliminate or reduce environmental impacts.

Alternative sediment augmentation systems can be divided into components:

- Sediment source areas
- Sediment delivery locations
- Sediment collection methods
- Sediment delivery methods and alignments
- Sand storage areas

Alternatives were evaluated for each component. The choice of the sediment source area and the delivery location helped to determine the requirements of the remaining components. A summary list of each component, and the alternatives considered, are presented in table 1. The alternative components that were considered technically feasible, and considered in some detail, are listed in a **bold** font. Alternative components that may be technically feasible, but were not considered in detail because they were judged to be more expensive, are listed in a normal font. Other alternative components that were considered to be technically or logistically infeasible are presented with a gray shading.

Table 1. Alternative sediment augmentation features.

Alternative Sediment Sources	**Lake Powell** • Colorado River data near Hite Crossing, Utah • San Juan River • Dirty Devil River • Escalante River • **Navajo Canyon**	Lake Mead	Terrestrial Site

Alternative Sediment Delivery Locations	**Directly below Glen Canyon Dam**	**Near Lees Ferry**	Other locations in Glen Canyon	Paria River

Alternative Sediment Collection Methods	**Clamshell dredge**	Hydraulic dredge	Other dredges

Alternative Sediment Conveyance Methods and alignments from Navajo Canyon	**Slurry pipeline submerged within Lake Powell to Antelope Point then overland to below Glen Canyon Dam**	Barge transport across Lake Powell to Antelope Point then truck transport to either below Glen Canyon Dam or Lees Ferry
	Slurry pipeline submerged within Lake Powell to Antelope Point then overland to Lees Ferry	Slurry pipeline overland from Navajo Canyon to either below Glen Canyon Dam or Lees Ferry

Alternative Sand Storage Areas	**Colorado River in Glen Canyon**	**Terrestrial site near Lees Ferry**

2.1 Alternative Sediment Sources

Alternative sediment sources include Lake Powell Deltas, the Lake Mead Delta (downstream from Grand Canyon), and terrestrial sites in the region between Glen Canyon Dam and Lees Ferry.

Lake Powell deltas are the preferred source of sediment because this reservoir sediment otherwise would have been transported through the Grand Canyon under natural conditions. Lake Powell contains a large volume of reservoir sediment and this volume continues to grow each year and gradually shortens the life of the reservoir. The sediments in Lake Powell generally tend to be sorted by grain size with sands concentrating in the reservoir deltas and fine sediment depositing farther downstream in deeper areas along the lake bed. Fluctuations in reservoir inflow and lake level result in layers of varying sediment size, so the reservoir sediments are not completely sorted.

The Lake Mead delta contains a large volume of sediment that already came through the Grand Canyon. The recycling of Lake Mead sediment through Grand Canyon would not affect the long-term sedimentation rates in Lake Mead. However, the long distances and elevations over which the sediment would have to be delivered make this alternative source area more expensive than sources within Lake Powell.

Sediments could be mined from land areas that are closer to the Colorado River, in the reach between Glen Canyon Dam and Lees Ferry, than sources in Lake Powell. However, the mining of sediment from terrestrial sources would not be sustainable over the long term. In addition, mining operations would have another set of environmental impacts. All of the nearby land is part of the Navajo Indian Reservation or Federally protected parks or wilderness.

The areas of Lake Powell that are believed to contain sufficiently large volumes of sediment to augment the Colorado River in Grand Canyon are shown in figure 3 and table 2. The largest delta volume is the Colorado River delta near Hite Crossing, Utah, followed by the San Juan delta. The Navajo Canyon delta is the closest to Glen Canyon Dam, followed by the Escalante River delta, San Juan River delta, Dirty Devil River delta, and the Colorado River delta.

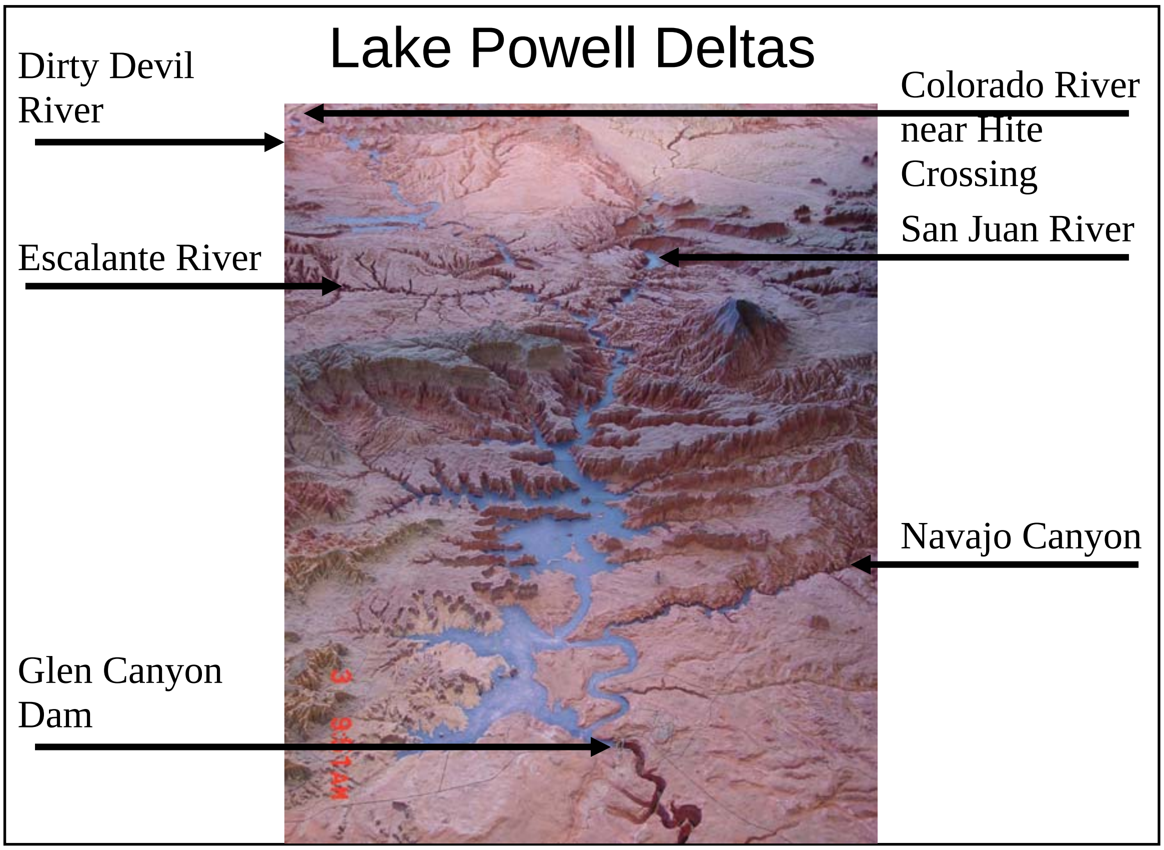

Figure 3. Lake Powell and delta locations.

Table 2. Lake Powell 1986 delta distances and sedimentation volumes (Ferrari, 1988 and Ferrari, Bureau of Reclamation, written communication, 2006).

Lake Powell Delta	Distance from Glen Canyon Dam		Sedimentation Volume	
	miles	km	Acre-feet	m^3
Colorado River near Hite, Utah	170	270	472,000	580,000,000
Dirty Devil River	160	260	22,000	27,000,000
San Juan delta	120	190	281,000	350,000,000
Escalante River	99	160	23,000	28,000,000
Navajo Canyon	33	52	29,000	36,000,000

2.1.1 Navajo Canyon

The sediments of Navajo Canyon are about 70 feet thick at the canyon mouth and about 60 feet thick at the upstream delta. The sediments at the mouth are submerged by 340 to 480 feet (110 to 150 m) of water and are likely silt or clay in size. At a full reservoir pool elevation of 3700 feet (1128 m), the reservoir portion of Navajo Canyon is 22 miles (35 km) long (see figure 4). At a distance of 11 miles (18 km) from the canyon mouth, the delta surface consists of fine sand with silt.

A sample was obtained from the delta surface, at about river mile 11 (18 km) during a reconnaissance field trip in November 2004 (see figure 5). The laboratory results from this sample are summarized below. More detailed results are presented in Appendix A.

- 57 percent silt and clay
- 43 percent sand
  - 30 percent very fine sand
  - 13 percent medium sand
- Angular quartz particles have high potential for abrasion of pipes, valves, and pumps
- The sample was analyzed for 39 elements, but no contaminants were found.

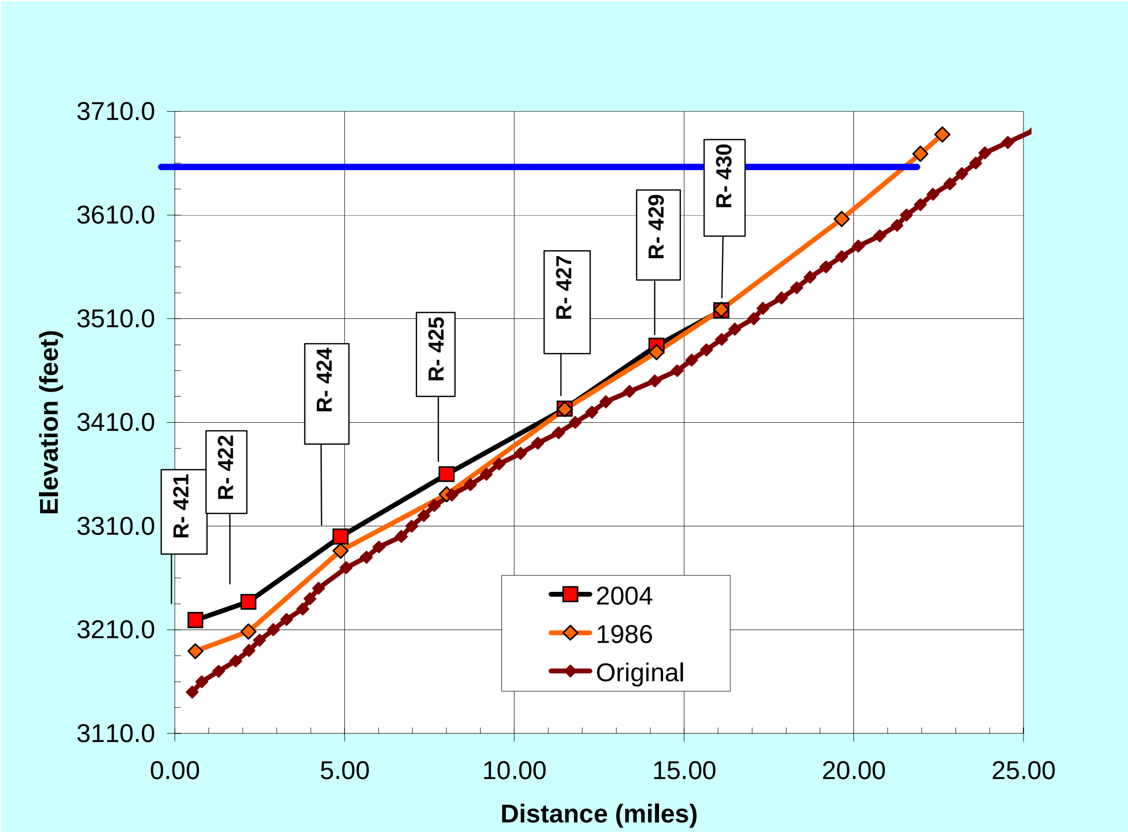

Figure 4. Longitudinal sediment profiles of Navajo Canyon.

Figure 5. Navajo Canyon delta surface near river mile 11 (18 km) on November 3, 2004.

The sediment in Navajo Canyon is the closest sediment to Glen Canyon Dam that is believed to be sufficiently large to support a sediment augmentation program for Grand Canyon. Therefore, the cost of delivering reservoir sediment from Navajo Canyon is expected to be significantly less than any other viable source within Lake Powell.

The sedimentation volume of Navajo Canyon is estimated to be a maximum of 30,000 acre-feet (37 million m^3), based on the Lake Powell surveys of 1986 (Ferrari, 1988) and 2004 (Ferrari, Bureau of Reclamation, written communication, 2006). Assuming a unit weight of 70 lbs/ft^3 (1.1 g/cm^3), the sediment mass is estimated to be a maximum of 40 million tons (36 million Mg), with an average annual sedimentation rate of 1 million tons per year (0.9 million Mg/yr). As previously stated, the sediment sample from the delta surface near the receded lake elevation was 57 percent silt and clay and 43 percent sand. An assumption is made that delta sediments farther upstream will contain a significantly higher percentage of sand while sediments that are father downstream will contain a significantly higher percentage of silt or clay. This assumption would have to be verified in subsequent investigations.

Antelope Canyon may also be another significant sediment source that is 5 miles (8 Km) closer to Glen Canyon Dam. The present sediment volume from Antelope Canyon is unknown. The drainage area of Navajo Canyon (760 mi^2 or 2,000 km^2) is 4.5 times larger than the drainage area of Antelope Canyon (170 mi^2 or 450 km^2). The larger drainage area of Navajo Canyon would be expected to have a greater sediment yield than the yield from Antelope Canyon. In addition, the longitudinal profiles of Lake Powell, measured in 1986, 2001, 2004, and 2005, all indicate the presence of a sediment deposit that extends 3 to 4 miles (5 to 6 Km) from the mouth of Navajo Canyon, along the old Colorado River channel submerged by Lake Powell (see figure 6). A similar such deposit is not evident in the longitudinal profiles at the mouth of Antelope Canyon. However, a submarine fan at the mouth of Antelope Canyon is evident in detailed bathymetry plots measured in June 2005 (see figure 7). This submerged fan extends longitudinally for a distance of one or two canyon widths (1,000 to 2,000 feet or 300 to 600 m).

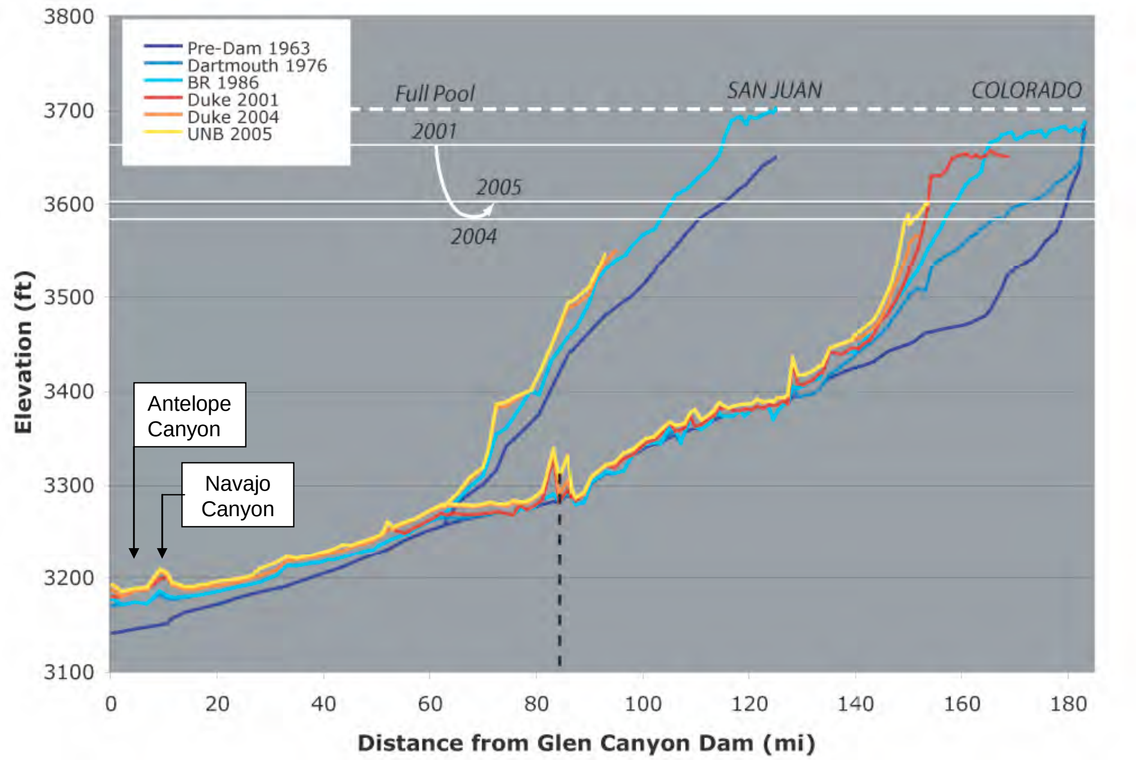

Figure 6. Longitudinal bottom profiles of Lake Powell (L. Pratson, Duke University, written communication, October 3, 2006).

