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The Economics of Using Sediment-Entrapment Reduction Measures in Lake and Reservoir Design

**UNIVERSITY OF ILLINOIS
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ABSTRACT

One of the most important impacts of building and maintaining a reservoir is the loss of storage capacity caused by sediment deposition behind the dam. Sediment deposition in the reservoir reduces the water storage volume and decreases or even negates the utility of the dam, and deteriorates the water quality. The loss of utility of a reservoir as a result of sedimentation or siltation can be considered an economic, environmental, and even a design failure. The objective of this study was to investigate, through an extensive literature search, the suitability and efficiency of several reservoir sedimentation reduction measures practiced in small- and medium-sized lakes.

Some of the methods successfully used for reducing sediment entrapment in reservoirs were watershed management, building check dams, bypassing sediment-laden flows, using density currents, flood flushing, drawdown flushing, flushing and emptying, siphoning, and dredging. The mitigation and operation methods so identified were evaluated with respect to their rate of success, cost, environmental impacts, and ease of implementation or retrofitting. The economies expected in using the identified alternative mitigative measures versus more conventional reservoir design were investigated in terms of reduced initial cost of reservoir and/or dredging costs.

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INTRODUCTION

Human-made or artificial reservoirs and lakes are very valuable natural resources. They can be designed, maintained, and operated to serve a number of purposes: domestic and industrial water supplies, water-based recreation, hydropower, flood control, irrigation, and water augmentation for navigation. But the construction of dams and reservoirs can disturb the social and economic environment, even before the project benefits start accruing. Therefore, their design, construction, and operation should minimize such disturbances and be environmentally beneficial, cost-effective, and in conformance with intergenerational equity considerations.

Water is generally considered as a renewable resource, which is true only if it is used wisely. In our effort to manage this resource, we build dams to control the irregularities of the stream discharges. However, in recent decades, especially in the United States, reservoir construction has been viewed as causing considerable harm to the environment.

Probably one of the most important impacts of building and maintaining a reservoir is the loss of storage capacity caused by sediment deposition behind the dam. Sediment deposition in the reservoir reduces the water storage volume and decreases or even negates the utility of the dam, and the water quality in the reservoir deteriorates. The loss of utility of a reservoir as a result of sedimentation or siltation can be considered an economic, environmental, and even a design failure.

When dam sites are abundant, another dam can be constructed to replace a silted one if economics is the only major issue. However, desirable dam sites are rather limited, and environmental impacts of dams must also be considered. Therefore, our goal in reservoir design and operation should be to preserve reservoir storage capacity and thus extend useful reservoir life to prolong the multipurpose benefits. For this reason, the reservoirs must be operated to regulate not only the runoff, but also the sediment.

There are two basic approaches for reservoir sedimentation control: 1) controlling soil erosion through watershed management, and 2) handling sediment where it creates the problem, namely, in the reservoir. Erosion of agricultural lands can be reduced by contour farming, terracing, and conservation tillage. However, even with the best management, the sediment inflow can be reduced only by 20-40% (except for very small watersheds). Moreover, the high cost of land management and the need for cooperation by a large number of landowners and farmers in the watershed, make this alternative difficult to implement in most cases.

The eroded water-borne material finds its way into the streams, and eventually into the reservoir. If the reservoir is not designed and operated properly, its relatively quiescent waters encourage the deposition of these sediments transported by the inflowing water. To maintain the utility of the reservoir, these sediments may have to be removed periodically. The reduction of sediment deposition in the reservoir, or sediment removal from the reservoir, can be effectively and expeditiously pursued by implementing controls and measures limited mostly to the dam and reservoir. Economics may dictate the adoption and success of any of these programs, however.

PROBLEMS WITH CONVENTIONAL RESERVOIR DESIGN AND OPERATION

The rate of reservoir capacity loss resulting from sedimentation depends on the quantity of sediment inflow, the density of the deposited sediments, and the percentage of the sediment trapped in the reservoir. The percentage of the sediment retained in the reservoir is referred to as the trap efficiency of the reservoir. Brune (1953) [8] has shown the trap efficiency to be a function of the ratio of reservoir capacity, C, to reservoir inflow, 7, or *C/I*. For most small- to medium-sized reservoirs built on relatively flat terrains, the median values of trap efficiency range from 60 to 94%, yielding *C/I* values of about 0.02 to 0.30, respectively. A significant portion of this sediment (70-80%) comes during high flow periods that occur only a few days or weeks during a particular year. Methods used for calculating the loss of reservoir capacity because of sedimentation become an important issue for long-term planning and reservoir management. For calculation of reservoir sedimentation rates, several methods have been proposed, which use trap efficiency, sediment density properties, and sediment consolidation [26, 75, 76].

Some of the problems inherent in the design and operation of dams and reservoirs with conventional overflow spillways are: 1) entrapment of a large portion of incoming sediment in the lake; 2) an initial design storage 30 to 80% higher (to accommodate sediments over the 40- to 50-year design period) than that with sediment entrapment reduction measures; 3) recycling of nutrients carried with the sediments deposited in a reservoir, causing algal blooms and reducing dissolved oxygen concentrations; 4) bed and bank scour downstream of the dam because overflows over the dam spillway carry less sediment; 5) coarse sediment deposited at the stream-lake interface, raising stages upstream and causing increased flooding there during high flow conditions; 6) increased flooding during high-flows because spillway increases flood levels upstream ; and 7) reservoirs considerably filled with sediments pose a threat for great environmental disaster in case of a dam failure.

If the reservoir is not designed and operated properly, the relatively sediment-free water from its top layers are discharged by the conventional overflow spillway, whereas most of the sediment is concentrated in the bottom layers and will eventually settle on the reservoir bed. The relatively sediment-free water discharged from the reservoir will change the river regime downstream. The flow released from the reservoir will try to meet its sediment-carrying capacity by eroding the streambed and banks, thus starting a new cycle of erosion [50]. The downstream degradation of the Nile River because of construction of the Aswan High Dam is a well-illustrated and documented case [69, 82]. Thus, the goal of reservoir operation and management should be not only to meet the project purposes, but also to entrap the least incoming sediment that is economically feasible. After all, reservoirs are built to store water, not sediment.

Although a great number of reservoirs built in the United States and around the world suffer from serious sedimentation problems, there are ways to mitigate the loss of storage capacity in reservoirs as a result of sedimentation. Sedimentation affects not only the storage capacity of a reservoir, but also several hydraulic operations of the reservoir. An analysis of 15 reservoirs in Taiwan illustrates the extent of damage sustained by turbines, sluice openings, and gales because of sediment carried by the flow [88]. Tarbela Dam in Pakistan is one of the many reservoirs that is seriously affected by sedimentation. The economics of operating these reservoirs hinges on their useful life, which may be severely shortened by sedimentation [4, 47].

The objective of this study was to investigate, through an extensive literature search, the suitability and efficiency of several reservoir sedimentation reduction measures practiced in small- and medium-sized lakes. The mitigation and operation methods so identified are evaluated with respect to their rate of success, cost, environmental impacts, and ease of implementation or retrofitting. The economies expected in using the identified alternative mitigative measures versus more conventional reservoir design were investigated in terms of reduced initial cost of reservoir and/or dredging costs.

LITERATURE SEARCH

A computer literature search was conducted by using the Water Resources Abstracts database. The search was extended to titles dating back to 1965. Combinations and variations of the following keywords were used in the search: reservoir, sediment, silt, venting, sluice, siphon, flushing, dredging, dam, construction, management, control, and economics. The search identified about 300 titles related to these keywords. Additional titles were found from the most recent journals, conference proceedings, government publications, and personal communications. A preliminary screening of the abstracts for those titles identified about 100 publications that were most relevant to the scope of this study. The articles in this preliminary list were then collected for study and to ascertain the extent of their relevancy. The list grew because additional titles were mentioned in the reference lists of the articles. After further analysis and to avoid excessive repetition, the number of articles were reduced to less than 100, which make up the core of the bibliography included in this report. Annotations are also provided for selected sources.