The annual sedimentation rates in Navajo Canyon are probably not be large enough to indefinitely sustain a sediment augmentation program for Grand Canyon providing 3.8 million tons (3.4 million Mg) annually (see figure 8). However, the existing sedimentation volume and the future rate of sedimentation likely would sustain a sediment augmentation program for one or two decades, assuming that Paria River supplies sediment, at an average annual rate of 1 million tons per year (0.9 million Mg/yr), to partially meet the objectives described in section 1.2. The removal of reservoir sediment from Navajo Canyon would not preclude the future removal of reservoir sediment from more distant areas of Lake Powell. Therefore, the Navajo Canyon area of Lake Powell is the only sediment source considered in detail for this investigation.

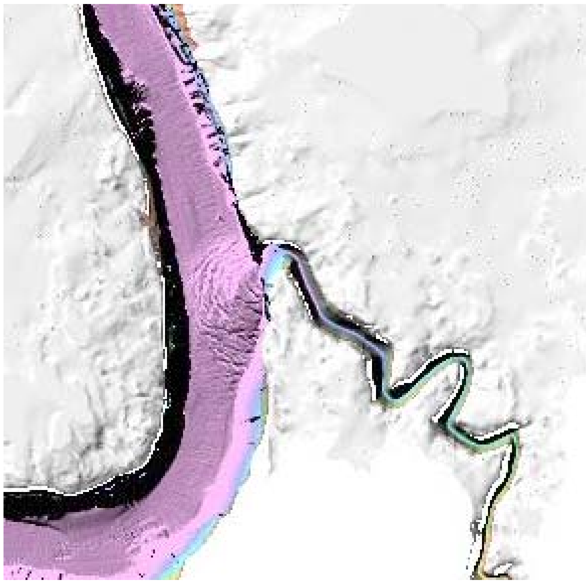

Figure 7. Detailed bathymetry at the mouth of Antelope Canyon shows a summarine fan deposit in the old Colorado River channel that extends longitudinally for a distance of one or two Colorado River canyon widths (L. Pratson, written communication, December 1, 2006).

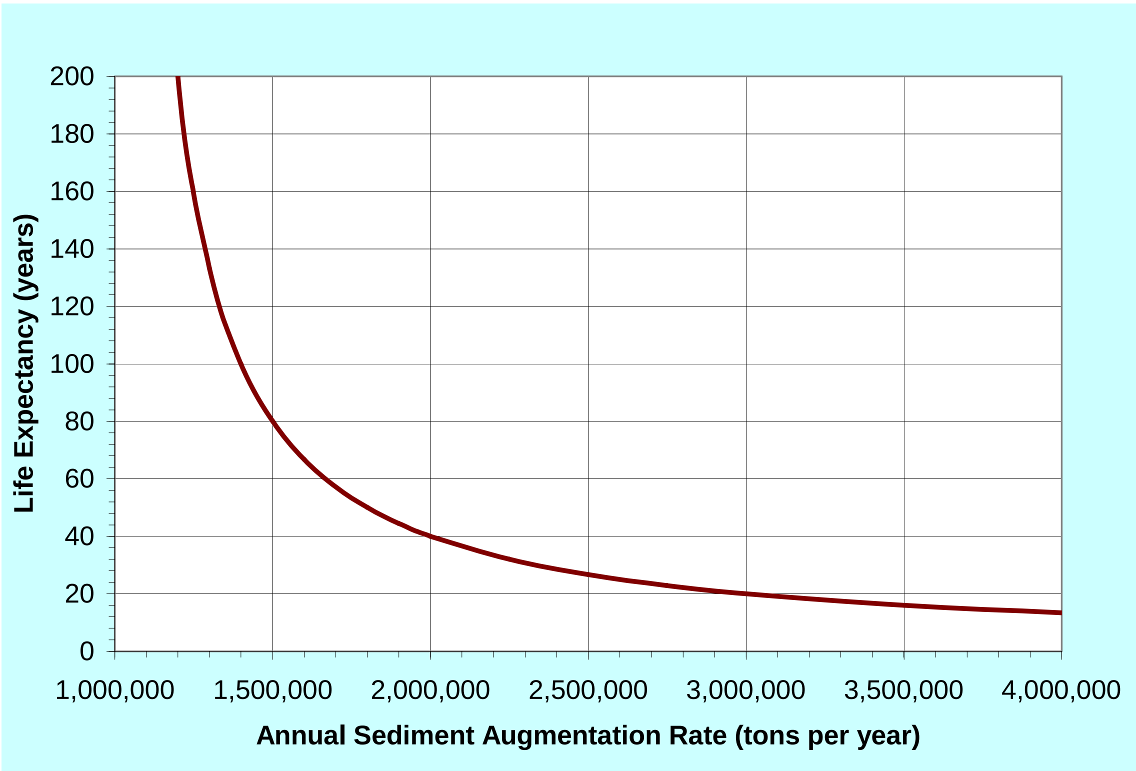

Figure 8. Life expectancy of the Navajo Canyon sediment source as a function of the annual sediment augmentation rate.

2.1.2 Other Sediment Source Areas Not Considered in Detail

The following sediment source areas of Lake Powell were not considered in detail for this study, but these areas may warrant additional study in the future:

- San Juan River delta
- Colorado River delta near Hite, Utah
- Dirty Devil River delta
- Escalante River delta

The Lake Mead delta also was not considered in detail because the long distances and elevations over which the sediment would have to be delivered make this alternative source area more expensive than sources within Lake Powell.

2.1.3 Sediment Source Areas Eliminated From Consideration

Wahweap Bay area of Lake Powell is very close to Glen Canyon Dam, there is good road access, and electrical power is readily available. However, the small sediment volume and large percentage of gravel make this an unsuitable source for the purposes identified in section 1.2.

Sediments could be mined from land areas that are closer to the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona than the sediment source areas within Lake Powell, but such sources would not be sustainable over the long term. In addition, mining operations would have another set of environmental impacts. All of the nearby land is part of the Navajo Indian Reservation or Federally protected parks or wilderness.

Some people have suggested that Paria River sediment loads be somehow increased or that a dam be built across the Paria River to store and regulate future sediment loads.

The Paria River enters the Colorado River 16 miles (26 km) downstream from Glen Canyon and is now the second largest source of sediment to the Grand Canyon (Wright et al, 2005). The Paria River naturally supplies an average annual sediment load of 3.0 million tons per year (2.7 Mg/yr) (Andrews, 1991). Any scheme to increase Paria River sediment loads would require that additional water be diverted into the Paria River basin. Additional water is not likely available for such purposes. Once sediments are eroded from the landscape, they cannot be eroded from the same location again. Increases in sediment loads over the short term would reduce sediment loads in subsequent years. Therefore, a sustained increase in Paria River sediment loads is not possible.

A dam and reservoir across the Paria River to regulate sediment loads is not technically feasible without a great deal of mechanical intervention. The reservoir sediment-trap efficiency decreases with increases in reservoir flow velocity and increases with sediment particle size (Strand and Pemberton, 1983). Sand and coarser sized sediments would tend to deposit in a reservoir pool while a large portion of the finer silts and clays would be transported through a sediment retention reservoir. The reservoir sediment-trap efficiency would reduce over time as the reservoir filled with sediment so that inflowing sediments would be transported through the reservoir. Sand sized sediments would deposit as a delta across the entire width of the reservoir while fine sediment would tend to be transported through the reservoir. If the reservoir were drawn down to release stored sediments, river flows would only erode a narrow channel through the reservoir sediments and a great majority of the reservoir sediments could only be removed through mechanical intervention (Morris and Fan 1997). In addition, the Paria River is in a federally protected wilderness area where the construction of dams or roads would not be allowed, except by special act of Congress.

2.2 Alternative Sediment Delivery Locations

The primary delivery points considered for this study are immediately downstream from Glen Canyon Dam and near Lees Ferry (see figure 9). Other delivery points within the Glen Canyon reach were considered such as Ferry Swale Canyon and Water Holes Canyon. However, these other locations do not expand the range of reasonable alternative delivery locations bounded by Glen Canyon Dam and Lees Ferry. Sediment delivery near Lees Ferry would avoid many of the impacts to the trout fishery in the Glen Canyon reach, but at more cost than sediment delivery below Glen Canyon Dam. Sediment delivery immediately below Glen Canyon Dam would have the potential to restore a portion of the pre-dam sediment transport conditions in the reach between Glen Canyon Dam and Lees Ferry. However, sediment delivered to the Glen Canyon reach may impact the trout fishery and the aquatic food base.

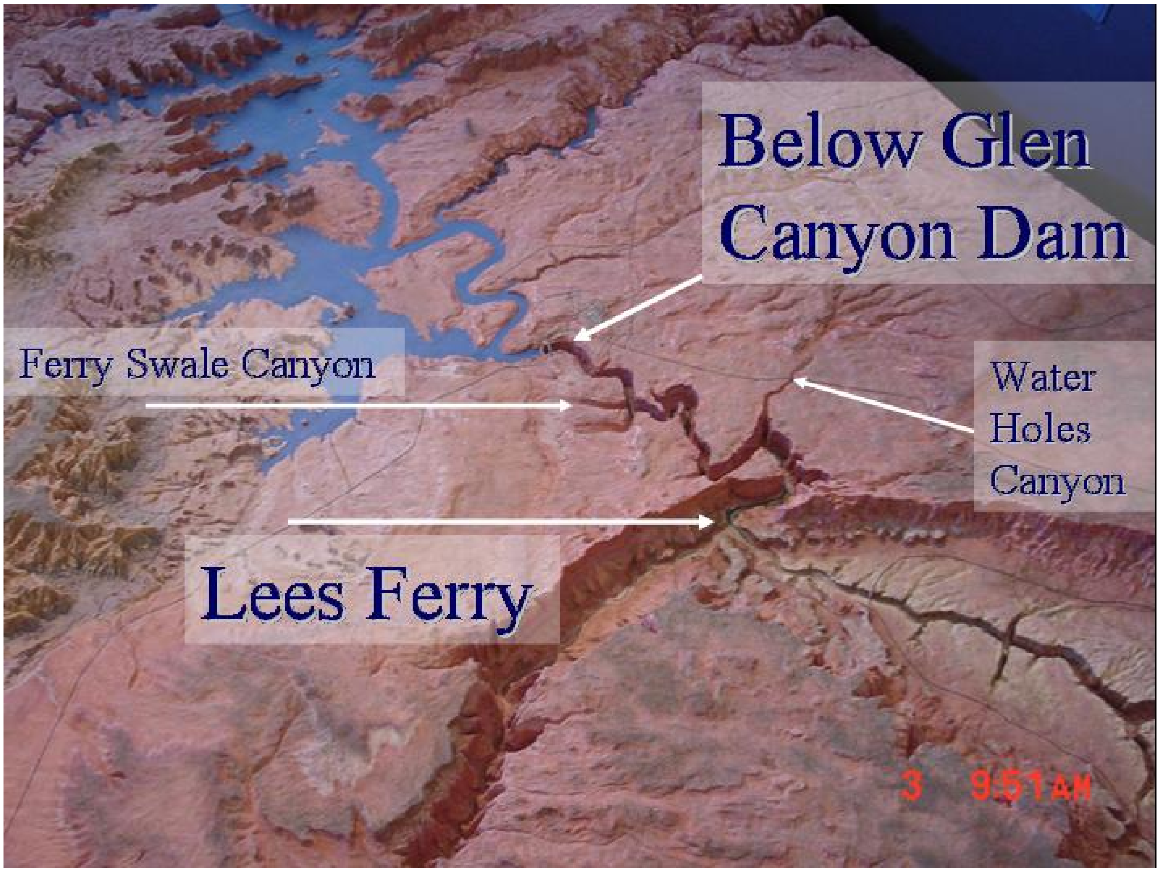

Figure 9. Glen Canyon reach of the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona.

2.2.1 Below Glen Canyon Dam or near Lees Ferry

The alternative sediment delivery locations are summarized below:

- Below Glen Canyon Dam
    - Sand: continuous year-round discharge
    - Silt and clay: continuous, seasonal discharge
- Lees Ferry
    - Sand: stock pile and discharge before beach-building flow
    - Silt and clay: continuous, seasonal discharge

For the purposes of this study, the following delivery requirements are assumed. These assumptions will have to be further evaluated and refined by subsequent studies.

- Delivery of 1 million tons (0.9 million Mg) of sand per year, which would be available for transport by the Colorado River in Grand Canyon a month prior to, and during, special beach-building flows released from Glen Canyon Dam.

- Delivery of enough silt or clay-sized material to continuously increase the suspended sediment concentration by 500 ppm during the period May through December of each year.

Although fine sediment needs to continuously discharge into the Colorado River, the sand must be stored somewhere prior to the beach-building flow. If the sand were delivered too early, then there is concern that it would be transported past Marble Canyon prior to the beach-building flow (Rubin et al, 2002). If sand were first delivered to the Colorado River at the beginning of the beach-building flow, then the discharge wave would be expected to travel through Marble Canyon faster than the sand augmentation (Rubin et al, 2002).

The slope of the Colorado River downstream from Lees Ferry is significantly steeper than in the Glen Canyon reach upstream from Lees Ferry. Sand delivered to the Colorado River just downstream from Lees Ferry is expected to be transported downstream through Marble Canyon in a matter of months (Rubin et al, 2002, Wright et al, 2005, and Topping et al, 2000a and 2000b). However, sand delivered to the Glen Canyon reach, just below Glen Canyon Dam, is expected to be transported at a much slower rate with a significant portion being stored in pools (Grams et al, in press).

Sand delivered to Lees Ferry would have to be stored in close proximity to the Colorado River. No sand storage areas exist immediately below Glen Canyon Dam, but sand introduced into the Colorado River below the dam may be deposited in deep pools of the Glen Canyon reach and remain there until periods of high flow. A very short-duration high flow, but less than the magnitude of the beach-building flow, could be released from the dam a month prior to the beach-building flow to initiate the sand transport to Marble Canyon. Existing sandbars might be scoured if the magnitude of the pre-high flow release were too high. A high-flow release with a few hours duration would likely attenuate rapidly as the discharge wave traveled downstream and thus reduce its sediment transport capacity past the Glen Canyon Reach. Once the sand is transported into the Marble Canyon reach, the beach-building flow could be released from Glen Canyon Dam. These assumptions need to be verified in subsequent studies.

Sands and fine sediments could be delivered to the Colorado River below Glen Canyon Dam through either slurry pipelines or by trucks. The slurry pipelines would join and enter Glen Canyon though a single inclined shaft, excavated by directional drilling from the canyon plateau.

The inclined shaft would have a high head at the discharge point and would require a control valve and concrete structure located at the approximate level of the river. The energy from these pipelines would be dissipated by the discharge of the slurry into a pool area of the Colorado River.

2.2.2 Sediment Delivery Points Eliminated from Consideration

The delivery of sediment to the Paria River canyon was eliminated from further consideration because there would no means of transporting the augmented sediments to the Colorado River in a timeframe that would meet management objectives. Augmented sediments would likely form a deposit that would only be transported episodically during flash floods.

The Paria River delivery point was also eliminated because of the Wilderness status for the river canyon.

2.3 Alternative Sediment Collection Methods

Sediment would be dredged from Lake Powell using two separate dredges. One dredge would be positioned in the downstream reaches of Navajo Canyon where the lake depths are deep and the bottom is believed to be covered with fine sediments. The second dredge would be placed farther upstream in Navajo Canyon where the lake surface intersects the delta and the sediments are believed to be primarily sand. This would require that sands would have to be transported farther than the fine sediments.

Each of the two dredges would require at least two to three personnel which includes a qualified dredge operator and a mechanic. This is required for both safety and to address general maintenance of the dredges. The dredges would be operated 24 hours a day (with short down times for maintenance and dredge positioning), so operators would have to work in shifts. A boat would be required to transport the various crews to and from the dredges.

The dredge excavating sands would be operated approximately year round to accumulate one million tons (0.9 million Mg) of sand. The dredge collecting the fine sediments would be operated from May through December of each year.

There are many types of dredges that can be used to excavate sediment (see appendix B):

- Suction Dredges
- Dragline Dredges
- Clamshell Dredges
- Auger Dredges
- Cutter Dredges
- Ladder-Bucket Dredges
- Hopper Dredges
- Rotary or Bucket Head Cutter Dredges
- Excavator or Backhoe Dredges

Due to the range of possible water depths, clamshell style dredges which have an excavating depth range of up to 300 feet (90 m) would be used. The clamshell dredges have two buckets (with a capacity of 13 yd^3 or 9.9 m^3), hinged together that close around the sediment and are then lifted back to the surface by a cable hoist system (see figure 10) The sediment is then dumped onto a mechanical separator that removes any rocks or woody debris from the dredged material. The sediment can then be either conveyed to a barge for transport or moved into a mixer where water is added by a fresh water pump to create the desired solids concentration for the slurry pipeline. Slurry pumps can then discharge this mixture into the slurry pipelines.

Figure 10. Clamshell dredge excavating sediment.

For every one million tons (0.9 million Mg) of sand that is dredged per year, 4,000 tons (3,600 Mg) of sand would be dredged per day, assuming 250 working days per year. For every one million tons (0.9 million Mg) of fine sediment that is dredged per year, 6,000 tons (5,400 Mg) of fine sediments would be dredged per day, assuming 166 working days per year. The expected life of the sediment collection system may be about a decade. However, the expected life has not been precisely determined for this study and would have to be determined at the next (feasibility) level of investigation.

2.4 Alternative Sediment Conveyance Methods and Alignments

The alternative sediment conveyance methods include sediment slurry pipelines, barges, and trucks. The sediment slurry pipeline was found to be the only viable method for conveying the large quantities of sediment from Lake Powell to the Colorado River (see table 3). Barges across Lake Powell are not a feasible method of sediment transport because of the excessive number of required barge trips (see section 2.4.2.1). Trucks are also not feasible because of the excessive number of required trips on the highways (see section 2.4.2.2).

Table 3. Feasibility summary of sediment delivery methods.

Conveyance Alternative from Navajo Canyon	Feasibility
Barge sediment across Lake Powell then convey overland by truck to the delivery point	Technically infeasible because of the large impacts to recreation use and aesthetics on portions of Lake Powell and the excessive number of trucks required on the highways.
Slurry pipeline within Lake Powell and overland slurry pipelines along existing roads to delivery points	Technically feasible at low enough concentrations (< 20 percent, by weight). At higher concentrations, the pipelines may clog during power outages when flow velocities would be reduced to zero.
Overland slurry pipelines out of Navajo Canyon and then continuing along existing roads to the delivery point	Technically infeasible because the access is too difficult, the head is too high, and because a floating pipeline or barges would still be required within Navajo Canyon.

Alternative slurry pipeline alignments were considered from the sediment source area of Navajo Canyon and to the Colorado River delivery points. The following criteria were used to evaluate alternative slurry pipeline alignments:

- The slurry pipelines would have to exit Lake Powell at a point where the topography would not be too steep to build a pumping plant at the lake shoreline elevation. The first land-based pumping plant would have to be constructed just above elevation 3700 feet (1128 m), the full pool elevation of Lake Powell. This is because the lake elevation could decrease by 150 feet (46 m). Road access to the pipeline and pumping plant also would have to be feasible.

- Permission would have to be granted for the pipeline alignment. Alignments across Federal lands or along existing highway right-of-ways would be most feasible.

- Significant impacts to cultural and natural resources (including aesthetics) should be avoided where possible.

Overland routes out of Navajo Canyon were eliminated from additional consideration because access is too difficult, the head to pump a sediment slurry is too high (1,000 feet or 300 m), and because a floating pipeline or barges would still be required in Navajo Canyon. In addition, any overland routes out of Navajo Canyon would have significant impacts to cultural and natural resources within the Navajo Nation.

The viable pipeline-alignment alternatives include submerged slurry pipelines across Lake Powell to Antelope Point, then overland to either below Glen Canyon Dam or Lees Ferry (see figure 11). A plan-view map and longitudinal profile of the pipeline alignment from Navajo Canyon to below Glen Canyon Dam are presented in figures 12 and 13. A plan-view map and longitudinal profile of the pipeline alignment from Navajo Canyon to Lees Ferry are presented in figures 14 and 15.

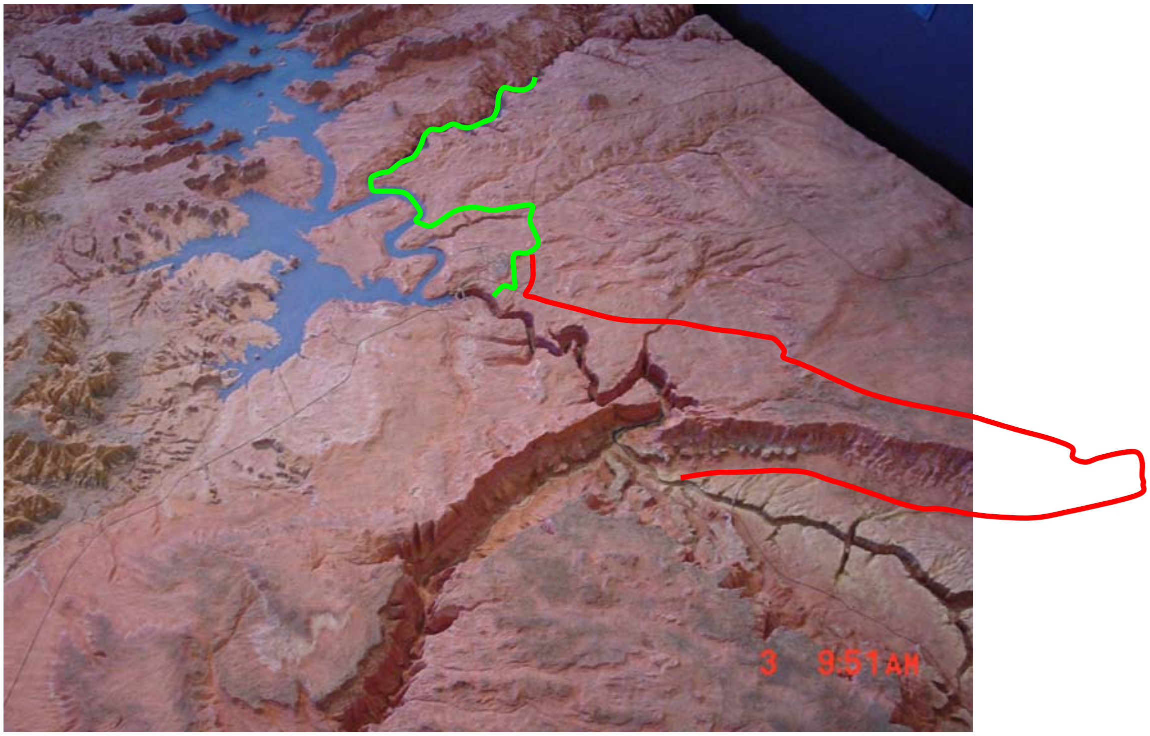

Figure 11. Alternative sediment slurry pipeline routes from Navajo Canyon to below Glen Canyon Dam and to Lees Ferry.

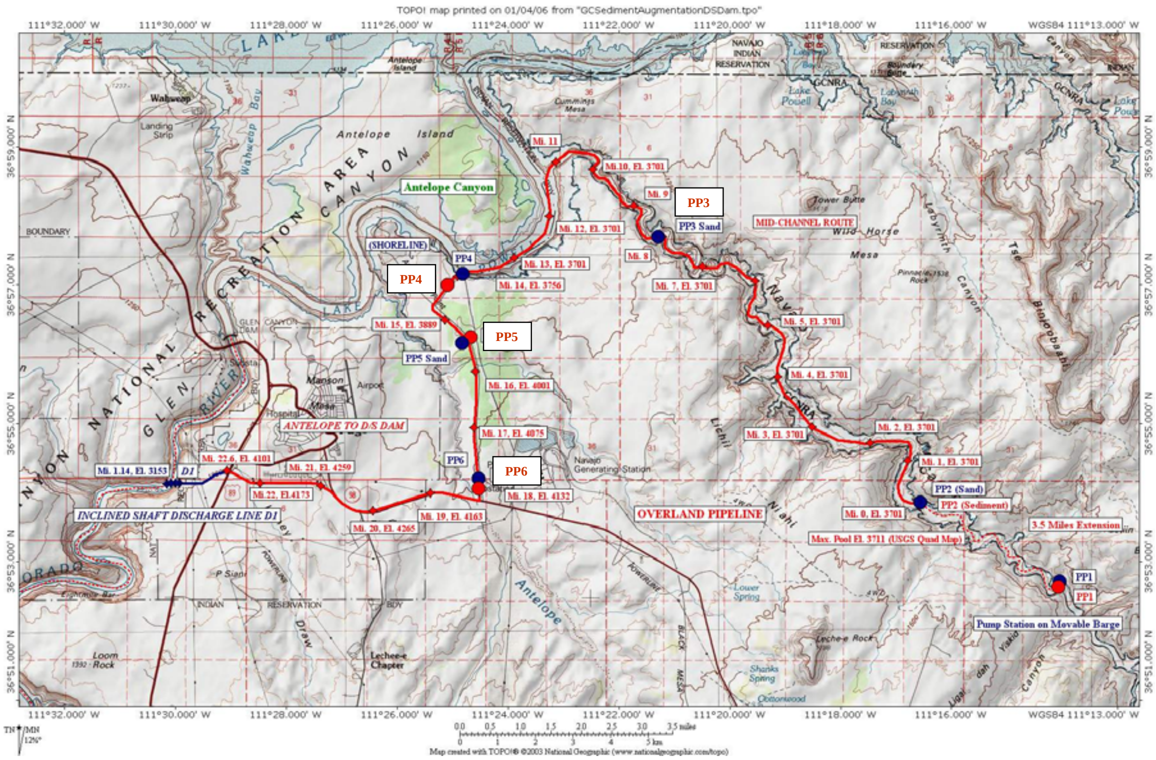

Figure 12. Plan-view map of the pipeline alignment from Navajo Canyon to Glen Canyon Dam (add 3.5 miles or 5.6 km to distances to determine the total pipeline length).

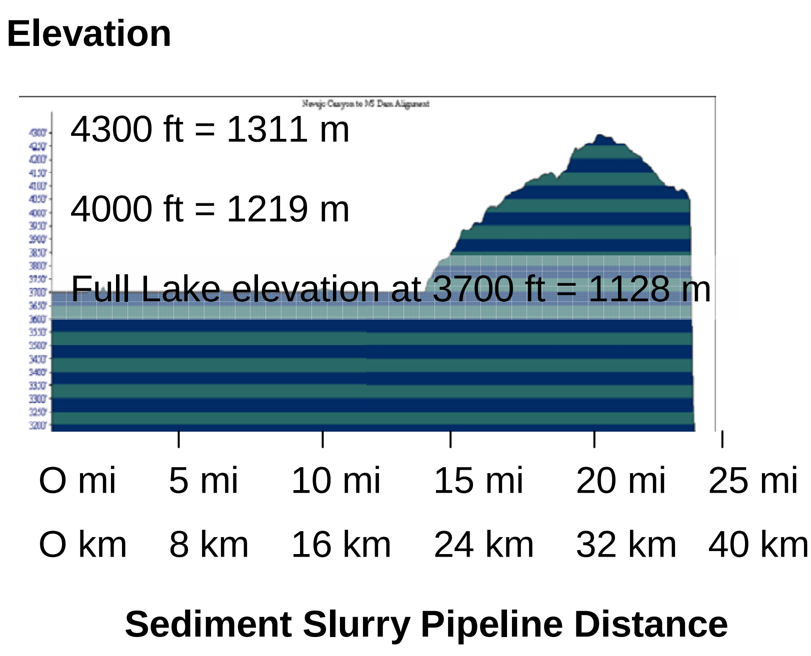

Figure 13. Longitudinal profile of the pipeline alignment from Navajo Canyon to Glen Canyon Dam (add 3.5 miles or 5.6 km to determine total pipeline length).

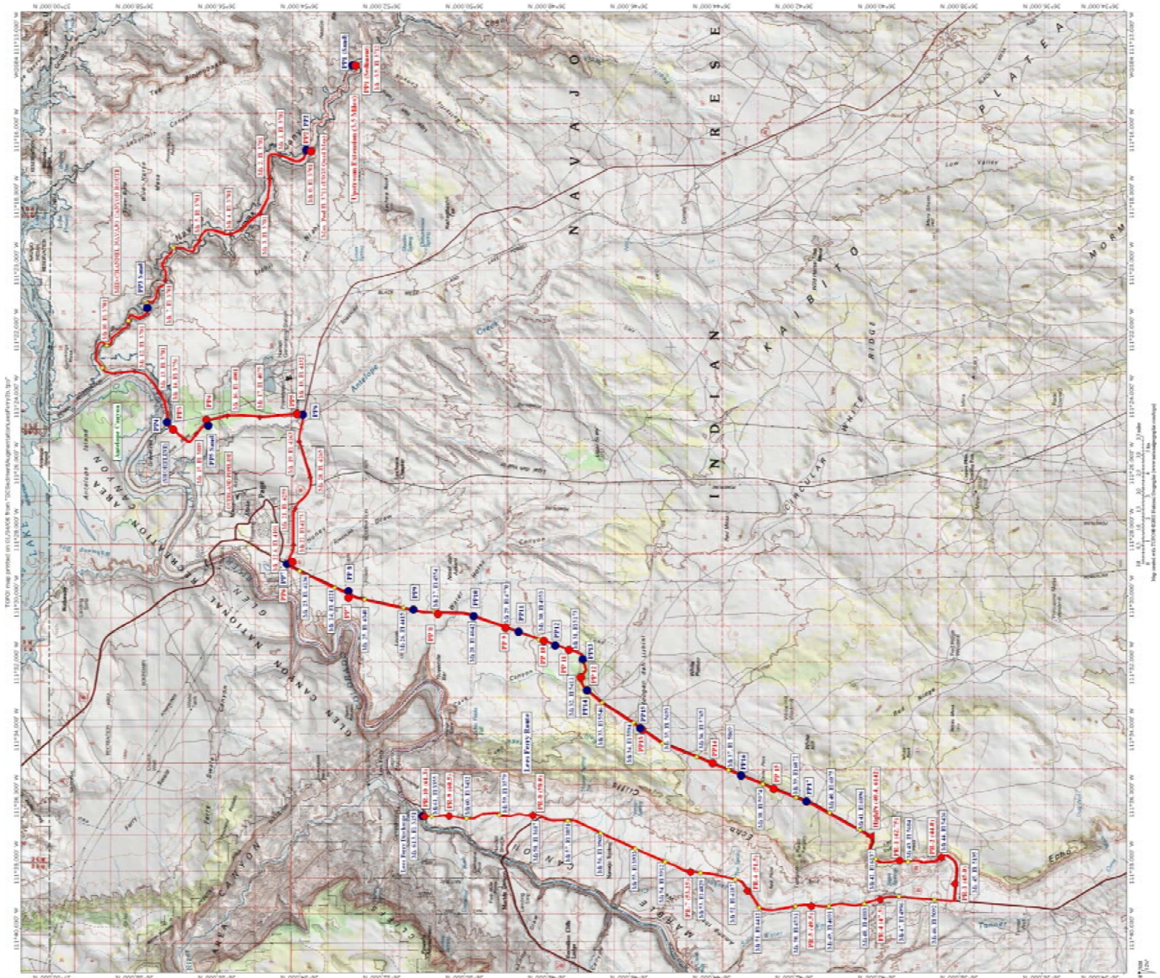

Figure 14. Plan-view map of the pipeline alignment from Navajo Canyon to Lees Ferry (add 3.5 miles or 5.6 km to distances to determine the total pipeline length).

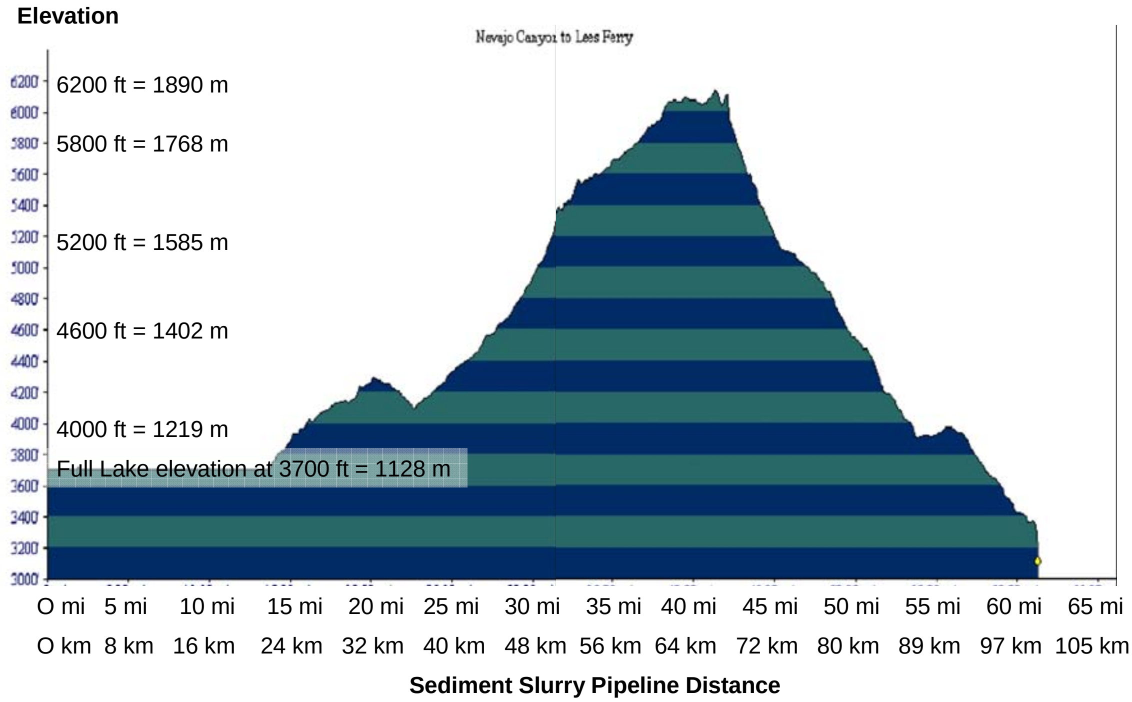

Figure 15. Longitudinal profile of the pipeline alignment from Navajo Canyon to Lees Ferry (add 3.5 mi or 5.6 km to distances to determine the total pipeline length).