The bibliography included in this study probably represents a small subset of all reservoir sedimentation case studies done in the world. Unfortunately, not all studies are reported in the technical journals, but we believe that the bibliography represents a good sample of the case studies illustrating the continuous struggle around the world to reduce sedimentation in reservoirs.

PRESERVING RESERVOIR CAPACITY

The most desirable method for controlling reservoir sedimentation is probably by reducing soil loss and erosion from the reservoir watershed. This can be achieved by reducing sediment inflow through soil conservation, watershed management, gully control, vegetative screens, and building check dams. However, these methods are usually difficult to implement so other methods may be required to deal with the sediment entering the reservoir.

The most commonly used methods for reducing sediment entrapment and/or deposition in reservoirs are identified as follows: reservoir flushing (either by flood flushing, drawdown flushing, or flushing and emptying); venting (usually by passing sediment-laden flows associated with density currents through undersluices); dredging (hydraulic or mechanical); siphoning; and reservoir operation policies oriented towards sediment releases.

These methods can be broadly classified under two major groups. In one group, the objective of operation is to reduce sediment deposition in the reservoir (or reduce the trap efficiency) by increasing sediment outflow from the reservoir through use of density currents, releasing flows with heavy sediment concentrations during floods, and/or drawing down and flushing the reservoir during high flows. In the other group, reservoir storage capacity is recovered by flushing the reservoir, dredging it, and/or siphoning the deposited sediments. The major difference between these two types of measures is that the first one facilitates the passage of sediments through the reservoir and downstream of the dam before they have a chance to deposit. On the other hand, the second group consists of methods that can be used to remove the sediments that have already settled in the reservoir.

Unfortunately, the term "flushing" has been used quite freely for several methods by several authors. In this study, an effort was made to differentiate between different types of flushing techniques. The selection of a particular flushing method usually depends on various factors, such as the rate of incoming sediment, reservoir size and purpose, economics, and environmental concerns.

The methods used for preserving reservoir capacity are discussed under three sections in this chapter: "Reducing Sediment Inflow into the Reservoir," "Reducing Sediment Deposition in Reservoirs," and "Recovering Reservoir Storage Capacity." The last section of this chapter provides some general information and guidelines for reservoir design and operation.

REDUCING SEDIMENT INFLOW INTO THE RESERVOIR

Watershed Management

Many of the articles examined during this study either mention or agree that poor or improper land use and management are the major contributing factors to reservoir sedimentation [6, 7,10, 29, 38, 48, 55, 56, 65, 73]. Delivery of sediment load from geographic areas varies significantly. The world distribution of runoff, sediment yield, and sediment load is shown in table 1.

The annual water and sediment yields of some of the world's major rivers are shown in table 2. The three largest contributors by yield (mg/L) are located in China, whereas Oceania has the highest yield in tons/km^2. However, agricultural areas in the United States and Europe can produce sediment yields much higher than the world average. Several publications suggested the need for watershed management to reduce

Table 1. World distribution of runoff, sediment yield, and sediment load (from [48]).

Geographic Area	Precipitation (mm)	Precipitation (km^3)	Runoff (km^3)	Measured Suspended Sediment Yield (tons/km^2/year)	Measured Suspended Sediment Load (billion tons/year)
Asia	740	25.7	10.8	380	6.35
South America	1,600	27.0	11.8	97	1.79
North America	756	15.8	6.6	84	1.46
Africa	740	19.7	4.2	35	0.53
Europe	790	7.5	2.7	50	0.23

Table 2. Annual water and sediment yields of some of world's rivers (from [48]).

River	Country	($10^6 \times km^2$)	Runoff (cm)	Sediment Yield (tons/km^2)	Sediment Yield (mg/L)
Haiho	China	0.050	4	1,620	40,500
Daling	China	0.020	5	1,800	36,000
Yellow	China	0.770	6	1,403	22,041
Chira	Peru	0.020	25	2,000	8,000
Liaohe	China	0.170	4	241	6,833
Colorado	Mexico	0.640	3	211	6,750
Nile	Egypt	2.960	1	38	3,700
Copper	USA	0.060	65	1,167	1,795
Ganges	Bangladesh	1.480	66	1,128	1,720
Purari	New Guinea	0.031	248	2,581	1,039

sediment input into the reservoirs [7,10, 24, 38, 48, 55, 58, 73, 77, 85, 91]. Measures like strip cropping, forestation, crop rotation, terracing, and gully control can significantly reduce the soil loss. However, these measures take a long time to be effective, and their effectiveness for large catchment areas cannot be estimated accurately [7, 48].

Check Dams

Other ways of reducing sediment inflow into the reservoirs include building debris dams or check dams (or trap dams). These low dams or settling basins built across the main sediment-contributing tributaries can control the flow of coarse sediments into the reservoir. These deposits can be flushed or bypassed via diversion tunnels or pipes downstream of the main reservoir dam during high flows, or periodically cleaned during low flows when the deposits are exposed. Several successful examples are the Marsyangdi Project in Nepal [72, 51]; Sanmen Gorge Dam on the Yellow River in China [65]; the Baira Siul and Trisuli hydroelectric projects, Yamuna Hydel, Maneri-Bhali Hydel, Giri Hydel, and Rishikesh-Hardwar Schemes in northern India [34, 51, 70]; and Shihmen Reservoir, Tien-Lun Reservoir, and Jonghua Dam in Taiwan [31, 44, 90]. Design recommendations and maintenance costs for small check dams are given in [28]. For Kickapoo Reservoir in Wisconsin, land management and building check dams were recommended to control reservoir sedimentation [84]. For small reservoirs, upstream check dams can be used for gully control, and they can be built with cheap, local material, if available. These dams are usually less than 2 meters high, and their maintenance costs are negligible [28].

Check dams are capable of trapping only the coarser sediments, which would otherwise form upstream deltas at the head of the main reservoir. Some of the examples given above contain check dams that are constructed close to the main dam of the power plants, to keep the intakes clear of coarse sediments by periodic flushing. In the arid regions of Africa, trap dams have been used not only to catch the sand and gravel carried by high flows, but also to supply water to small communities from groundwater in the entrapped sand and gravel [2].

The use of check dams and watershed management can reduce the inflow of sediments into the reservoir. However, a significant amount of sediment will still enter the reservoir, either because of their inefficient use or because of their inability to trap fine, suspended sediments. The scope of this study was to identify and evaluate the methods that can be used to increase the sediment outflow, and/or the removal of deposited sediments from the reservoirs efficiently and effectively.

REDUCING SEDIMENT DEPOSITION IN RESERVOIRS

Reservoirs can be operated to regulate the flow during the flood season to maximize sediment release from the reservoir based on the characteristics of the silt-laden flows. About 80% of the annual sediment load enters the reservoir during high flow periods and up to 80% of this sediment can be vented through properly designed undersluices.

Venting Density Currents

Density currents are caused by the difference in density of the relatively cleaner reservoir water and the sediment-laden incoming streamflow. Density differences can be generated either by the high concentrations of suspended sediment particles in the incoming streamflow, or by the temperature differences between the streamflow and the reservoir waters. In reservoirs, density currents usually travel at the bottom of the reservoir downstream of the plunge point. According to Wunderlich and Elder (1973) [92] "... any flow seeks its density level and moves along this level into storage position. If this level happens to be the withdrawal zone, the inflows will move directly through the reservoir. In other cases, water may be stored for considerable periods of time."

The necessary conditions for the occurrence of density currents have been established, but these are not sufficient conditions for effectively venting the density currents. It is best to vent density currents from the very beginning, so that the sediments are not allowed to stabilize, and the bottom slope of the reservoir is maintained for the efficient movement of density currents.

Density currents have been observed not only in reservoirs on rivers with flows having heavy sediment concentrations, but also in reservoirs on rivers with flows having low sediment concentrations [20]. Data on the density currents vented out of several reservoirs show that the ratio of outflow to inflow of silt discharge ranges between 0.18 and 0.65 [7, 23]. All these reservoirs are large with storage capacities ranging between 160 x 10^6 m^3 and 38.4 x 10^9 m^3, and reservoir length ranging between 12 km and 128 km. The density current properties of these reservoirs (Iril Emda, Algeria; Lake Mead and Elephant Butte Lake, United States; Nebeur Dam, Tunisia; and Fengjiashan Reservoir, Guanting Reservoir, Sanmenxia Reservoir, and Liujiaxian Lake, all in China) are documented in several publications [7, 20, 21, 23, 55]. Despite their size, density currents have been observed to travel up to 100 km before venting out through the diversion outlets in Lake Mead. Density currents have also been observed in Serre-Poncon Reservoir [20], and Sautet Reservoir [55] in France.

The efficiency of density current venting for reducing reservoir sedimentation depends on reservoir bed topography, reservoir operation, location and capacity of bottom outlets, and the characteristics of the density currents [19, 21]. The provision of venting density currents for decreasing reservoir trap efficiency should be considered during the design stage. In most cases, such provisions should include flexibility in reservoir operation and management. Provision of multi-level, multiple outlets improves the venting efficiency of the density currents and provides the flexibility required for alternate reservoir management (see [55] for details, benefits, and maximum effectiveness).

Flood Flushing

Frequent flushing of sediments may be necessary during the high-inflow season when the excess flows may be routed through the sluices. The purpose of regulating the flows during the flood season is to release as much sediment as possible from the reservoir. This takes advantage of the silt-carrying capacity of floodwaters in the reservoir and in the downstream reaches of the river. Generally, this operation greatly reduces sediment entrapment. By inhibiting formation of an extensive delta at the stream-reservoir interface, increased flood levels and flooding along the stream are minimized. The regulation of flood flows can be achieved by using the bottom sluices and lowering the reservoir water level before the floodwaters enter the reservoir.

Flood flushing evacuates flows with high sediment concentrations, which are typically observed during the rising limb of the flood hydrograph. However, during the same period, sediment and water discharge from an overflow spillway of a reservoir is smaller than the incoming discharge because of the backwater effects and a decrease in the flow velocity in the reservoir. The reservoir water level can be lowered before the flood peak arrives, and the flood peak carrying the high concentration of sediments can be released from the reservoir by increased discharge through the bottom outlets. The reservoir can be restored to its full storage capacity by impounding the relatively sediment-free water from the falling limb of the flood hydrograph.

By far, flushing of flood flows through low-level sluices to evacuate flows with high concentrations of sediments is the most common method to preserve reservoir capacity. The technique of venting sediments through undersluices has been used in Spain since the sixteenth century to keep the reservoirs free of sediment deposits [86]. The Sanmenxia Reservoir, which was formed by the completion of the Sanmen Gorge Dam in 1960 on the Yellow River in China, trapped 90% of the incoming sediment in the first few years [65]. After 1962 a diversion tunnel and some penstocks were converted to sluiceways for flushing sediment, and reservoir operation was changed by lowering the water level during flood season. With these measures the trap efficiency was reduced to less than 20%.

Similar flushing methods have been used in the Honglingjin, Guanting, Heisonglin, and Naodehai Reservoirs in China [7]. In the Heisonglin Reservoir the annual deposition rate (540,000 m^3/year) has been reduced to about 100,000 m^3/year by flood-flushing practices [7, 49]. Model studies for the Loiza Reservoir in Puerto Rico indicate that flood flushing can minimize sedimentation but cannot prevent it completely [56, 57]. However, requirements for water-supply needs and concerns about downstream damages had made it difficult to implement flood flushing for the reservoir [56].

Flood flushing operation is also one of the main regulation practices in the Sanmenxia Reservoir. It has been suggested that the sluicing of sediments in the reservoir should be carried out under large discharges to minimize sediment deposition downstream, and that sluicing should be accompanied by the lowering of the water levels in the reservoir [46]. Annual flood-flushing operation has been proposed for the Trinity and Lewiston Dams on the Trinity River in North Carolina to maintain the fisheries [58].

Drawdown Flushing

Drawdown flushing is different from venting density currents and flood flushing, and it is implemented to evacuate the sediments that have already been deposited in the reservoir. However, the other two methods are used mostly to discharge the incoming sediments before they have a chance to settle and consolidate. Drawdown (or hydraulic) flushing involves the release of water from a reservoir through a low-level outlet, while reducing the pool to an allowable minimum level. The efficiency of drawdown flushing depends on the reservoir topography, outlet capacity and elevation, characteristics of the incoming sediment material, operation of the reservoir, and duration of the flushing operation.

Drawdown flushing is probably one of the most commonly used methods in the world for recovering reservoir capacity, which otherwise could not be maintained by venting density currents, flood flushing, or both. Numerous cases of drawdown flushing have been documented in the literature and are included in the annotated bibliography. Some of the noteworthy examples are briefly described below.

The Warsak Dam in Pakistan is a 76-m high multipurpose dam built in 1960 on the Kabul River. The dam's gross storage capacity is 170 x 10^6 m^3, and its dead storage capacity is 80 x 10^6 m^3 . In the first five years of operation, the reservoir lost about 70 x 10^6 m^3 of its capacity, and by 1980 the reservoir had almost completely silted up. During 1976 and 1979, five flushing operations were carried out while lowering the pool level to the spillway crest. During the 490 hours of flushing, about 4.2 x 10^6 m^3 of deposits were evacuated from the reservoir [7]. With this limited flushing, about 6.4% of the average annual measured sediment load was removed. There is no record of low-level sluices on the Warsak Dam.

The Sefidrud Dam is a 106-m high buttress gravity dam on the Ghazel Ozan River in northwest Iran. The reservoir has a storage capacity of 1,800 x 10^6 m^3, and its trap efficiency has been estimated as 70% [7]. The dam has outlets at three elevations, with the lowest one located about 9.5 m above the riverbed. Flushing operations were performed at the end of the cropping season by lowering the pool level at the rate of 1 m/week. A total of 148 x 10^6 m^3 of sediment was removed from the reservoir between 1980 and 1983, with an average of 120 days of flushing each year.

The Ouchi-Kurgan Reservoir in the USSR, which has a storage capacity of 56.4 x 10^6 m^3 and dead storage capacity of 20 x 10^6 m^3, is used for irrigation and power generation [7]. The dam has eight bottom outlets located 20.8 m below the power intakes, with a discharge capacity of 350 m^3/sec. During drawdown flushing, the pool level is lowered by 5 m. This way about 12 x 10^6 to 14 x 10^6 tons of sediment was discharged annually, and sediment deposition in the reservoir was stabilized.

The old Roman dams used for irrigation had bottom outlets that were used to draw down and flush the reservoir at the end of the irrigation season. Some of these reservoirs are still in operation [67]. Zemo-Afchar Reservoir in the USSR has two bottom outlets with a total width of 15 m. An optimal operation was reached after several unsuccessful operations. Highest flushing efficiency occurred when the outlets were opened fully while the pool level was lowered [7]. Emptying and flushing of the reservoir was also recommended as an option.

The Khashm El Girba Reservoir in Sudan, which has a storage capacity of 950 x 10^6 m^3, has been flushed twice in July of 1971 and 1973. Almost all the annual sediment inflow, about 84 x 10^6 tons, had been discharged during each flushing operation, which took 4-5 days each time [7]. More cases of successful drawdown flushing and model studies exist in the literature for the USSR [52, 55, 59], Iran [59], China [23, 65], Switzerland and Austria [55], and Algeria [1]. The results of a reservoir sedimentation model for the Kamatavi Dam in Zimbabwe showed that the use of low-level outlets to flush sediments would significantly extend the useful life of the reservoir [87]. Moreover, this operation will be effective if the flushing occurs at low reservoir levels during a period of high river flows; thus, it is feasible if the required water yield of the reservoir is less than the annual river flow.