Antelope Point is suggested as the location to exit the slurry pipelines from Lake Powell because of the gently sloping topography and the existing road access. The option of aligning the submerged pipelines all the way to Glen Canyon Dam was not considered feasible. This is because there is no place to construct a pumping plant near the dam at the full pool lake elevation and the near vertical canyon walls are still 60 feet (20 m) above the full pool elevation. If the lake surface elevation were to drop 150 feet (46 m), the last floating pumping plant would have to pump the slurries the elevation of the receded reservoir plus any additional elevation rise to the next pumping plant on the canyon rim. The total elevation rise could be as much as 210 feet (64 m) at Glen Canyon Dam and may not be possible.

The option of routing the pipelines through the dam also was considered infeasible because of the safety concerns about drilling a hole through the dam and the long-term abrasion of the sediment slurry pipelines. In addition, there are logistical problems of drilling holes through the dam at depths as much as 160 ft (49 m) within Lake Powell. The actual depth would depend on the lake elevation at the time of construction. Although the lake might be drawn down 150 ft (46 m) during the time of construction, the lake might be full when the slurry pipelines need to b replaced. Even if the slurry pipelines could be routed through Glen Canyon Dam, this would not facilitate the alternative of delivering sediment to Lees Ferry. A slurry pipeline through the 16 mi (26 km) reach of Glen Canyon is not feasible because there is no road access from which to construct the pipeline, there is no room for the pipeline, and there would be tremendous construction-related impacts to cultural and natural resources in Glen Canyon.

Exiting the slurry pipelines from Lake Powell at a point about 1 mile (1.6 km) upstream from Glen Canyon Dam may be a feasible option because the topography is not too steep to construct a pumping plant and new spur road. Another option may be to route sediment slurry pipelines up the upstream face of Glen Canyon Dam, over the dam adjacent to one of the abutments, then down the downstream face of the dam and terminating at the base of the dam. This option would not work for the alternative to deliver sediment to Lees Ferry. The options of exiting the lake 1 mile (1.6 km) upstream from Glen Canyon Dam or over the dam may be a less expensive than exiting the lake at Antelope Point and they could be considered at the next (feasibility) level of investigation.

The alternative pipeline alignment to Lees Ferry was assumed to follow the existing right-of-way for U.S. Highway 89. This alignment tends to avoid adverse impacts from construction activities to cultural and natural resources within the Navajo Nation or the Glen Canyon National Recreation Area. Other shorter alignment options may exist, at potentially less cost, but only if the construction and operations impacts can be tolerated.

2.4.1 Slurry Pipelines

Sediment slurry pipelines can efficiently transport large quantities of sediment over long distances. The required water volumes are small (0.2 percent) compared to the flow of the Colorado River. All of the water released through the slurry pipelines would be counted as part of the Upper Basin deliveries to the Lower Basin. Pumping stations would be required to convey the sediment along both the water and land portions of the pipeline routes. A summary of pipeline lengths and pumping plants is presented in table 4.

Table 4. Summary of alternative sediment slurry pipeline alignments.

	Submerged Pipeline Length		Buried Pipeline Length		Number of Pumping Plants	
Slurry Pipeline Alignment	(miles)	(km)	(miles)	(km)	Floating	Land-based
Navajo Canyon to below Glen Canyon Dam	18	29	11	18	3	3
Navajo Canyon to Lees Ferry	18	29	50	80	3	14

Sediment mixing stations would have to be assembled for the dredging stations in Navajo Canyon to provide the proper sediment concentrations in the pipelines. In order to take advantage of the natural sorting of sediments within the reservoir, the dredging of sand would occur at shallower depths and farther upstream than the dredging of silt and clay. For the Lees Ferry alternative alignment, settling basins and sand stockpile areas would be required at the delivery point near Lees Ferry (see Appendix C).

On Lake Powell, slurry pipelines would be supported by buoys and submerged to a depth of between 10 and 15 feet (3 to 5 m) so that the pipelines would not impede boat traffic or impact aesthetics. The pipelines would raise and lower with the water surface elevation of Lake Powell. The pipelines would be flexible and aligned along the centerline of the submerged river channel so that the pipelines would not come in contact with, and be damaged by, the canyon walls during lake-level fluctuations. The buoys would be spaced about every 500 feet (150 m) and would divide boat navigation into upstream and downstream lanes of traffic. However, boats would be able to cross over the pipelines between buoys. Anchors for the buoys would rest on the existing lakebed sediments so they would not additionally impact any cultural resources submerged within Lake Powell. Pulleys and counterweights would be used to maintain the required depth of submergence. A metal frame would be used to keep the pipelines together. A submerged electrical power line would be included with the pipelines to provide power for the pumping plants (see figure 16). The submerged power line would be protected by a thick casing and the surrounding pipelines. Electrical power would automatically shut off in the event the power line was cut or severed.

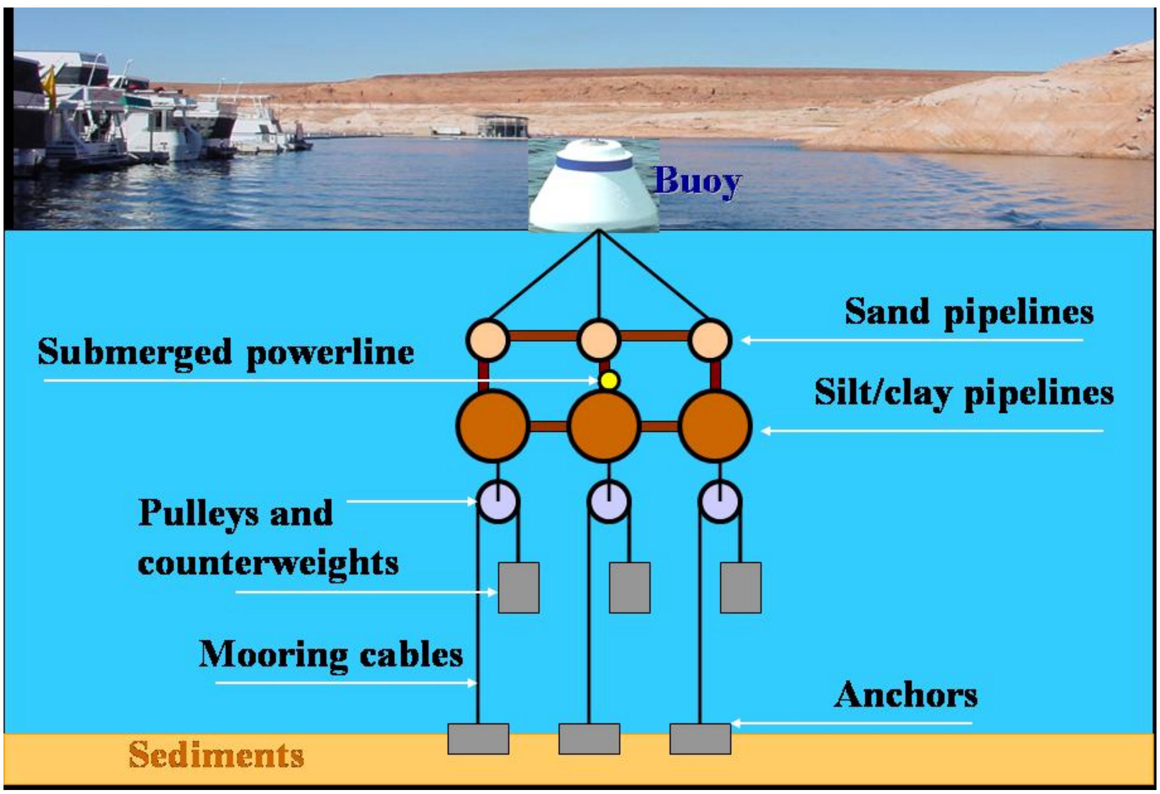

Figure 16. Submerged sediment slurry pipelines.

Other power sources were considered and eliminated for the floating pumping plants because of their infeasibility or unacceptable impacts. These other alternatives include the continual supply of gasoline or diesel fuel or electrical power through an overhead power line.

- The fuel requirements for gas or diesel engines could be quite significant for all the floating pumping plants. The use of gas or diesel engines to power the pumps would create local impacts related to noise and air quality. There would also be some risk of fuel spills in Lake Powell.

- The construction of an overhead power line to the floating pumping plants would impact cultural, natural, and aesthetic resources along the shoreline of Lake Powell. Electric pumps would be quieter than gas or diesel motors and avoid the local impacts to air quality and avoid the risk of fuel spills. However, no scheme was identified to connect a stationary overhead power line to the floating pumping plants on a fluctuating lake surface.

A submerged power line (attached to the slurry pipeline) would avoid the impacts to cultural and aesthetic resources along the shoreline of Lake Powell, but there would still be the aesthetic impacts from the floating pumping stations.

Sand would be conveyed through two 12-inch (30 cm) diameter high-density polyethylene (HDPE) pipelines. Because the sand pipelines would be used year round, a third 12-inch (30 cm) diameter HDPE pipeline would be provided as a backup to be used during maintenance, repair, or replacement of the pipelines. The flow rate through these pipelines would be 4.1 ft^3/s (0.12 m^3/s) with a sand concentration of 20 percent, by weight. The annual water volume would be 2,900 acre-feet per year (3.6 million m^3/yr).

Fine sediment would be conveyed through three 24-inch (61 cm) diameter HDPE pipelines. No backup fine-sediment pipeline would be provided because the pipelines would be operated eight months per year. The flow rate through the fine sediment pipelines would be 23 ft^3/s (0.64 m^3/s) with a fine sediment concentration of 20 percent, by weight. The annual water volume would be 11,000 acre-feet per year (14 million m^3/yr). The combined annual flow volume through all pipelines would be 14,000 acre-feet per year (17 million m^3/yr), which is 0.17 percent of the minimum annual flow release from Glen Canyon Dam (8.23 million acre feet per year or 10 billion m^3 per year). Any water released through the sediment slurry pipelines would be counted as deliveries from the Upper Basin to the Lower Basin. The mass and volumetric flow rates through the slurry pipelines are presented in table 5.

The service life of a sediment slurry pipeline, made of HDPE, is expected to exceed 20 years. With adequate particulate suspension, HDPE pipe has an extremely high resistance to abrasion from slurries. In some applications, HDPE pipe has outlasted steel pipe by as much as a factor of 4 (http://www.kwhpipe.ca/know_faqs.asp#10). Slurry TransportDriscoPlex™ piping has demonstrated superiority to other types of piping where corrosion and erosion problems exist. Design information on slurry piping design, velocity and particle size can be found in the Performance Pipe Engineering Manual. (www.performancepipe.com).

Table 5. Sediment slurry pipeline mass and volumentric flow rates.

Colorado River below Glen Canyon Dam				
8,230,000	acre-ft/yr =	1.015E+10	m^3/yr	Minimum annual flow release from Glen Canyon Dam
11,360	ft^3/s =	321.7	m^3/s	Average annual flow release from Glen Canyon Dam
708,873	lbs/s =	321,543	Kg/s	Mass flow rate of water
500	ppm =	500	ppm	Target suspended sediment concentration (May 1 through December 31)
354	lbs/s =	161	Kg/s	Suspended sediment mass flow rate
15,312	tons/day =	13,891	Mg/day	Suspended sediment mass flow rate
245	days/yr =	245	days/yr	Fine sediment delivery period (May 1 through December 31)
3,751,355	tons/yr =	3,403,207	Mg/yr	Annual sediment delivery
Fine Sediment Slurry Pipeline				
1,772	lbs/s =	804	Kg/s	Sediment slurry mass flow rate (water, clay, and silt)
20%		20%		Sediment slurry pipeline concentration, by weight
354	lbs/s =	161	Kg/s	Sediment mass flow rate
1,418	lbs/s =	643	Kg/s	Water mass flow rate
22.7	ft^3/s =	0.643	m^3/s	Water volumetric flow rate
24	inch =	61	cm	Pipeline diameter
3		3		Number of operational pipes
7.57	ft^3/s =	0.214	m^3/s	Water volumetric flow rate per pipe
2.41	ft/s =	0.735	m/s	Average water velocity per pipe
Sand Slurry Pipeline				
1,000,000	tons/yr =	907,194	Mg/yr	Target annual sand delivery rate
365	days/yr =	365	days/yr	Delivery period
2,740	tons/day =	2,485	Mg/day	Average daily sand delivery rate
63	lbs/s =	29	Kg/s	Sediment mass flow rate
20%		20%		Sediment slurry pipeline concentration, by weight
317	lbs/s	144	Kg/s	Sediment slurry mass flow rate
254	lbs/s	115	Kg/s	Water mass flow rate
4.07	ft^3/s =	0.115	m^3/s	Water volumetric flow rate
12	inch =	30	cm	Pipeline diameter
2		2		Number of operational pipes
1		1		Spare pipeline
2.03	ft^3/s =	0.058	m^3/s	Water volumetric flow rate per pipe
2.59	ft/s =	0.789	m/s	Average water velocity per pipe

The pipelines for silt and clay are expected to experience little wear because of the low kinetic energy with which fine particles strike the pipe surface. The transport of silt and clay at concentrations up to 35 percent by volume may be possible, but there could be clogging problems during power outages when the flow velocity would become zero and sediment particles would settle within the pipes.

Sand is expected to have greater wear on pipelines than silt or clay. The polyurethane lining of the sand slurry pipelines and pumps may extend their life expectancy to 20 or more years. Wear of the pipeline surface is proportional to the concentration and, in addition to clogging, is another reason to keep concentrations less than 20 percent by weight. The flow velocity in the sand slurry pipelines may be below the critical sedimentation velocity for a 12-inch (30-cm) diameter pipe, so a smaller diameter pipeline may have to be used. However, the assumption of a 12-inch (30-cm) diameter pipe would provide for a higher cost estimate.

On Lake Powell, pumping plants would float on modular barges that would also raise and lower with lake levels (see figure 17). The pumping plants would be covered by a building to protect the plants from waves and the elements and to minimize noise on the lake. The buildings could be made to resemble house boats or painted to blend in with the canyon walls. Floating pumping plants were considered rather than submerged pumps because of the need for maintenance access. Submerged plants could be considered, but a barge may still be needed as a maintenance platform and to support the weight of the submerged pumps. During periods of lake recession, the floating pumping plants may have to be moved to deeper areas of the lake. A floating pumping plant would be less likely to get stuck in the reservoir sediment than a submerged pumping plant.

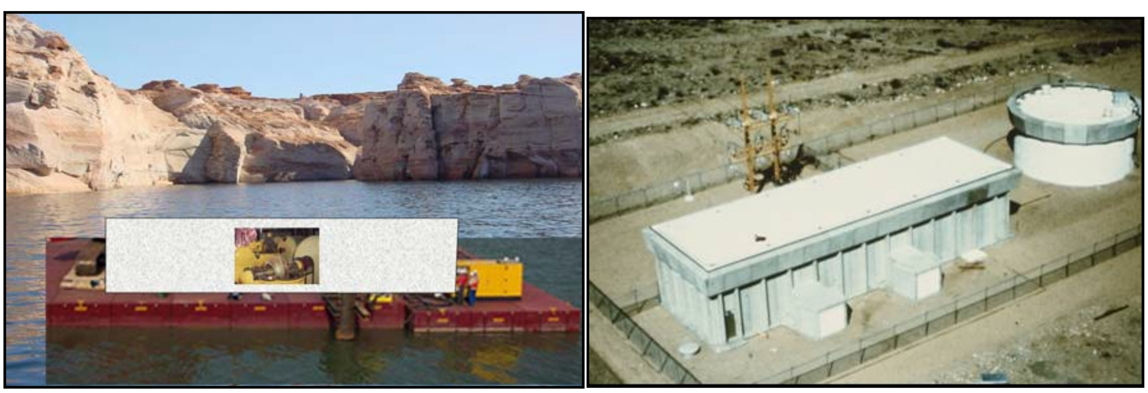

Figure 17. Pumping plants on Lake Powell would be floated on modular barges while pumping plants on land would be contained within permanent buildings.

Land-based pumping plants would be protected by permanent buildings. Both the floating and land-based pumping plants would be about 30 feet (9 m) wide, 60 feet (18 m) long, and 10 feet (3 m) high. Pressure reduction stations would be required along the descending segment of the pipelines to Lees Ferry.

The submerged pipelines would require some sort of shoreline anchors where the pipelines exit the lake. The pipeline anchors would have to protect the pipelines at a range of lake elevations (3550 to 3700 feet) to protect them from movement against the bedrock caused by wave action. This would be accomplished by submerging the pipelines to a depth below the rim of the submerged Colorado River canyon and exiting the canyon rim through an inclined shaft drilled through the bedrock. The inclined shaft would be excavated by directional drilling over a vertical distance of 30 to 50 feet (9 to 12 meters). Past the inclined shaft, the pipelines would be buried in a trench excavated in the sandstone bedrock. If construction occurred during times of high lake elevation, then the anchor blocks would be attached to the pipelines and it would be submerged on the bedrock of the lake bottom. Later, pipelines could be buried during the lake recession. The drilling of the inclined shaft and the cut and cover through the bedrock was assumed to be the more expensive option, therefore, was included in the cost estimate.

On land, the pipelines would be buried along the right-of-ways of existing roads and highways.

The alternatives that deliver sand, silt, or clay to below Glen Canyon Dam (Options 1, 3, and 5) would require drilling an inclined shaft through 860 vertical feet of sandstone bedrock (elevations 4000 to 3140 feet). All the pipelines could be fed into the same shaft, but the shaft would have to be lined to slow abrasion. The lining could be replaced about once every decade.

The alternatives that deliver silt and clay to Lees Ferry (Options 2, 3, and 4) would require drilling an inclined shaft through 200 vertical feet of sandstone bedrock at the canyon rim. All the fine-sediment pipelines and water from the sand pipelines could be fed into the same shaft, but the shaft would have to be lined to slow abrasion. Sand would be settled and stock piled along the canyon rim.

2.4.2 Sediment Conveyance Methods Eliminated from Consideration

The sediment conveyance alternatives of barge transport on Lake Powell and overland transport by truck were found to be infeasible and eliminated from additional consideration.

2.4.2.1 Barge Transport on Lake Powell

This alternative would attempt to barge the sediments from the dredging sites to Antelope Point, near Glen Canyon Dam. From there the sediments would be transported by trucks or through slurry pipelines to the Colorado River, either below Glen Canyon Dam or to Lees Ferry.

Barges on Lake Powell would have to navigate the narrow canyons of the reservoir and be able to cope with heavy recreation boat traffic during summer. Assuming that each barge could transport 110 tons (100 Mg) of sand, 9,100 barge loads would be required to deliver 1 million tons (0.9 million Mg) of sediment per year. The delivery of 1 million tons (0.9 million Mg) of sand would require 36 barge loads per day, assuming 250 working days per year. The delivery of 3.8 million tons (3.4 million Mg) of fine sediment would require 206 barge loads per day, assuming 166 working days per year. A maximum number of 242 barge loads per day would be required to meet the delivery targets for both sand and fine sediment.

Barging does not appear to be a desirable option due to the following reasons:

- The narrow winding canyons would make barge access, passage, and turn-around difficult.
- Barges would be large, slow, and not very maneuverable.
- Once the barges reach the loading and unloading points, the task of moving the sands or fine sediments to and from each barge could be a slow process. This may create a bottle neck in the barging process and may increase the number of barges needed.
- A large number of personnel would be required for barge operations. Personnel would be needed to move the barges between the dredging sites and at the unloading point. Additional personnel would be needed to position and load the barges from the dredges and to unload the barges and then load the trucks or slurry pipelines.
- The large number of barge loads would require a continuous convoy of barges between Navajo Canyon and Antelope Point, which may require the restriction of recreation boat traffic in these areas of Lake Powell.

2.4.2.2 Overland Transport by Truck

The concept of trucking sediments directly from the dredging sites within Navajo Canyon to either Lees Ferry or just below Glen Canyon Dam has been eliminated due to the following factors:

- There is no road access to the Navajo Canyon dredging sites.
- The steep canyon walls of Navajo Canyon would make road construction nearly impossible or very expensive due to the 1,000-foot (300-m) elevation rise from Lake Powell to the canyon plateau (see figure 18). The construction of a two-lane road would require a lot of rock blasting through the pristine canyon. A tunnel access roadway may need to be constructed, similar to the tunnel leading to the base of Glen Canyon Dam. However, a tunnel could not be constructed below a full lake elevation.

- The changing level of Lake Powell would require the changing location of the dredges, so barges or slurry pipelines would be needed to convey sediment from the dredge site to a newly constructed road.

- The roadways in the canyon and on the plateau all would be on Navajo Nation lands and permission to construct the roadways would be required.

Another eliminated alternative was to transport sediment from Navajo Canyon, across Lake Powell by barge or slurry pipeline, to Antelope Point where trucks could then transport the sediments to the Colorado River below Glen Canyon Dam or near Lees Ferry. For the delivery point below Glen Canyon Dam, a new road access tunnel would have to be constructed to route trucks to the bottom of Glen Canyon. The large number truck loads would be in direct conflict with present traffic uses in the existing road access tunnel to the base of the dam.

Figure 18. There are no roads in the remote area of Navajo Canyon where bedrock rises 1,000 feet (300 m) from the surface of Lake Powell.

The road access tunnel would become a restriction for the size of trucks. Smaller single, rear-axle dump trucks, with a load capacity of 5 tons (5 Mg) per truck, would have to be used because there would not be room for large trucks to maneuver at the bottom of the tunnel. The annual delivery of 1 million tons (0.9 million Mg) of sand would require approximately 800 truck loads per day, assuming 250 working days per year. Another 4,500 truck loads per day would need to be needed to deliver 3.8 million tons (3.4 million

Mg) of fine sediments, assuming 166 working days per year. The delivery of sand and fine sediment would require up to 5,300 total loads per day, which is equivalent to a truck dumping a sediment load every 16 seconds. If larger trucks were used with a 10 ton per load capacity, the number of truck loads would be reduced in half, but the number of truck loads would still be excessive. The endless parade of trucks driving from Antelope Point would require that new roads be constructed to bypass the City of Page, Arizona.

Truck transport would be a 24-mi (38-km) round trip from Antelope Point to below Glen Canyon Dam and a 110-mi (180 km) round trip from Antelope Point to Lees Ferry.

Sediment transport by truck from Antelope Point to Lees Ferry was also considered. Larger trucks with a 30-ton hauling capacity could be used, but the trucks would have to travel a 110-mile (180-km) round-trip distance along steep and winding grades, which would increase the travel times and fuel consumption of the trucks. The annual delivery of 1 million tons (0.9 million Mg) of sand would require approximately 130 truck loads per day, assuming 250 working days per year. Another 750 truck loads per day would need to be needed to deliver 3.8 million tons (3.4 million Mg) of fine sediments, assuming 166 working days per year. The delivery of sand and fine sediment would require up to 890 total loads per day, which is equivalent to a truck dumping a sediment load every 97 seconds.

2.4.2.3 Slurry Pipeline Overland from Navajo Canyon

This alternative was determined to be very difficult to implement, more costly than the submerged pipelines, and have more environmental impact than the submerged pipelines.

- Overland access to Navajo Canyon would be very difficult because of the steep bedrock topography of the canyon, there is more than 1,000 feet of elevation difference between the reservoir and the plateau, and no roads cross this pristine area.

- Pumping plants would be required for every 50 feet of elevation gain and a road would have to be constructed to each pumping plant. Road construction would require blasting and excavation in this pristine area. At least 20 pumping plants would be required just to deliver sediment to the top of the plateau.

- The high elevation difference along this overland route would also require a leaner sediment concentration than a pipeline along Lake Powell.

- A floating pipeline or system of barges would still be required to deliver sediment from the dredging operation to where the overland pipeline would reach the reservoir shoreline in Navajo Canyon.

2.5 Sand Storage Alternatives

For the alternative pipeline alignment to Lees Ferry, sand would be settled from the slurry and stockpiled on the canyon plateau near Lees Ferry, overlooking the Colorado River from the left side, looking downstream (see figure 11). The stockpiled sand would be dumped into the Colorado River up to one month before the release of the beach-building flow. Two settling basins would alternatively be used to settle the sand from the slurry pipeline. Each basin would be operated for about one month while the other basin is drained and cleaned out. Water from the settling basin would drain through the inclined shaft into the Colorado River. The settling basin operation would run year round to meet the quantities of sand needed. Each basin would be 900 feet by 250 feet (275 m by 75 m) and each basin would be expected to fill in about one month.

Bulldozers, loaders, and trucks would be used to remove the sand from each settling basin for storage of 1 million tons of sand on the plateau overlooking the Colorado River. The sand storage volume would be 2,500 feet (760 m) long, 400 feet (120 m) wide, and 20 feet (6 m) high. The stored sand would be pushed into the Colorado River by bulldozers (D-10) prior to the release of the beach-building flow.

The sands would be removed from the stilling basin by a truck, bulldozer and loader operation. The dozer would assist the loading of the sand into dump trucks or trucks with 40 foot dump trailers. The trucks would then haul the sands up to one half mile to the stockpile area where they would dump and store the sands. It is estimated that one D8 series dozer and 999 series loader would be needed to fill the haul trucks. Four to five haul trucks would be needed to keep up with the loader. These estimates are based on 10 hour shifts and 20 days per month, see Appendix B.

Approximately 1 million tons of sand (0.9 million Mg) would be stockpiled on the canyon plateau overlooking the Colorado River near Lees Ferry. At the appropriate time, the stockpiled sands would be pushed into the Colorado River. This would be accomplished about one month prior to the beach-building flow. To accomplish this, up to eight D10 series bulldozers may be required. The dozers would push the stock piled sand over the bank and into the river, where the water would move the sands on downstream into the canyon. The D10 series dozers would only be required during the time period when the sands need to be pushed into the Colorado River.

2.6 Summary of Complete Alternatives

Based on analysis of the sediment augmentation system components, five alternatives were selected for cost estimation. The first three alternatives would meet the objectives for turbidity and sand. The last two alternatives would only meet the objectives for turbidity and not for sand.

1. Silt-clay and sand slurry pipelines from Navajo Canyon to below Glen Canyon Dam.

2. Silt-clay and sand slurry Pipelines from Navajo Canyon to Lees Ferry.
3. Silt-clay slurry pipelines from Navajo Canyon to Lees Ferry and sand pipelines from Navajo Canyon to below Glen Canyon Dam.
4. Silt-clay slurry pipelines from Navajo Canyon to Lees Ferry (no sand slurry pipelines).
5. Silt-clay slurry pipelines from Navajo Canyon to below Glen Canyon Dam (no sand slurry pipelines).

Theses alternatives contrast the range of sediment delivery locations and the size of sediments (clay, silt, and sand). A summary of these five alternatives is presented in table 6.

Table 6. Summary of complete sediment augmentation alternatives.

System components	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Sediment source area	Navajo Canyon	Navajo Canyon	Navajo Canyon	Navajo Canyon	Navajo Canyon
Dredges	2 Clamshells	2 Clamshells	2 Clamshells	2 Clamshells	2 Clamshells
Fine sediment slurry pipeline delivery location	Below Glen Canyon Dam	Near Lees Ferry	Near Lees Ferry	Near Lees Ferry	Below Glen Canyon Dam
Submerged route distance	18 mi (29 km)	18 mi (29 km)	18 mi (29 km)	18 mi (29 km)	18 mi (29 km)
Number of floating pumping plants	3	3	3	3	3
Overland buried slurry pipeline					
Buried route distance	11 mi (18 km)	50 mi (80 km)	50 mi (80 km)	50 mi (80 km)	11 mi (18 km)
Number of land-based pumping plants	2	12	12	12	2
Number of pressure reducing stations	0	10	10	10	0
Sand slurry pipeline delivery location	Below Glen Canyon Dam	Near Lees Ferry	Below Glen Canyon Dam		
Submerged					
Submerged route distance	18 mi (29 km)	18 mi (29 km)	18 mi (29 km)	0	0
Number of floating pumping plants	3	3	3	0	0
Overland buried slurry pipeline					
Buried route distance	11 mi (18 km)	50 mi (80 km)	11 mi (18 km)	0	0
Number of land-based pumping plants	3	14	3	0	0
Number of pressure reducing stations	0	10	0	0	0
Sand storage area	Colorado River in Glen Canyon	Terrestrial site near Lees Ferry	Colorado River in Glen Canyon	none	none

3.0 Appraisal-level Cost Estimates

An appraisal cost estimate represents a preliminary project cost in determining whether more detailed investigations of a potential project are justified. These estimates are intended to be used as an aid in selecting the most economical plans by comparing alternative features. Given the preliminary investigations at this phase, appraisal cost estimates are not suitable for requesting project authorization or construction funding appropriations from the Congress.

Appraisal cost estimates (January 2006 dollars) were prepared for five sediment augmentation alternatives. A summary comparison of these cost estimates are presented in table 7. More cost estimate details for each alternative are presented in tables 8 through 12.

These appraisal-level costs estimates do not directly include any costs for the purchase of land or right-of-way for pipelines or pump stations. Also, the estimates do not include any costs associated with traffic control or traffic disruption during construction activities. These cost estimates do include operating costs for the dredge system and power for the pump stations. Maintenance and replacement costs for pumps and motors are included, but not for any other items. These appraisal-level cost estimates are sufficient for comparing alternatives, but a more complete investigation of operations, maintenance, and replacement costs are needed at the next (feasibility) level of analysis.

Table 7. Summary comparison of appraisal cost estimates for five sediment augmentation alternatives.

Alternative	Project Capital Cost (Jan. 2006)	Annual Operating Cost (Jan. 2006)
1. Sand and Silt-Clay Slurry Pipelines from Navajo Canyon to below Glen Canyon Dam	$220 million	$6.6 million/yr
2. Sand and Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry	$430 million	$17 million/yr
3. Sand Pipelines from Navajo Canyon to below Glen Canyon Dam and Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry	$380 million	$11 million/yr
4. Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry (No sand slurry pipelines)	$300 million	$7.9 million/yr
5. Silt-Clay Slurry Pipelines from Navajo Canyon to below Glen Canyon Dam (No sand slurry pipelines)	$140 million	$3.6 million/yr

Table 8. Appraisal-level cost estimate for alternative 1 (January 2006 dollars).

Alternative 1: Sand and Silt-Clay Slurry Pipelines from Navajo Canyon to below Glen Canyon Dam

Dredge system construction			$9,693,340
Silt and clay slurry pipelines (three, 24-in diameter pipes, 7.57 cfs per pipe)			$48,065,190
	18	miles floating HDPE pipelines	
	11	miles buried HDPE pipelines	
Silt and Clay pumping plants			
	3	floating plants	
	2	land-based plants	
Directional drilling with inlet basin and valve discharge structure	1,600	feet	

Sand slurry pipeline (three, 12-inch diameter pipes, 2.03 cfs per pipe)			$23,943,102
	18	miles floating HDPE pipelines	
	11	miles buried HDPE pipelines	
Sand pumping plants			
	3	floating plants	
	3	land-based plants	
Directional drilling with inlet basin and valve discharge structure	1,600	feet	

Electrical plant control and distribution	$1,673,000
Electrical power distribution (buried lines and submerged marine cabling)	$20,130,000
SCADA System requirements	$4,356,600

Subtotal		$107,861,232
Mobilization	5%	$5,400,000
Subtotal with mobilization		$113,261,232
Unlisted items	15%	$16,989,185
Contract Cost		**$130,000,000**
Contingencies	25%	$35,000,000
Field Cost		**$165,000,000**
Non-contract cost allowance	30%	$50,000,000
Project Cost		**$220,000,000**

Annual Operations	
Dredge system operations	$3,276,424
Power for pump stations	$3,225,600
Maintenance and replacement of pump motors	$130,000
Total Operations Cost	**$6,600,000**

Table 9. Appraisal-level cost estimate for alternative 2 (January 2006 dollars).