There have been a few cases where drawdown flushing had limited success, however. In the Shuicaozi Reservoir in southwest China, and in the Guernsey Reservoir on the North Platte River, the amount of sediment discharged was less than anticipated, primarily because overflow spillways were used for drawdown and due to the topography of the reservoir [7, 48]. Drawdown flushing is more effective in narrow gorge-type reservoirs with impounding dams equipped with bottom outlets.

RECOVERING RESERVOIR STORAGE CAPACITY

The first two methods discussed in this section (namely, siphoning, and flushing and emptying) can also be used for increasing sediment flow through reservoirs with proper operation. However, their applications are more suitable to reservoir storage recovery, and thus they are discussed in this section. On the other hand, dredging can only be used for recovering reservoir storage capacity.

Siphoning

Siphon devices or hydroaspirators can be used to evacuate sediment in small capacity (less than 10×10^6 m^3) to medium capacity ($10\text{-}100 \times 10^6$ m^3) reservoirs. Siphoning differs from ordinary suction dredging in that it exploits the hydraulic head difference between the water levels upstream and downstream of the dam, and operates automatically. Its primary advantages are that it requires less water to operate than other methods, it is flexible and can be used under different operating conditions, and its installation and operation costs are very low. However, it may not be suitable for removing large quantities of sediments from large reservoirs, unless it is used in conjunction with bottom outlets. Several examples are given below for successful siphoning operations.

An experimental siphon device was installed in 1975 in Tianjiawan Reservoir, Shanxi Province, China. The reservoir has a capacity of 9.42×10^6 m^3, with a dam height of 29.5 m. From 1960 to 1975, 4×10^6 m^3 of sediment had deposited in the reservoir, at an average rate of 250,000 m^3/year [13]. The 550-mm diameter steel siphon pipeline is attached with flexible joints, and is connected to the reservoir outlet by a valve chamber. The 229-m long pipeline, which has a scraper nozzle, is suspended by pontoons and submerged under water. The siphon is operated by a barge. In 1977, 320,000 m^3 of sediment was removed by 695 hours of operation (about 460 m^3/hr) [7, 13]. The sediment concentration in the siphoned water was 15.6% by volume. If siphoning were used for agricultural withdrawals in Tianjiawan Reservoir, the amount of sediment removed could be doubled.

During the 1950s, siphoning was tested extensively at Gen-Shan-Pei Reservoir, but its effect was found to be local [90]. It was concluded that a flexible pipeline was needed to connect the siphon to the reservoir bottom outlets. The head part of the siphon pipeline should also be movable to reach sediment deposits at different locations.

A simple but successful siphoning device is installed at the Rioumajou Dam in France [7,18]. The siphon straddles the gravity arch dam 21 m in height. The siphon entrance is located between the water intakes and the sluice to keep the area clear of sediment deposit, which otherwise blocks the intakes located 4 m higher in about a year. The siphon operates automatically when the spillway functions. The upstream branch of the pipeline is 20 m long and 450 mm in diameter, and is equipped with a priming nozzle. The downstream branch is 24 m long with 400 mm diameter. The device can discharge about 1 m^3/sec and carry 15 kg of sediment. The installation cost is about $110,000 (1992 dollars). The cost would be higher if a more convenient access location had been chosen. Maintenance costs are very low, because the siphon operates only when needed. It has almost amortized itself within one year.

For the restoration of Lake Ballinger, Washington, a hypolimnetic injection and siphon withdrawal system was used to stop the eutrophic process. The project involved injecting the oxygen-rich water taken from an upstream intake structure into the hypolimnion of the lake by a 276-m long, 305-mm diameter pipe. The withdrawal pipe extends 381 m with a 305-mm diameter pipe to the lake-level control structure. The system works as a siphon and replaces the hypolimnetic water of the lake with epilimnetic water from upstream [25].

Another siphoning system has been proposed to lower the trap efficiency of reservoirs through a "bottom-withdrawal spillway" [63]. The spillway is basically a pipeline extending from upstream to downstream of the dam. The main difference is that the siphon action of the bottom-withdrawal spillway is controlled by an air vent near the apex. The elevation of this vent determines when the siphoning action starts and stops.

Flushing and Emptying

Flushing and emptying may be used in reservoirs in which a balance between deposition and erosion cannot be maintained by a method or a combination of methods after several seasons. Reservoir-emptying operations may be used periodically, especially for small reservoirs, where the methods mentioned earlier have not been successful in maintaining reservoir storage capacity. Because a great part of the useful storage capacity in a small reservoir is located near the dam, flushing and emptying the reservoir may remove the deposits, if the outlets are installed and operated properly. The flushing may have to be done in a riverine situation so that a channel can be scoured into the old deposits. Such a channel becomes part of the storage capacity and also helps convey the density currents to the dam site more easily. Periodical flushing and emptying recovers useful storage capacity by removing floodplain deposits and carving a channel in the reservoir bottom.

Greater recovery of capacity could be achieved if the reservoir were emptied just before the arrival of a flood, so that the floodwaters could exert their strongest erosive force on the exposed, but not yet consolidated sediment deposits. However, flushing operations should be restricted to flood seasons to avoid causing serious deposition downstream. Following is a brief summary of applications of the flushing and emptying operation application. This practice, as indicated by the high number of documented cases, must be one of the most widely used methods for restoring reservoir storage capacity, along with the dredging method, which will be discussed later.

The Jensenpei Reservoir in China is a small reservoir with a storage capacity of 7×10^6 m^3, and a drainage area of 10.6 km^2. It provides industrial water supply, and has an annual silting rate of 237,000 m^3 [32, 59]. Periodic flushing and emptying has been done between the months of May and June, permitting natural flows through the dam via a flushing tunnel, thereby reducing the annual silting rate to 1,200 m^3/year [32, 59]. A similar method has been proposed for the Ho-Ku Reservoir with a check dam and a flushing tunnel, connecting the flushing tunnel downstream of the main dam.

The Gen-Shan-Pei Reservoir in Taiwan has a storage capacity of 6.98×10^6 m^3, with an annual silting rate of 224,000 m^3 [89]. After 20 years of operation the reservoir lost about 60% of its original capacity. A sluice tunnel 203 m long and 1.5 m in diameter, with a maximum flow capacity of 9.28 m^3/sec, was constructed along with two hydraulic gates 15.6 m downstream of the inlets [89]. Prototype and model studies indicated that best results could be achieved under a riverine situation, with the reservoir almost completely emptied. For an average desilting period of 53 days per year, about 329,000 m^3 of sediment could be evacuated from the reservoir. Average sediment concentration in the sluice flow is estimated to be about 8.94% [89, 90]. Hydraulic flushing through low-level sluices has also been applied at Kukuan and Tien-Lun Reservoirs, with coarse sediment characteristics. However, problems with blockage of the gates and increased abrasion of structures have been observed [44, 90].

Sluicing and flushing applications for the Sanmenxia Reservoir in China have been reported in several studies [46, 59, 62, 65]. However, it is not clear if this application is drawdown flushing, flushing and emptying, or a combination of both.

The Mangahao Power System in New Zealand was built in 1925 with an upstream sediment trap dam. By 1958 the lower dam lost about 59% of its capacity to sedimentation. In 1969 a low-level diversion tunnel was used to sluice the accumulated silt. In one month, with releases from the upstream dam, 75% of the old sediments were flushed out (about 880,000 m^3), and the operation has been implemented annually since then. Problems with debris have been reported [36].