Alternative 2: Sand and Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry

Dredge system construction			$9,693,340
Lees Ferry sand storage area			$2,071,000
Silt and clay slurry pipelines (three, 24-inch diameter pipes, 7.57 cfs per pipe)			$114,672,135
	18	miles floating HDPE pipelines	
	50	miles buried HDPE pipelines	
Silt and clay pumping plants			
	3	floating plants	
	12	land-based plants	
	10	pressure reducing stations	
Directional drilling with inlet basin and valve discharge structure	300	Feet	

Sand slurry pipeline (three, 12-inch diameter pipes, 2.03 cfs per pipe)			$47,366,565
	18	miles floating HDPE pipelines	
	50	miles buried HDPE pipelines	
Sand pumping plants			
	3	floating plants	
	14	land-based plants	
	10	pressure reducing stations	
Directional drilling with inlet basin and valve discharge structure	300	Feet	
Electrical plant control and distribution			$4,916,000
Electrical power distribution (buried lines and submerged marine cabling)			$30,010,000
SCADA System requirements			$9,725,600

Subtotal		$218,454,640
Mobilization	5%	$11,000,000
Subtotal with mobilization		$229,454,640
Unlisted items	15%	$34,418,196
Contract Cost		**$260,000,000**
Contingencies	25%	$70,000,000
Field Cost		**$330,000,000**
Non-contract cost allowance	30%	$100,000,000
Project Cost		**$430,000,000**
Annual Operations		
Dredge system operations		$3,276,424
Lees Ferry sand storage operations		$3,928,800
Power for pump stations		$9,487,800
Maintenance and replacement of pump motors		$380,000
Total Operations Cost		**$17,000,000**

Table 10. Appraisal-level cost estimate for alternative 3 (January 2006 dollars).

Alternative 3: Sand Pipelines from Navajo Canyon to below Glen Canyon Dam and Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry

Dredge system construction			$9,693,340
Silt and clay slurry pipelines (three, 24-inch diameter pipes, 7.57 cfs per pipe)			$114,672,135
	18	miles floating HDPE pipelines	
	50	miles buried HDPE pipelines	
Silt and clay pumping plants			
	3	floating plants	
	12	land-based plants	
	10	pressure reducing stations	
Directional drilling with inlet basin and valve discharge structure	300	feet	

Sand slurry pipeline (three, 12-inch diameter pipes, 2.03 cfs per pipe)			$23,943,102
	18	miles floating HDPE pipelines	
	11	miles buried HDPE pipelines	
Sand pumping plants			
	3	floating plants	
	3	land-based plants	
Directional drilling with inlet basin and valve discharge structure	1,600	feet	

Electrical plant control and distribution	$3,783,000
Electrical power distribution (buried lines and submerged marine cabling)	$32,610,000
SCADA System requirements	$6,900,600

Subtotal		$191,602,177
Mobilization	5%	$9,600,000
Subtotal with mobilization		$201,202,177
Unlisted items	15%	$30,180,327
Contract Cost		**$230,000,000**
Contingencies	25%	$60,000,000
Field Cost		**$290,000,000**
Non-contract cost allowance	30%	$87,000,000
Project Cost		**$380,000,000**

Annual Operations	
Dredge system operations	$3,276,424
Power for pump stations	$7,408,800
Maintenance and replacement of pump motors	
Total Operations Cost	**$11,000,000**

Table 11. Appraisal-level cost estimate for alternative 4 (January 2006 dollars).

Alternative 4: Silt-Clay Slurry Pipelines from Navajo Canyon to Lees Ferry (No sand slurry pipelines)

Dredge system construction			$4,846,670
Silt and clay slurry pipelines (three, 24-inch diameter pipes, 7.57 cfs per pipe)			$114,672,135
	18	miles floating HDPE pipelines	
	50	miles buried HDPE pipelines	
Silt and clay pumping plants			
	3	floating plants	
	12	land-based plants	
	10	pressure reducing stations	
Directional drilling with inlet basin and valve discharge structure	300	feet	

No sand slurry pipelines

Electrical plant control and distribution	$3,165,000
Electrical power distribution (buried lines and submerged marine cabling)	$21,910,000
SCADA System requirements	$4,847,800

Subtotal		$149,441,605
Mobilization	5%	$7,500,000
Subtotal with mobilization		$156,941,605
Unlisted items	15%	$23,541,241
Contract Cost		**$180,000,000**
Contingencies	25%	$50,000,000
Field Cost		**$230,000,000**
Non-contract cost allowance	30%	$69,000,000
Project Cost		**$300,000,000**

Annual Operations	
Dredge system operations	$1,380,786
Power for pump stations	$6,274,800
Maintenance and replacement of pump motors	$260,000
Total Operations Cost	**$7,900,000**

Table 12. Appraisal-level cost estimate for alternative 5.

Alternative 5: Silt-Clay Slurry Pipelines from Navajo Canyon to below Glen Canyon Dam (No sand slurry pipelines)			
Dredge system construction			$4,846,670
Silt and clay slurry pipelines (three, 24-inch diameter pipes, 7.57 cfs per pipe)			$48,065,190
	18	miles floating HDPE pipelines	
	11	miles buried HDPE pipelines	
Silt and clay pumping plants			
	3	floating plants	
	2	land-based plants	
Directional drilling with inlet basin and valve discharge structure	1,600	feet	
No sand slurry pipelines			
Electrical plant control and distribution			$1,055,000
Electrical power distribution (buried lines and submerged marine cabling)			$12,030,000
SCADA System requirements			$2,170,800
Subtotal			$68,167,660
Mobilization	5%		$3,400,000
Subtotal with mobilization			$71,567,660
Unlisted items	15%		$10,735,149
Contract Cost			**$82,000,000**
Contingencies	25%		$23,000,000
Field Cost			**$105,000,000**
Non-contract cost allowance	30%		$32,000,000
Project Cost			**$140,000,000**
Annual Operations			
Dredge system operations			$1,380,786
Power for pump stations			$2,091,600
Maintenance and replacement of pump motors			$90,000
Total Operations Cost			**$3,600,000**

4.0 Environmental Impacts

A brief listing of environmental impacts from the sediment augmentation alternatives is presented below:

- Construction activities of the slurry pipelines and pumping plants would create noise and visual impacts.

- The discharge of sediment into the Colorado River would impact water quality and would require compliance with the Clean Water Act (see section 4.1.1).

- Tunneling through the bed rock at the Antelope Point shoreline and the canyon wall below Glen Canyon Dam would create a permanent disturbance to the landscape.

- Excavation for the buried pipelines and tunneling could affect cultural resources.

- The dredging operations would limit access in portions of Navajo Canyon upstream of the most downstream dredge.

- Operations of the clamshell dredges and floating pumping plants would create noise impacts on Lake Powell.

- Presence of the floating pumping plants and overland pumping plants would create visual impacts.

- Sand settling basins and stockpile areas would create dust, noise, and visual impacts for alternative 2 near Lees Ferry.

4.1 Water Quality

Water quality would be impacted by the discharge of sediments to the Colorado River, either below Glen Canyon Dam or near Lees Ferry. The primary impact to water quality would be the increase in suspended sediment concentration and turbidity. The alternatives all use the same sediment source from Navajo Canyon.

A composite sediment sample collected during November 2004 from Navajo Canyon was submitted to the USGS Mineral Resources Laboratory in Denver, Colorado, for chemical analysis (see Appendix A for details). The sample was analyzed for 39 elements, some of which would be considered contaminants, but most of which would not be. The elemental composition of the sample agrees well with that of typical sandstone.

Potential contaminants of particular concern include mercury and selenium. Mercury is a concern because of the proximity of the canyon to the Navajo Powerplant. However, mercury was below its detection limit. Elevated selenium concentrations have been implicated in wildlife toxicity in irrigation return flows in the Upper Colorado Basin. Selenium was also below its detection limit in the sample. A comparison of other potential contaminants with their respective sediment quality guidelines showed none to be elevated. Although this initial screening showed no evidence of the presence of contaminants in the sediments, a much broader sampling program would be needed to confirm the preliminary conclusion.

4.1.1 Regulations

The discharge of suspended sediment from Lake Powell to the Colorado River would have to be evaluated against the Corps of Engineers (Corps) and the Environmental Protection Agency (EPA) regulations implementing Section 404 of the Clean Water Act. Section 404 regulates the discharge of dredged or fill material to waters of the United States. The regulations require a permit from the Corps before such a discharge can be made. All permits are reviewed by the EPA for compliance with their regulations implementing Section 404(b)(1) of the Clean Water Act. EPA also has veto power over any permit under Section 404(c) of the Act. In addition, no permit can be issued without first complying with the National Environmental Policy Act.

Section 401 of the Clean Water Act gives State water quality agencies review authority over Federal permits, such as a 404 permit. The State review is limited to compliance with State water quality standards. Before a permit can be issued, the State must certify that the discharge is in compliance with the water quality standards. In Arizona, the only water quality standard that appears to apply is the one for suspended sediment. That standard is 80 mg/L for the protection of aquatic life.

It should be noted that the Arizona water quality standards make a provision for an exception from certain water quality standards if a net ecological benefit from the discharge can be demonstrated. Reclamation and the Fish and Wildlife Service made this point in the development of the Platte River Endangered Species Recovery Implementation Program in Nebraska. Both the Corps and EPA felt that was a valid point.

4.2 Cultural Resources

The submerged sediment slurry pipelines in Lake Powell would not have permanent impacts. The dredges, submerged pipelines, buoys, cables, floating pumping plants, and electrical power lines could all be removed. The buoy anchors would rest on existing reservoir sediment rather than the natural topography of the reservoir bottom. The dredges would excavate both existing and future reservoir sediment.

A tunnel would be drilled in the bedrock near the lake shoreline at Antelope Point and the buried pipelines and above-ground pumping plants would cross Navajo Nation lands. For the alternative route to below Glen Canyon Dam, directional drilling would be required through the canyon bedrock. For the alternative route to Lees Ferry, the buried sediment slurry pipelines, above-ground pumping plants, and pressure reduction stations would cross Navajo Nation lands along Highway 89. The settling basins and sand storage area near Less Ferry would also be on Navajo Nation lands.

Attempts have been made to minimize the impacts to cultural resources, but the exact impacts are unknown. Cultural resource studies and consultation with the Navajo Nation would have to be conducted to estimate the impacts to cultural resources.

5.0 Conclusions

Sediment slurry pipelines that would deliver sediment from the Navajo Canyon arm of Lake Powell to the Colorado River below Glen Canyon Dam or near Lees Ferry are believed to be technically feasible. Five sediment augmentation alternatives have been formulated and evaluated. Alternatives are available to deliver fine sediment and sand to the Colorado River, either below Glen Canyon Dam or near Lees Ferry.

Attempts have been made to formulate each alternative to minimize environmental impacts and to avoid cultural resource impacts. No major environmental impacts for any of the five alternatives have been identified at this time.

Sediment source areas in Lake Powell seem to be the most logical choice because of cost and because the sediments in Lake Powell would have naturally reached the Colorado River below the site of Glen Canyon Dam. Sediment source areas in Navajo Canyon are much closer to Glen Canyon Dam than other major source areas in Lake Powell. Laboratory analysis of one sediment sample from Navajo Canyon did not detect any contaminants above background levels. A more intensive sediment sampling program would be needed to verify if this finding is applicable to more of the sediments within Navajo Canyon.

Although the present and future sedimentation volumes in Navajo Canyon may not be enough to sustain a Grand Canyon sediment augmentation program over the long term, the volumes should be sufficient for one or two decades (see figure 8). Sediments in Navajo Canyon could be dredged first and then the submerged slurry pipelines and floating pumping stations could be moved to an upstream source such as the Escalante River or San Juan River deltas.

Sediment slurry pipelines can deliver large quantities of sediment, and over long distances, much more efficiently and at less cost than barges or trucks. Submerging sediment slurry pipelines in Lake Powell appears to be a viable option with much less impact than overland routes from major sediment source areas in Lake Powell where no direct roads presently exist.

The augmentation of fine sediment should be considered in conjunction with alternatives that would increase the summer water temperatures released from Glen Canyon Dam (e.g., selective withdrawal of water from Lake Powell). Native and endangered fish in Grand Canyon National Park are impacted by less turbidity and colder water temperatures in summer compared to natural conditions (U.S. Department of the Interior, Bureau of Reclamation, 1995). Turbidity may provide native fish with cover from predation. In the absence of turbid conditions, native fish tend not to be active during the day (U.S. Department of the Interior, Bureau of Reclamation, 1995). Although, colder water temperatures may impact young-of-the-year native fish in summer, the colder temperatures may also keep non-native warm-water fish from migrating upstream through Grand Canyon National Park. If water temperatures are increased, there is a concern that non-native warm-water fish may have the advantage (U.S. Department of the Interior, Bureau of Reclamation, 1995). The augmentation of fine sediment may provide the necessary cover for native and endangered fish.

6.0 Future Investigations

If there is continued interest in pursuing a Grand Canyon sediment augmentation system, then the following steps are recommended:

1. Conduct more sampling and testing of sediments in Lake Powell, especially in Navajo Canyon. Additional samples are needed over a larger spatial area, and at greater depth, to more thoroughly document grain size distribution and test for the presence of contaminants above background levels.
2. Conduct environmental studies to verify the need for both sand and fine sediment augmentation.
3. Prepare an environmental impact statement with public involvement.
4. Conduct an engineering feasibility study to refine alternatives, verify technical feasibility, and accurately determine costs.
5. Submit a record of decision and feasibility design report to Congress
6. Seek congressional authorization.
7. Conduct a final engineering design with construction specifications.
8. Obtain construction bids.
9. Construct and operate the project.

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Appendix A – Sediment Quality

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During a field trip to Lake Powell during November 2004, a sample of Navajo Canyon sediment was collected for a variety of analyses. In addition to various physical characteristics, the chemical composition was analyzed. For the chemical analysis, the sample was dried and sieved through a 0.25 mm mesh. The sample was submitted to the U.S. Geological Survey (USGS) Mineral Resources Laboratory in Denver, Colorado. The sample was digested in the laboratory and analyzed for 37 elements by ICP-MS as described in Briggs and Meier (1999). Mercury was analyzed by cold-vapor atomic absorption (O'Leary *et al.*, 1996), and selenium was analyzed by hydride generation atomic absorption (Hageman and Welsch, 1996). The results are presented in Table 13.

In addition to the analytical results of the analysis of the Navajo Canyon sediment samples, Table 13 shows two different estimates of the elemental composition of the earth's crust. Crustal abundance values (CAV) as presented in Table 13 can serve as a basis for comparison to evaluate potential contaminants. The CAV represents the average elemental composition of the various rock types that make up the earth's crust. The elements are weighted by the average amount of each rock type in the crust. If a sample result deviates greatly from the average composition, then there should be a reason for that deviation. For example, in mineral exploration, areas characterized by metal concentrations 3 or more times above the CAV are routinely investigated (Church *et al.*, 1997). In the case of Navajo Canyon, it may be that the sediments came from an area that deviates greatly from the average, or in the case of very high values, the deviation may indicate contamination.

The results in Table 13 do not indicate contamination. If anything, most element concentrations are inordinately low in comparison with the CAV data. The only sample result that meets the criterion for mineral exploration is the bismuth concentration. However, that is only true of the Fortescue (1992) CAV; the Emsley (1998) CAV is over 5 times higher than the Fortescue (1992) CAV and the Navajo Canyon result is only about twice as high as the Emsley (1998) CAV (Table 13). As far as bismuth is concerned, it is regarded as one of the less toxic heavy metals and is commonly used as a medicine for stomach upsets (Emsley, 1998; Slikkerveer and de Wolff, 1996).

Section 404 of the Clean Water Act (CWA) regulates the discharge of dredged materials to waters of the United States. The sediment enhancement project would be subject to regulation under Section 404 of the CWA. A major concern under the regulations is potential toxicity of the discharge sediments. The EPA and Corps of Engineers (EPA, 1998) have developed a tiered approach to sediment quality evaluation. Over the course of the last decade, there has been an effort to develop sediment quality guidelines (SQG) for screening sediments for toxicity. The most recent, which were developed for use in the Great Lakes, are shown in Table 14.