The Bitsch Hydroelectric Scheme in Switzerland has a series of dams in the Massa and the Rhone Valleys. The Gebidem Reservoir located on the lower end of the Massa River has a storage capacity of 9×10^6 m^3, with an estimated annual sediment deposition of 500,000 m^3 [79, 80]. About 25% of the sediment is coarse sand and gravel brought down by the glaciers each year. Flushing and emptying is planned just before the high-flow season to discharge the previous year's deposits, as soon as the flow of the Massa River reaches 25 to 30 m^3/sec. Flushing is done only at high-flow conditions to avoid the impacts of increased sediment concentrations downstream. The dam is equipped with two 2 m by 2.3 m flushing sluices, and lined with steel to resist abrasion. The scouring can be done either by sluicing under pressure, or under free-flow conditions.

The Baira Siul Project in northern India envisions using the combined flow of three tributaries (Siul, Baira, and Bhaledh) of the Ravi River for production of hydropower [33]. The Baira Siul Reservoir has a storage capacity of 2.4 x 10^6 m^3 , with dead storage of 1.56 x 10^6 m^3. Although the annual silting rate had been estimated at 0.092 x 10^6 m^3, about 450,000 m^3 had deposited in the first 18 months of operation [33, 59]. After model studies, a D-shaped diversion tunnel 7 m high and 5 m wide was used to flush out the sediments by lowering the reservoir to its minimum drawdown level [33, 51, 59]. Up to 150 m^3/sec of discharge was passed through the tunnel until the reservoir was fully emptied. About 380,000 m^3 of sediment had been removed from the reservoir during 34 hours of operation. The average sediment concentration in the flushing flow had been estimated at 100,000 ppm [33]. It is recommended that flushing and emptying preferably be carried out when the discharge is about 100 m^3/sec and a flushing duration of 24 hours is sufficient. The prototype results were in good accord with the model studies [33, 51].

The Santo Domingo Reservoir in Venezuela has a storage capacity of 3 x 10^6 m^3, of which 2.6 x 10^6 m^3 is useful storage. The 72-m archdam has three 3 x 2.5 m bottom outlet structures for flushing out sediment. The maximum annual sediment inflow to the reservoir was estimated at 167,000 m^3. To ensure the flow through the outlet structures when they are covered by sediment, each structure is also equipped with a 0.8-m diameter siphon pipe. In May 1978, after four years of operation, the flushing operation was undertaken over a three-week period. During the first three or four days of flushing under free-flow conditions, about 60% of the sediment deposits were cleared out. After three weeks of intermittent operation (because of low river flows) a total of 620,000 m^3 of sediment was cleared out [41, 59].

The Hengshan Reservoir in China is a gorge-type reservoir with a storage capacity of 13.3 x 10^6 m^3 . The 69-m high dam has a small bottom outlet (located 2.6 m above the original river-bed) that can discharge 17 m^3/sec, and an outlet for flood flushing, set 14.5 m above the river-bed, with a capacity of 1,260 m^3/sec. During its first eight years of operation (1966-1973), 3.19 x 10^6 m^3 of sediment had accumulated in the reservoir [20, 23]. In 1974, after the reservoir was flushed and emptied for 37 days, 800,000 m^3 of storage was recovered. A second flushing operation in 1979 lasted for 52 days and recovered 1.03 x 10^6 m^3 of storage capacity. Experience in the Hengshan Reservoir indicates that the efficiency of flushing was high when the main channel had been silted by sediments over a one- to four-year period, depending upon the sedimentation rate.

For Welbedacht Dam in South Africa, a model study was carried out for deflecting river sand and silt away from water-supply intakes and directing them to the five sluices with gates in the dam [35]. It was found that venting of sediments through the gates could be improved by providing two deflector groins or walls upstream of the dam to induce a meander pattern.

Dredging

One of the most popular methods in dealing with reservoir sedimentation is sediment dredging. Dredging is also probably the most controversial issue in reservoir storage rehabilitation. There are strong views concerning the environmental benefits and/or hazards of dredging. Although the number of dredging projects undertaken in the United States is very large, there was little documented information to assist engineers and aquatic ecologists in determining the impacts of dredging [60]. Usually environmentalists view dredging as a "dragon in paradise", which destroys valued natural resources [60, 83]. While dredging is not without adverse environmental impacts, it may be appropriate and economical for certain lake restoration projects [39].

One of the major environmental concerns is that dredging resuspends sediments which may release toxic substances. The second most important factor in dredging is the transportation and disposal of the dredged material [11, 60, 61, 66]. If the removed sediments contain hazardous material, disposal of the dredged material may be a major problem, environmentally and economically [11, 60, 83]. And the costs of dredging, even by modern techniques, may be prohibitive. Even so, dredging is undertaken to remove sediments from reservoirs if a) flushing is not successful, b) building a bypass is impossible, c) pool drawdown is not acceptable, d) it is impossible to raise the dam, e) or any other option is unfeasible [7]. Technological improvements in the dredging industry may reduce or eliminate some of the concerns about the environmental impacts of dredging in the future, and the reuse of the dredged material may also make it more feasible [66, 83].

In most cases, the economic and/or environmental success of a dredging operation depends on certain criteria, such as the type of sedimentation problem (amount and depth of material to be removed, and quality of sediment), duration of dredging, financing, disposal and use of sediment material, and the type of equipment to be used. These issues are discussed in depth for various projects [11, 27, 43, 53, 60, 66, 83]. But in general, each case of dredging is unique, and for each potential dredging project these criteria should be evaluated to determine whether dredging is warranted.

A sample of the documented dredging cases will be briefly explained with emphasis on the environmental and engineering difficulties encountered, and the cost of the projects.

The Shihmen Reservoir in Taiwan, which started operation in 1963, has a storage capacity of 309 x 10^6 m^3 [31]. Although the annual sedimentation rate was estimated at 800,000 m^3/year, the first major flood brought about 10.5 x 10^6 m^3 of sediment into the reservoir [31, 90]. Several measures such as construction of small check dams and adopting soil conservation practices reduced the sediment inflow to the reservoirs, but the annual silting rate still remained at about 2.3 x 10^6 m^3. A hydraulic dredger with a submersible dredge pump having a pumping capacity of 900 m^3/hour was utilized to remove material from as deep as 80 m. The suction head was equipped with a jet nozzle. With this method high-capacity dredging was possible and the mud concentrations could reach up to 30%. However, the water pollution problem induced by the disposal of dredged material into the downstream channel was extensive [90]. The cost of dredging was estimated at \$6.27/m^3, which includes the construction of settling basins [31].

One of the largest dredging projects in Illinois is the removal of about 2.7 x 10^6 m^3 of sediments from the upstream delta portion of Lake Springfield. This four-year project cost approximately \$10 million [55]. When constructed, the lake's storage was about 73.9 x 10^6 m^3, but it was reduced to 64.4 x 10^6 m^3 in 51 years. The dredged material was discharged to an upland disposal area on flat land within 1 km of the reservoir. Details of other dredging projects in Illinois are also available [3,15, 64].

The storage in Loíza Reservoir in Puerto Rico was reduced from 25.3 x 10^6 m^3 to 14.4 x 10^6 m^3 in 39 years as a result of sedimentation. Conservation methods and upstream dams to reduce sediment inflow into the reservoir were not feasible, and it was not possible to raise the dam or build a new reservoir. Other alternatives such as drawdown flushing could not be implemented because of a lack of bottom outlets and the risk of not being able to refill the reservoir, which supplies water to 750,000 people [56]. Hydraulic dredging was analyzed and found to be economically and technically feasible. Dredging was considered as a complement to flood flushing. Restoration by dredging was estimated to cost from \$10-20 million (1990 dollars) depending on the sediment disposal option.

The dredging of a five-lake system in Baton Rouge, Louisiana, involved removal of about 488,000 m^3 of sediments in 1981. However, the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers rejected the use of near-site disposal areas. Because off-site disposal was so costly, a combination of off-site and in-lake disposal (islands, etc) was used. The more than \$3 million cost of the project also included other rehabilitation works and matching funds [40].