Table 13. Comparison of the results from an ICP-MS scan of the Navajo Canyon sediment sample with crustal abundance values from 2 sources (all in ppm)

Element		Navajo Canyon	Crustal Abundance	
			Fortescue (1992)	Emsley (1998)
Silver	Ag	< 3	0.08	0.07
Aluminum	Al	39,800	83,600	82,000
Arsenic	As	3.7	1.8	1.5
Barium	Ba	493	390	500
Beryllium	Be	1	2	2.6
Bismuth	Bi	0.1	0.0082	0.048
Calcium	Ca	26,400	46,600	41,000
Cadmium	Cd	0.07	0.16	0.11
Cerium	Ce	28.6	66.4	68
Cobalt	Co	4	29	20
Chromium	Cr	20.1	122	100
Cesium	Cs	3.2	2.6	3
Copper	Cu	10.4	68	50
Iron	Fe	11,000	62,200	41,000
Gallium	Ga	7.5	19	18
Mercury	Hg	< 0.02	0.086	0.05
Potassium	K	23,900	18,400	21,000
Lanthanum	La	14.8	34.6	32
Lithium	Li	32	18	20
Magnesium	Mg	9,640	27,640	23,000
Manganese	Mn	344	1,060	950
Molybdenum	Mo	0.24	1.2	1.5
Sodium	Na	3,200	22,700	23,000
Niobium	Nb	5.1	20	20
Nickel	Ni	7.5	99	80
Phosphorus	P	360	1,120	1,000
Lead	Pb	11.8	13	14
Rubidium	Rb	74.8	78	90
Antimony	Sb	0.32	0.2	0.2
Scandium	Sc	4.3	25	16
Selenium	Se	< 0.1	0.05	0.05
Strontium	Sr	102	384	370
Thorium	Th	4.5	8.1	12
Titanium	Ti	1,300	6,320	5,600
Thallium	Tl	0.5	0.72	0.6
Uranium	U	1.3	2.3	2.4
Vanadium	V	25	136	160
Yttrium	Y	10.7	31	30
Zinc	Zn	27.8	76	75

Table 14. Comparison of sediment collected at upper reach of Navajo Canyon with EPA sediment quality guidelines (Ingersoll et al., 2000; MacDonald et al., 2000)

Element	Observed (ppm)	Guidelines (ppm)		Comparison	
		TEC	PEC	TEC	PEC
Arsenic	3.7	9.79	33	< TEC	< PEC
Cadmium	0.07	0.99	4.98	< TEC	< PEC
Chromium	20.1	43.4	111	< TEC	< PEC
Copper	10.4	31.6	149	< TEC	< PEC
Lead	11.8	35.8	128	< TEC	< PEC
Mercury	< 0.02	0.18	1.06	< TEC	< PEC
Nickel	7.5	22.7	48.6	< TEC	< PEC
Silver	< 3	1	3.7	—	< PEC
TEC – Threshold Effects Concentration PEC – Probable Effects Concentration					

Table 14 shows two different sets of SQGs. The first, which is labeled as TEC, represents a concentration at which effects are not expected to occur, while the PEC is a concentration above which adverse effects are expected to frequently occur (Ingersoll *et al.*, 2000). As can be seen in Table 14, all of the samples from Navajo Canyon are below the TEC concentrations and the sediment should present no hazard to aquatic life. However, only one sample has been collected. Before the sediment can be deemed completely safe, more samples would have to be collected and analyzed. Nevertheless, the one sample does indicate that there are likely no contributing sources of the toxic substances shown in Table 14.

The sample was analyzed for mercury because of the proximity of the site to Navajo Powerplant. The results do not indicate any significant local deposition of airborne mercury (Table 14). A study of the Four Corners Powerplant, which is also located on the Navajo Nation, showed that residue levels of mercury in soils near the powerplant were low (Crockett and Kinnison, 1977). The results from Navajo Canyon are consistent with that finding.

Parker (1967), in addition to a set of CAV data, presents the average composition of various types of sedimentary rocks. Figure 19 shows a plot of the Navajo Canyon results plotted against the composition of a typical sandstone as presented in Parker (1967). For the most part, the fit of the data to the sandstone chemical profile is rather good. There are a few elements that plot away from the line, but the major elements plot reasonably close to it. Among the major ions, potassium plots farthest from the typical sandstone line. Gustavsson *et al.* (2001) show that potassium is somewhat elevated (2.1-2.3 ppm) in surficial rocks of the Colorado Plateau and even higher in the Rocky Mountains that constitute the headwaters of the Colorado River. In general, the data, including potassium, fit reasonably well to the line of the typical sandstone.

A number of trace elements plot well above the typical sandstone line. The most obvious are barium (Ba), copper (Cu), nickel (Ni), and niobium (Nb). Based on the information in Gustavsson *et al.* (2001), the Colorado Plateau surficial deposits are much higher than the typical sandstone in barium (475-500), copper (10-40), and nickel (10-20). The data from Navajo Canyon are actually low by Colorado Plateau standards (compare data in table 13 with the preceding).

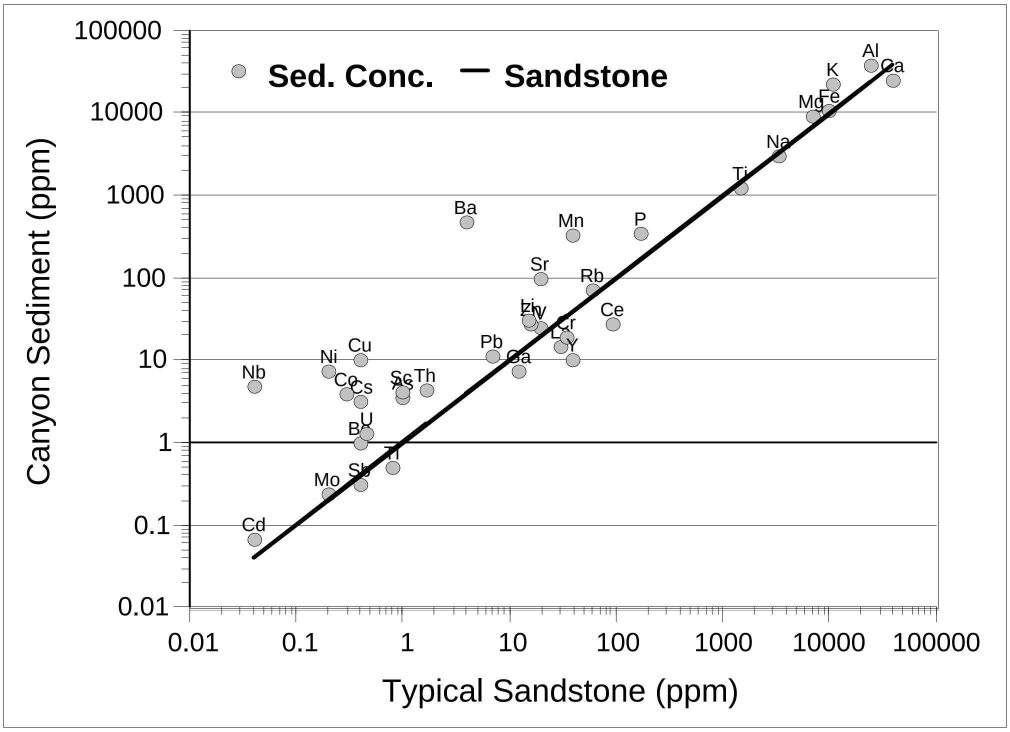

Figure 19. Comparison of the concentrations of elements from the ICP-MS scan of Navajo Canyon sediments with concentrations typical of sandstone.

The niobium concentration is about halfway between what is typical of sandstones and shales, based on the data in Parker (1967). However, the niobium concentration in Table 13 is only about ¼ of its CAV. In the weathering of rocks, niobium tends to become concentrated in hydrolysate sediments and is therefore found in shales and clays, rather than limestone or sandstone (Gornitz and Warde, 1972). The high niobium concentration in Navajo Canyon may simply reflect the presence of fines in the sediment sample.

Hart *et al.* (2004) studied several side canyons in Glen Canyon Reservoir in 2002. A complete chemical analysis on duplicate bed sediment samples was reported from Moqui Canyon, which is located about ½ mile up the reservoir from Bullfrog Marina. Their data are plotted on Figure 20 for comparison with the Navajo Canyon data and to show within sample variation. The typical sandstone line is also shown on Figure 20. Unlike the Navajo Canyon data, the major ions from Moqui Canyon plot parallel to, but below, the typical sandstone composition line. The elements that plotted above the typical sandstone data on Figure 19, *i.e.* barium (Ba), copper (Cu), and nickel (Ni), also plot above the line on Figure 20. Although there are no data for niobium from Moqui Canyon, tantalum (Ta), which is chemically similar to niobium, occupies a somewhat similar position on Figure 20.

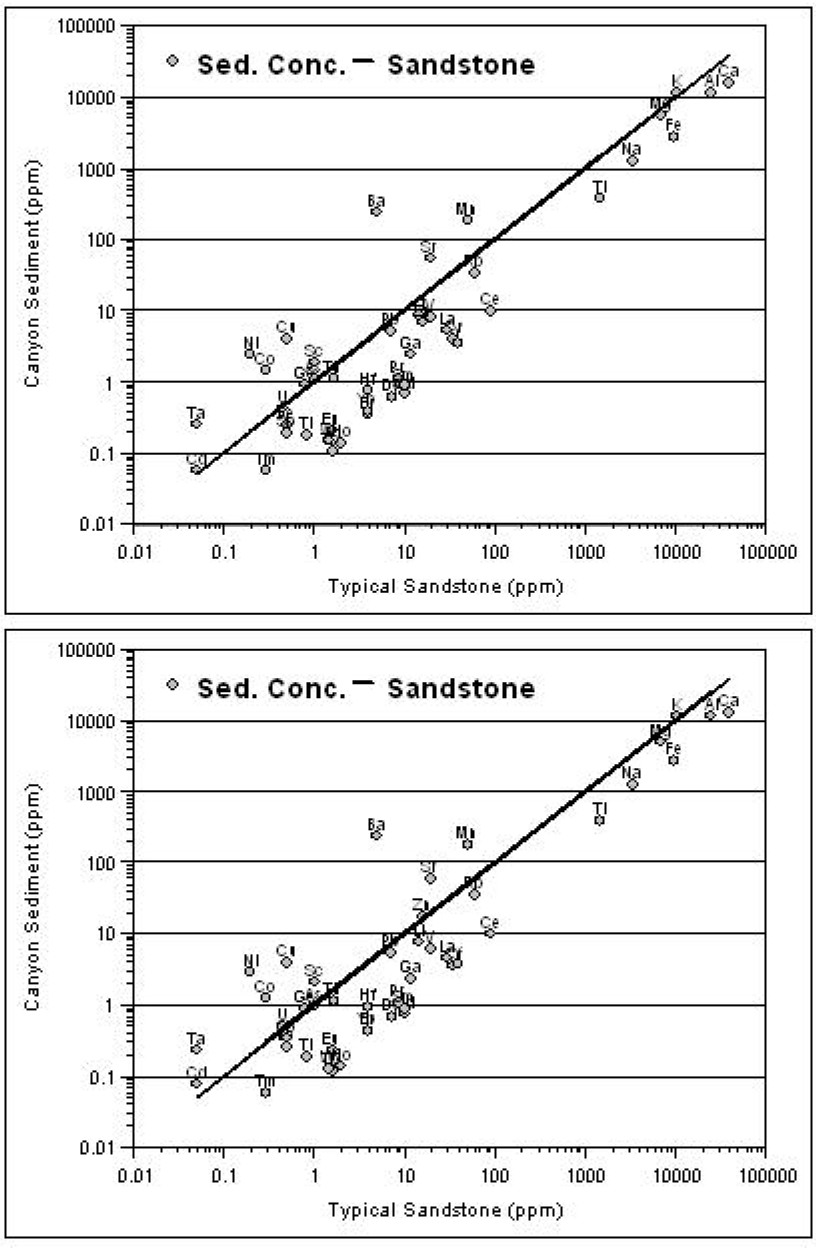

Figure 20. Comparison of the concentrations of elements in duplicate samples of Moqui Canyon sediments with concentrations typical of sandstone (Parker, 1967).

The differences between the data on figures 19 and 20 appear to represent the equivalent of a dilution in water. The total of the elements on Figure 19 is about 110,000 ppm, while their total in the typical sandstone is about 100,000. Because the total is similar, the Navajo Canyon data plot near the line. The total of the elements on Figure 20 for the Moqui Canyon data is about 50,000 ppm, or about ½ the total of the Navajo Canyon sample and the typical sandstone composition. Because the total is lower, the individual elements plot somewhat uniformly below the typical sandstone line.

If the sample analyses were anywhere near complete, the total of the elements would approach 1 (actually 1 million ppm). Major components of the typical sandstone include silicon (36.8 percent) and oxygen (46 percent). Neither of these are included in the analytical totals from Glen Canyon Reservoir. A petrographic analysis of a split of the Navajo Canyon sediment sample was about 90 percent quartz. Based on the weight of silicon in quartz, the Navajo Canyon sample would have been about 47 percent quartz. Although the elements are plotted on figures 19 and 20, they, like the silicon, would most likely be present in the sediments as oxides of the elements. The evident dilution that is mentioned above may simply be a result of differing amounts of quartz sand in the sediments.

In addition to the duplicate sample shown above, Hart *et al.* (2004) collected a total of 12 other samples. However, they only reported trace element concentrations in those samples, although aluminum and iron were also included. From the perspective of this study, Hart *et al.* (2004) reported selenium concentrations in the sediments of all 3 of the canyons. Selenium is a known contaminant in the Green, San Juan, and Colorado rivers above Glen Canyon Reservoir. However, there was no detectable selenium in any of those 12 samples. The Navajo Canyon sample also had no detectable selenium (Table 13), indicating that the probability of selenium contamination, as it is in Moqui Canyon, is low.

The preceding represents a preliminary analysis of potential contamination based on only 1 sediment sample. While 1 sample may be enough to discourage further investigation if a high degree of contamination is indicated, a single sample cannot define an absence of contamination. If sediment delivery from Lake Powell proves to be physically and economically viable, then further investigation of sediment contamination would be necessary. It should also be noted that the chemical results reported here are based on a different methodology than is recommended for toxicity testing. The digestion used in this study included a series of acids to completely (or nearly so) dissolve the sediments. For toxicity, a simple *aqua regia* digestion is recommended (EPA, 1998). In addition, a representative set of samples from a much more extensive area of the sediment deposits would need to be collected and analyzed to provide better coverage of the source area. Nevertheless, given the nature of the local Navajo Canyon drainage basin, there seems to be little likelihood that contaminants would be found.

Appendix B – Dredging Text Research and Information

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Mechanical Engineers
Mechanical Equipment Group

Dredge Design Types

1.) Suction Dredges
- Uses suction to remove sediment (some spray out jets to help loosen sediment). Mainly used for loose sediments like sand or gravel
- Original hydraulic dredge design

2.) Dragline Dredges
- Use a drag bucket to gather sediments
- Usually land based

3.) Clamshell Dredges
- Come in many configurations but all have two buckets, hinged together that close around the material and then are lifted back to the surface by a steel cable system
- Can handle most types of sediments except large boulders

4.) Auger Dredges
- Another hydraulic dredge that uses a cutting mechanism to dislodge sediment
- Cutter looks similar to snow plows but is on a long boom that lowers the cutter to the desired depth
- Cuts a wide even path in sediment
- Good dredge for shallow water situations and fine to medium sediments

5.) Cutter Dredges
- Similar to auger dredges but uses a corkscrew shaped cutter to cut into sediments
- Most versatile dredge

6.) Ladder-Bucket Dredges
- Use a bucket and conveyor system to move material, similar to trenchers

- Large machines, only can dig as deep as ladder is long, so larger depth means larger machine

7.) Hopper Dredges
- Another hydraulic dredge that uses a trailing suction device to gather sediments; like a big vacuum
- The dredge is also its own barge, for quick transport

8.) Rotary or Bucket Head Cutter Dredges
- Another hydraulic dredge that uses a spinning drum to dislodge sediments

9.) Excavator or Backhoe Dredges
- These dredges look like large, backhoe arms that have been placed on a barge
- Digging depth limited by the arm length

Dredging Manufacturers

1.) Ellicott
- Largest dredge manufacture in the world
- Specialize in cutter and auger dredges
- Models:

  1. Dragon 1170:
     - 150 to 700 yd^3/hr
     - 33' nominal depth (can be ordered to dig deeper)
     - 54' x 23' (L x W)
     - www.dredge.com/specs/dragon1170.htm

  2. Dragon 1870:
     - 200 to 1,200 yd^3/hr
     - 50' nominal depth (can be ordered to dig deeper)
     - 82' x 27' (L x W)
     - www.dredge.com/specs/dragon1870.htm

  3. Super Dragon 4,170:
     - 400 to 4200 yd^3/hr
     - 58' nominal depth (can be ordered to dig deeper)
     - 114' x 30' (L x W)
     - www.dredge.com/specs/superdragon4170.htm

  4. MC-2000 Mud Cat:
     - 20' nominal depth (can be ordered to dig deeper)

- 48’ x 14.5’ (L x W)
- www.dredge.com/specs/superdragon4170.htm

2.) IMS Dredges

- All models use a unique propulsion system called a “Starwheel Drive,” which is a pair of paddle wheels that are extended to the bottom of the water to push the dredge along
- All products are auger dredges
- Models:

1. Versi Dredge 5012
    - 1,040 yd^3/hr
    - 22’ nominal depth (extensions for 28’, 35’ and 45’)
    - 42’ x 10’ 7” (L x W)
    - http://www.imsdredge.com/products/versidredge/5012.htm

2. Versi Dredge 7012
    - 1,190 yd^3/hr
    - 25’ nominal depth (extensions for 28’, 35’ and 45’)
    - 42’ x 10’ 7” (L x W)
    - http://www.imsdredge.com/products/versidredge/7012.htm

3.) Twinkle Co. Dredges

- Specialize in ladder, cutter and bucket style dredges
- Website provides little explanation of their dredges’ specifications
- The ladder, boom designs of these dredges would limit their ability to dig to deeper depths
- http://www.twinkleco.com

4.) Dredging Supply Company, Inc.