An environmental evaluation of eight dredging projects in the northeastern United States from 1978 to 1986, shows that the limiting concerns were environmental ones, especially the impact on water quality and wetlands [9]. These rather small lakes (7,500-273,000 m^3 in capacity) were dredged by hydraulic or mechanical methods. The total dredging costs varied from \$1.44/m^3 to \$5.32/m^3, with 10-30% of the costs being attributed to environmental controls [9]. Two other small-lake dredging projects in New Jersey involved the mechanical dredging of 56,000 m^3 of sediment from Etra Lake, and hydraulic dredging of 41,700 m^3 of sediment from Sylvan Lake, respectively. The projected costs, \$8.26/m^3 for Etra Lake and \$4.80/m^3 for Sylvan Lake, do not include the cost of engineering and administration [30]. The costs for Etra Lake were higher because the disposal site required construction of dikes.

The dredging projects for Blue Lake in Iowa [45], Lake Accotnik in Virginia [12], and Mohawk Lake in Ontario [16] are other examples of small-scale dredging projects, removing sediment volumes from about 153,000 m^3 to 286,000 m^3. Each case had different water quality, permit requirements, and disposal site selection difficulties. More detailed summaries of several lake dredging projects undertaken in the United States and elsewhere are presented by other researchers [11, 60, 61], in regard to the volume of sediments removed, environmental, water quality, and disposal problems, and cost factors. The general conclusion is that dredging is not without adverse environmental impacts. Each case needs to be evaluated for its benefits, alternatives, and adverse impacts, as well as the cost of the overall project. In the United States the mean dredging costs for lake restoration projects by dredging varied between \$1.34/m^3 in the Great Lakes area to \$5.63/m^3 in the northeast region [60].

RESERVOIR DESIGN AND OPERATION

The examples summarized so far illustrate the extent of efforts made and resources used in battling the sedimentation problem in reservoirs. In some cases, it is a matter of diminishing water supply for domestic, industrial, or agricultural uses; in other cases, it may be the loss of hydropower generation. The feasibility of reservoir rehabilitation depends largely on the intended use of the reservoir and the severity of the sedimentation problem. If no other sites are available to build a new reservoir, rehabilitation may have to be done whatever the costs. In hydropower projects, the problem can be alleviated by cleaning the intake areas, but in multipurpose reservoirs a major rehabilitation may be required, one considering water quality, water supply, and environmental issues. Several attempts have been made in evaluating the marginal economic benefits and the benefit/cost ratios of sedimentation control and reservoir rehabilitation [42, 54, 74], but these are mostly empirical studies.

The planning for alleviating reservoir sedimentation should start at the design stage, which should include provisions for sediment reduction measures for alternative operation policies. A reliable sediment yield estimate of the reservoir watershed is also vital in determining the sediment inflow into the reservoir, and thus the useful life of the reservoir. Several methods have been proposed to deal with this problem [10, 22, 24], but these are mostly empirical in nature.

Another important aspect in the design of reservoirs is the use of physical and mathematical models. Prototype experiments are too costly, and engineers have to rely on models for design purposes. The benefits of hydraulic model studies in the implementation of desilting operations have been documented in several studies [1, 32, 35, 44, 52, 57, 62], and the subsequent prototype tests have been satisfactory.

In his keynote speech Shen [71] summarized the Chinese experience in dealing with reservoir sedimentation. First, reduce sediment inflow to the reservoir by soil conservation, tilling, warping, and bypassing sediment-laden flows. Second, increase sediment outflows from the reservoir by density currents, flood flushing, and drawdown flushing. And third, if there is still a sedimentation problem, recover storage volume by emptying and flushing, siphoning, and dredging. Some of the methods that can be used in preserving reservoir storage capacity are schematically illustrated in figure 1.

However, the implementation of this schedule requires the dams to be equipped with low-level outlet structures. Possible arrangements for bottom outlets depend on the multiplicity of the purposes to be served. In dimensioning the capacity and positioning of bottom outlets, the following factors need to be considered: the occasional

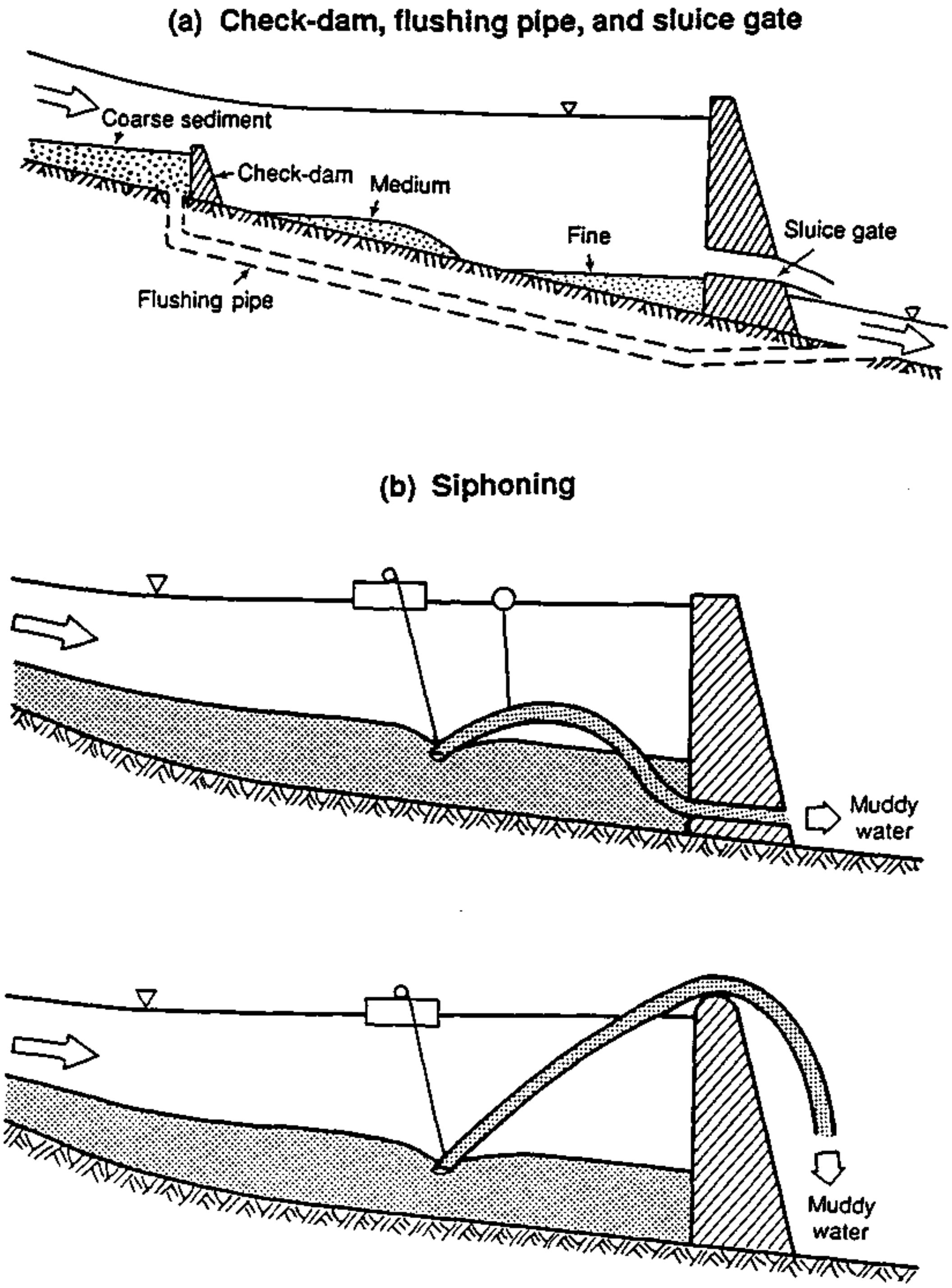

Figure 1. A schematic representation of typical installations of sediment entrapment reduction measures.

need to increase discharge through the bottom outlets, withdrawal of substantial quantities of water during certain periods, flexibility in controlling reservoir storage, providing rapid drawdown during emergencies, and conducting essential repairs [5, 37, 46, 62].

For more efficient operation of the bottom outlets the following guidelines should be followed in reservoir design and operation:

- lower the head on the sluices
- locate the sluices as deep as possible
- build wider sluices
- increase the duration of flushing
- maintain steeper reservoir bottom slope
- maintain sufficient outlet capacity to release flood waters
- flush towards the end of the high-flow season
- consider time required to refill the reservoir during flushing
- flush intermittently (to allow sediments to move closer to dam)
- flush under pressure no more than 10 minutes (to avoid damage to outlet structures)
- use free-flow flushing if possible
- flushing is more efficient if the reservoir is at least half empty

ECONOMICS OF SEDIMENT-REDUCTION MEASURES

Reservoir design based on storage conservation should be of prime importance considering the dearth of feasible sites for new reservoirs. Economic analyses for different storage-maintenance measures (such as low-level outlets, flushing or bypassing pipes, and siphoning devices) should be investigated in terms of reduction in initial reservoir design storage, cost of installing these measures, and cost of any alternative operations such as dredging.

It is obvious that a reservoir equipped with sediment reduction measures will store less sediment than a reservoir without such measures. Considering a fixed gross (or useful) storage at the end of useful reservoir life, a reservoir without sediment reduction measures will require a larger initial design capacity to compensate for the storage loss due to higher sediment entrapment. A reservoir equipped with sluices, for example, can be smaller but still meet the fixed gross storage at the end of its service life, but its initial cost may be higher or lower depending on whether the total cost of the smaller reservoir with sluices, and the maintenance costs, exceed the total cost of the larger reservoir without sluices. An economic analysis can determine the economic feasibility of incorporating sedimentation reduction measures in dam design and reservoir operation.

The minimum gross storage of a reservoir should be sufficient to meet the demands and evaporation losses for the design drought event. If a reservoir is designed for a *T*-year drought (a drought expected to occur once every *T* years), then conservatively the gross storage at the end of the T-year period should be adequate to meet the demands with the design drought occurring at the end of *T* years. The initial design storage of the reservoir should therefore be the gross storage plus the dead storage needed to accommodate the sediments entrapped over *T* years. Therefore, any sediment reduction measures used in the design of a reservoir should decrease the trap efficiency, and subsequently, decrease the initial design storage and the cost of the reservoir. The question is whether the savings resulting from incorporation of trap-efficiency reduction measures will be sufficient to cover the extra cost of integrating such measures in reservoir design and construction.

STORAGE CALCULATIONS

The approach to this problem in this study was to develop a methodology to estimate the difference in the capacity and the corresponding design cost of a reservoir with and without the sediment reduction measures. Twelve potential reservoir sites in Illinois were selected for this analysis. The spatial distribution of these reservoirs (one each in western and northwestern Illinois, seven in central Illinois, and three in southern Illinois) follows the general distribution pattern of surface water reservoirs in Illinois. The locations of these potential reservoir sites are shown in figure 2.

The design storages were calculated by using all possible combinations of the selected values of trap efficiencies (one conventionally from Brune's curve, and two trap efficiencies achievable with sediment-venting measures), drought recurrence intervals, and gross draft rates. The three selected values for each of these parameters are:

1. Trap efficiency, T_E: from Brune's curve, 25, and 10 %
2. Design drought recurrence interval: 25, 40, and 50 years
3. Gross draft rate as percent of average annual flow: 2,10, and 20 %

The design drought and the gross draft rates determine the gross yield of the reservoir needed to survive the design drought. The gross storage capacity is determined from a mass-curve analysis carried out on the basis of the recurrence interval of the drought [81]. This method differs from the standard Rippl method because it includes the design drought recurrence interval and associated critical reservoir drawdown period.

The design storage equation for a reservoir can be written as

$$C_0 = C_T + S \cdot T \tag{1}$$

in which C_0 is the initial, required, or design storage capacity of the reservoir; S is the average annual sedimentation rate; and CT is the minimum useful reservoir storage capacity or gross storage capacity needed over an operation period of T years. If the useful reservoir life is T years (i.e., CT is sufficient to meet the water-supply demand in the T-th year), the design storage capacity C_O can be determined from eq. 1.

The annual sedimentation rate, or storage loss, is given empirically as [75, 76]

$$S = \frac{392.9\, K \cdot A^{0.88}\, T_E}{100\, \bar{\delta}_T} \tag{2}$$

in which the constant K is defined for various land-resource areas in the state of Illinois and varies from 500 to 4,500; A denotes the watershed area in square kilometers, T_E is the percent trap efficiency of the reservoir; and $\bar{\delta}_T$ is the average density of sediment, in kg/m^3, deposited over a period of T years, accounting for consolidation with time. The average density of the sediment deposits is governed by the makeup of the sediments. The percent mixture of sand, silt, and clay of the sediment deposits for each potential reservoir site was determined from the sediment content contour maps, which were

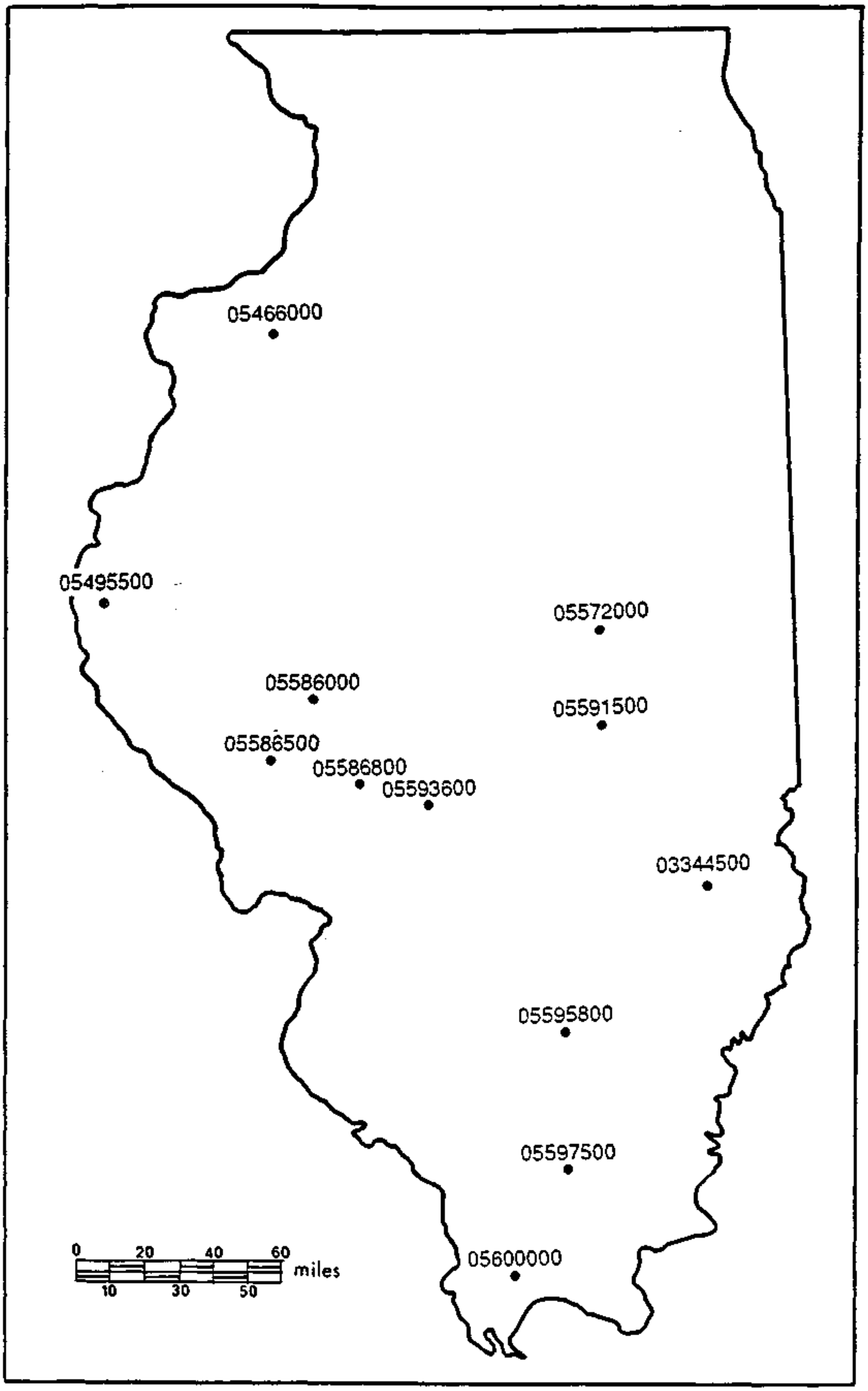

Figure 2. Locations of potential reservoir sites used in the study.