- They have deep digging cutter, suction dredges that can dig to 150’+
- Specialize in customizing dredges to customers needs
- Models:

1. Marlin Class
    - 35’ to 150’+ nominal depth
    - http://www.dscdredge.com/marlin-dredge.html#

2. Shark Cutter Class
    - 65’ nominal depth
    - http://www.dscdredge.com/shark-dredge.html#

5.) Crisafulli Dredges

- All dredges are self propelled
- Can be moved by tractor-trailer on highways
- Only sell auger style dredges
- Models:

    1. Rotomite-6000
        - 150 yd^3/hr
        - 20’ nominal depth (60’ optional)
        - 32.5’ x 8.5’ (L x W)
        - http://www.dredge.net/Rotomite1/rfeatures.html

    2. Rotomite-8000
        - 325 yd^3/hr
        - 26’ nominal depth (50’ optional)
        - 40’ x 8.5’ (L x W)
        - http://www.dredge.net/Rotomite1/rfeatures.html

6.) Supreme Manufacturing, Inc.

- Clamshell Dredges
- Large capacity and deep digging dredges
- Models:

    1. 13 Yard Clamshell Bucket Dredge
        - 13 yd. bucket
        - Conveyor Off-loader
        - 300’ Digging Depth
        - http://www.suprememfg.net/Dredge.htm

    2. 8 Yard Modular Clamshell Dredge
        - 8 yd. bucket
        - Conveyor Off-loader
        - 300’ Digging Depth
        - http://www.suprememfg.net/Dredge.htm

Dredging

Possible Uses:

- Dredge sands and fine sediments from lake delta to begin the sediment augmentation system.

Pros:

- Clamshell dredges can dredge to 300 foot depths
- Move large quantities of sand or fine sediments very quickly
- Mobile, can be moved to dredging sites at various locations

Cons:

- All of the dredges seemed to be limited to a 3,000 foot long pipeline distance with small elevation change, unless booster pumps are provided
- Dredges could create navigational hazards with their floating pipelines
- Most hydraulic dredges seemed to be designed for shallow water use unless they were very large vessels
- Dredges require labor to operate
- Dredges require placement of anchor points along the shoreline or canyon walls, with pulling/positioning lines

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Dredges (Clamshell Type)

	Amount	Unit	Comments/Assumptions
Sediment	1,000,000	tons/year	Amount of sand or sediment required to be moved
Days	250	days/year	Assumes working 5 days a week & 11 Holidays off
Amount per Day	4,000	tons/day	Amount required to be dredged per work day
Bucket Load	8	yards/bucket	
Bucket Load	12.0	tons/bucket	3,000 lbs/yd³
Tons/hour @ 50 ft	353	tons/hr	80% Efficiency
Tons/hour @ 100 ft	288	tons/hr	80% Efficiency
Tons/hour @ 200 ft	211	tons/hr	80% Efficiency
Tons/hour @ 300 ft	166	tons/hr	80% Efficiency
Dredging time per day	11.35	hours	Time needed to meet 4000 tons/day @ 50ft
Time needed to dredge 110 tons	18.72	min	Amount per barge
Dredging time per day	24.08	hours	Time needed to meet 4000 tons/day @ 300ft
Time needed to dredge 110 tons	39.73	min	Amount per barge
Bucket Load	13	yards/bucket	
Bucket Load	19.5	tons/bucket	
Tons/hour @ 50 ft	632	tons/hr	80% Efficiency
Tons/hour @ 100 ft	534	tons/hr	80% Efficiency
Tons/hour @ 200 ft	408	tons/hr	80% Efficiency
Tons/hour @ 300 ft	330	tons/hr	80% Efficiency
Dredging time per day	6.33	hours	Time needed to meet 4000 tons/day @ 50ft
Time needed to dredge 110 tons	10.44	min	Amount per barge
Dredging time per day	12.13	hours	Time needed to meet 4000 tons/day @ 300ft
Time needed to dredge 110 tons	20.02	min	Amount per barge

The same amount of fine sediments and sand are required for a total of 2,000,000 tons. The above table shows what is needed for only one or the other.
This does not take into account the travel time of workers to get to the dredges; this could cut into the time worked on an 8 hour shift.
The dredges may need to operate 24 hours a day to continually feed a pipeline, or they would have to stockpile the dredged materials on a large barge or at a site on shore (if available) so the pipeline could have a surplus to use up over night.

Barges

Possible Uses:

- Movement of sands and fine sediments from dredging sites to Antelope Point near Glen Canyon Dam.

Pros:

- No floating pipes, cables or other obstacles for boaters
- Can move sediment to areas where off-loading would be easier
- Easy to switch to a new dredging site

Cons:

- Need a processing station to load sediments from hydraulic dredges
- May be too big for the canyons, didn’t find any smaller than 100’ x 30’
- Needs support equipment; unloading crane or conveyor system
- Slow moving, would need tug boats to help assist them in docking

Barge Transport				
	Sand	**Fine Sediment**	**Unit**	**Comments/Assumptions**
Annual sediment load	1,000,000	3,800,000	tons/year	Amt. of sand or sediment moved/year
Days per year	250	166	days/year	Working 5 days/week, & 11 Holidays off
Amount per Day	4,000	22,892	tons/day	Amount required to be moved/work day
Barge load capacity	110	110	tons/barge	
Barge loads per Day	36	208	barges	
Shortest load distance	28	28	miles	Distance/round trip
Longest load distance	40	40	miles	Distance/round trip
Average barge speed	5	5	mph	Average speed
Short distance time / load	7.6	7.6	hours	Avg. time/trip, plus 2 hrs unloading
Long distance time / load	10	10	hours	Avg. time/trip, plus 2 hrs unloading
Number of barges required for short distance trips	35	198	barges	8 hrs worked/barge/day
Number of barges required for long distance trips	45	260	barges	8 to 10 hrs worked/barge/day
Barge load capacity	110	110	tons/barge	
Barge loads per Day	36	208	barges	
Shortest load distance	28	28	miles	Distance/round trip
Longest load distance	40	40	miles	Distance/round trip
Average barge speed	10	10	mph	Average speed
Short distance time / load	4.8	4.8	hours	Avg. time/trip, plus 2 hrs unloading
Long distance time / load	6	6	hours	Avg. time/trip, plus 2 hrs unloading
Number of barges required for short distance trips	22	125	barges	8 hours worked/barge/day
Number of barges required for long distance trips	27	156	barges	8 hours worked/barge/day
Barge load capacity	110	110	tons/barge	
Barge loads per Day	36	208	barges	
Shortest load distance	28	28	miles	Distance/round trip
Longest load distance	40	40	miles	Distance/round trip
Average barge speed	15	15	mph	Average speed
Short distance time / load	3.87	3.87	hours	Avg. time/trip, plus 2 hrs unloading
Long distance time / load	4.67	4.67	hours	Avg. time/trip, plus 2 hrs unloading

Number of barges required for short distance trips	18	101	barges	8 hrs worked/barge/day
Number of barges required for long distance trips	21	121	barges	8 hrs worked/barge/day
This does not take into account the travel time of workers to get to the barges; this could cut into the time worked on an 8 hour shift.				
Assumes dredging does not interfere with the barges cycle time				
Number of barges required could be doubled, if they have to be filled over a day or night then moved to the unloading site during the following day. Barges would have to end a shift at either the dredging loading area or at the unloading area.				

Sediment Slurry Piping System

Possible Uses:
- Transport of dredged sands or fine sediments from dredging sites to the Colorado River below Glen Canyon Dam or Lees Ferry.
- Moving dredge materials from the dredging sites to a stock piling yard either near the dam or downstream by Lees Ferry.
- If barges used, the slurry pipeline could transport sediments from the off-loading site Antelope Point to the delivery points, either below Glen Canyon Dam or to Lees Ferry.

Pros:
- Easily integrates into most hydraulic or clam shell type dredging systems
- Less visible impact on surroundings

Cons:
- Need for many booster pumps
- Long distance to transport, especially to Lees Ferry

Trucking

Possible Uses:

- Moving sands and fine sediments from one site to another

Truck Requirement:

- Assuming ~30 tons of sediment per truck, it would take over 33,333 truck loads to move one million tons of material a year; that is ~133 truck loads per day (assumes 250 working days per year)
- Assuming ~25 tons of sand or sediment moved per truck, it would take over 40,000 truck loads to move one million tons of material a year; that is ~160 truck loads per day (assumes 250 working days per year)
- Assuming ~10 tons of sand or sediment moved per truck, it would take over 100,000 truck loads to move one million tons of material a year; that is ~400 truck loads per day (assumes 250 working days per year)
- Assuming ~5 tons of sand or sediment moved per truck, it would take over 200,000 truck loads to move one million tons of material a year; that is ~800 truck loads per day (assumes 250 working days per year)
- It is around a 140 mile round trip from the delta of Navajo Canyon, a 110 mile round trip from Antelope Point to Lees Ferry, or around a 24 mile round trip from Antelope Point to just below Glen Canyon Dam (uses tunnel)

Pros:

- Proven ability to move materials
- Uses existing structures; road ways in place

Cons:

- Noisy
- Added traffic and wear to the area's roadways
- Massive amount of trucks needed

Off Highway Trucking

Possible Uses:

- Moving sands and fine sediments from one site to another
- Move sediments from dredging sites to a stock piling area close by (2-15 miles) or to an area near the dam (15-40 miles)
- Assuming ~60 tons of material moved per truck, it would take over 16,666 truck loads to move one million tons of sediment a year; that is ~67 truck loads per day (assumes 250 working days per year)
- Assuming ~100 tons of material moved per truck, it would take over 10,000 truck loads to move one million tons of sediment a year; that is ~40 truck loads per day (assumes 250 working days per year)

- Caterpillar offers a variety of trucks ranging from 40 to150+ tons

Pros:

- Proven ability to move material

Cons:

- Needs a new roadway system built specifically for the trucks
- Would have to use a separate road system, so less interaction with the public
- Slow movement rate of vehicles; 30-40 mph at top speed
- Large number of trucks needed
- Large amount of capital needed to buy and maintain the trucks

Truck Transport				
	Sand	**Fine Sediment**	**Unit**	**Comments/Assumptions**
Annual sediment load	1,000,000	3,800,000	tons/year	Amt. of sand or sediment to be moved/year
Days per year	250	166	days/year	Work 5 days/week, & 11 Holidays off
Load per day	4,000	22,892	tons/day	Amt required to be moved/work day
Truck load capacity	25	25	tons/truck	
Trucks loads per Day	160	916	trucks	
Lees Ferry distance	110	110	miles	Distance/round trip
Average truck speed	20	20	mph	Average speed
Lees Ferry travel time	6	6	hours	Time/trip, plus 15min loading & 15min unloading
Trucks need for Lees Ferry	120	241	trucks	Assumes 8 hrs worked/truck/day
Average truck speed	30	30	mph	Average speed
Lees Ferry travel time	4.2	4.2	hours	Time/trip, plus 15min loading & 15min unloading
Trucks need for Lees Ferry	83	477	trucks	Assumes 8 hrs worked/truck/day
Truck load capacity	30	30	tons/truck	
Trucks loads per Day	133	763	trucks	
Lees Ferry distance	110	110	miles	Distance/round trip
Average truck speed	20	20	mph	Average speed
Lees Ferry travel time	6	6	hours	Time/trip, plus 15min loading & 15min unloading
Trucks need for Lees Ferry	63	358	trucks	Assumes 8 hrs worked/truck/day
Average truck speed	30	30	mph	Average speed
Lees Ferry travel time	4.2	4.2	hours	Time/trip, plus 15min loading & 15min unloading
Trucks need for Lees Ferry	69	397	trucks	Assumes 8 hrs worked/truck/day
Truck load capacity	5	5	tons/truck	

Trucks loads per Day	800	4,578	trucks	
GCD distance	24	24	miles	Distance/round trip
Average truck speed	20	20	mph	Average speed
GCD travel time	1.7	1.7	hours	Time/trip, plus 15min loading & 15min unloading
Trucks needed for GCD	170	973	trucks	Assumes 8 hrs worked/truck/day
Average truck speed	30	30	mph	Average speed
GCD travel time	1.3	1.3	hours	Time/trip, plus 15min loading & 15min unloading
Trucks needed for GCD	130	744	trucks	Assumes 8 hrs worked/truck/day
Truck load capacity	10	10	tons/truck	
Trucks loads per Day	400	2,289	trucks	
GCD distance	24	24	miles	Distance/round trip
Average truck speed	20	20	mph	Average speed
GCD travel time	1.7	1.7	hours	Time/trip, plus 15min loading & 15min unloading
Trucks needed for GCD	85	486	trucks	Assumes 8 hrs worked/truck/day
Average truck speed	30	30	mph	Average speed
GCD travel time	1.3	1.3	hours	Time/trip, plus 15min loading & 15min unloading
Trucks needed for GCD	65	372	trucks	Assumes 8 hrs worked/truck/day
Assumes dredging and barging does not hold up trucking				

Conveyor Systems

Possible Uses:

- Loading or offloading barges or trucks

Pros:

- Proven ability to move material fast
- Easily integrates into most dredging systems
- Can easily fill trucks, barges or stockpile sediments for later use

Cons:

- Noisy
- Visibly ugly

Appendix C - Stilling Basin Operations

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Mechanical Engineers
Mechanical Equipment Group

Assumptions	**Amount**	**Unit**	**Comment**
Sand	1,000,000	tons/year	Amount of sand to be moved, weight
Volume of Sand	666,667	yd^3/year	Sand to be moved, volume (1 ton -1.5 cu. yd)
Stilling Basins	2	basins	One is filled while one is emptied, switch monthly
Sand Gathered per Month	55,556	yd^3/mon	Amount of sand gathered by a basin in a month

Cleaning Out Stilling Basins and Moving the Sand to Stockpile Area

Sand to Move	55,556	yd^3/mon	Sand to be moved to stockpile each month
Sand per Day	2,778	yd^3/day	Assumes 20 work days per month
Yards per Truck	20.0	yd^3/truck	Assumes 30 tons per truck, 1.5 tons/cu.yd.
Truck loads per day	139	trucks	
Truck loads per hour	14	trucks	Assumes 10 hour work day
Load time per truck	4.2	min	Time allowed to load each truck
Turnaround time per Truck	15.0	min	Time from loading to being ready to be reloaded
Trucks Needed	4	trucks	

Moving Sand From Stockpile Area Into or Along the River Bank
(Prior to and During the Simulated Flood)

3 Week Push In at 5 Days per Week

Sand per Day	44,444	yd^3/day	Assumes 15 days to push all of the sand in
Push Rate	700	yd^3/hour	Push rate @ 300ft avg. for a D10 dozer
Yards per Day per Dozer	5600	yd^3/day	8 hour work day
D10 Dozers Needed	8	dozers	

3 Week Push In at 7 Days per Week

Sand per Day	31,746	yd^3/day	Assumes 21 days to push all of the sand in
Push Rate	700	yd^3/hour	Push rate @ 300ft avg. for a D10 dozer
Yards per Day per Dozer	5600	yd^3/day	8 hour work day
D10 Dozers Needed	6	dozers	

3 Week Push In at 5 Days per Week

Sand per Day	44,444	yd^3/day	Assumes 15 days to push all of the sand in
Push Rate	700	yd^3/hour	Push rate @ 300ft avg. for a D10 dozer
Yards per Day per Dozer	7000	yd^3/day	10 hour work day
D10 Dozers Needed	7	dozers	

3 Week Push In at 7 Days per Week

Sand per Day	31,746	yd^3/day	Assumes 21 days to push all of the sand in
Push Rate	700	yd^3/hour	Push rate @ 300ft avg. for a D10 dozer
Yards per Day per Dozer	7000	yd^3/day	10 hour work day
D10 Dozers Needed	5	dozers	