developed from reservoir sedimentation surveys [75]. Similarly, *K* values for each potential reservoir site were determined based on the soil characteristics, land and channel slope, land use, and the K values of the nearby reservoirs for which there were sedimentation surveys. The trap efficiency values were calculated from the Brune's curve by using the *C/I* ratios, for the conventionally operated reservoirs. For the cases in which sediment reduction methods were assumed to be in use, T_E values of 25% and 10% were used. The larger of these values has been shown to be practically achievable through several methods discussed in the previous chapter, and the lower value applies under the maximum sediment reduction conditions.

COST CALCULATIONS

The capital cost of building a reservoir in Illinois was computed by using the following equation [78], adjusted for 1989 conditions by using engineering cost indices [17]. "

$$\mathit{Capital\ Cost} = 1.3325 \times 10^6 (C_0)^{0.54} + 1.5\, LC \cdot WSA \tag{3}$$

where C_O is the initial (design) capacity of the reservoir in 10^6 m^3 , *LC* is the land cost in dollars per hectare, and *WSA* is reservoir water surface area in hectares at normal pool level expressed empirically as [14]

$$WSA = 31.59 (C_0)^{0.87} \tag{4}$$

Then eq. 3 becomes

$$\mathit{Capital\ Cost} = 1.3325 \times 10^6 (C_0)^{0.54} + 47.39\, LC\, (C_0)^{0.87} \tag{5}$$

The physical properties of all the potential reservoirs, and their gross storage capacities *(CT)* for all combinations of draft rates and design droughts are given in table 3.

The design storage capacities (C_0) of these potential reservoirs were calculated by using eqs. 1 and 2, and the corresponding capital costs (or the initial design cost) were calculated for these C_0 values by using eq. 5, assuming a land cost of $5,040 per hectare for prime farmland in Illinois for 1989 [68]. The C_0 and the corresponding capital costs for all the potential reservoirs are shown in tables 4-15, for the selected T_E , drought recurrence period *T*, and draft rates.

ANALYSIS OF MARGINAL CAPITAL COSTS

For low draft rates (2 % annual flow), the reservoir capacities are usually small (less than 2,000 acre-feet). Decreasing T_E from the Brune's curve value to T_E = 25% yields capital cost reductions varying from 14% (for Asa Creek at Sullivan) at T =25 years, to 37% (for Bear Creek near Marcelline) at T = 50 years. Similarly, by decreasing the trap efficiency to T_E = 10%, the reduction in capital cost at 2% draft rate become 20% (for Asa Creek at Sullivan) at T = 25 years, and 57% (for Bear Creek near Marcelline) at T = 50 years. Although Asa Creek has the lowest K value among the reservoirs, and Bear Creek has one of the highest values, the variation of capital costs is not uniform with respect to change in K values.

At 10% draft rate, the capital cost reduction that can be achieved by sediment-reduction measures is most emphasized by the K value. The average percent reduction in capital cost (averaged for T = 25, 40, and 50 years) for reservoirs with high K values were in the range of 19-27% for T_E = 25%, and 24-37% for T_E = 10%. For reservoirs with low K values, these reductions were 6.5-15.6% for T_E = 25%, and 8.1-20.2% for T_E = 10%. The variation of change in capital cost is better defined by the K value than by the lower draft rate.

A similar trend is also observed at 20% draft rate, with larger capital cost reductions being associated with larger K values (except for Edwards River near Orion), caused by the sediment-reduction measures. At this draft rate, with large K values, capital costs can be reduced by 9.5-18% with T_E = 25%, and by 11.6-22.6% with T_E = 10%. For small K values these reductions are generally less than 10% with both T_E values.

In general, capital cost reductions increase as T_E values decrease, and as K and T values increase. However, as the reservoir capacities get progressively larger because of increased draft rates, the percent reduction in capital cost decreases. The results obtained from this study were not meant to give a feasibility analysis of using the previously mentioned sediment reduction measures, because there is no available information on the cost of installing these measures, and we have not incorporated the cost of operation, management, and maintenance costs. If we assume a 15% reduction on the capital cost as a marginal value, then installing sediment-reduction measures in reservoirs with small K values (600-1,500) would not be desirable at high draft rates. However, as the K value gets larger, using these measures would be feasible even at T_E = 25%, regardless of the draft rate.

Table 3. Watershed characteristics and gross storage capacities, C_T, of potential reservoir sites used in the study.

Station ID	Drainage Area (sq mi)	Annual[†] Flow (acre-feet)	K Value	Sediment Content %Clay % Silt %Sand	Gross Storage Capacity, C_T (acre-feet) T (years)	Draft Rate Percent Annual Flow 2	10	20
03344500	7.6	4,237 (10.44)	1,500	20	25	41	308	849
Range Creek near Casey				57	40	50	398	1,065
				23	50	60	448	1,152
05466000	155.0	71,424 (8.64)	1,500	48	25	83	2,000	6,000
Edwards River near Orion				52	40	105	2,250	6,257
				0	50	118	2,343	6,635
05495500	349.0	138,483 (7.44)	2,500	45	25	1,184	8,064	21,362
Bear Creek near Marcelline				54	40	1,256	9,121	25,252
				1	50	1,281	9,915	26,312
05572000	550.0	288,640 (9.84)	1,200	50	25	684	12,585	31,681
Sangamon River at Monticello				45	40	753	13,615	33,667
				5	50	770	14,162	34,335
05586500	2.3	1,163 (9.48)	1,200	51	25	14	98	217
Hurricane Creek near Roodhouse				47	40	23	130	398
				2	50	25	189	717
05586800	61.1	28,937 (8.88)	1,300	57	25	346	2,072	6,517
Otter Creek near Palymra				38	40	554	3,667	14,542
				5	50	652	6,117	20,320
05591500	8.1	4,276 (9.96)	600	50	25	66	331	688
Asa Creek at Sullivan				45	40	98	636	1,288
				5	50	129	661	1,314
05593600	17.3	8,415 (9.12)	1,750	65	25	104	712	2,104
Bluegrass Creek near Raymond				27	40	180	1,101	4,613
				8	50	202	2,025	6,204
05595800	21.1	11,478 (10.20)	2,500	58	25	88	726	1,666
Seven Mile Creek near Mt. Vernon				34	40	148	900	2,008
				8	50	167	975	2,109
05597500	31.7	17,651 (10.44)	1,200	20	25	206	1,118	2,556
Crab Orchard Creek near Marion				75	40	206	1,183	3,174
				5	50	206	1,234	3,571
05600000	32.2	27,203 (15.84)	3,500	20	25	44	794	2,397
Big Creek near Wetaug				75	40	60	929	2,644
				5	50	86	985	2,861
05586000	21.9	11,914 (10.20)	2,500	45	25	109	799	2,023
N. Fork Mauvaise Terre Creek near Jacksonville				53	40	137	1,314	4,350
				2	50	173	2,104	7,008

t Annual flow is given in acre-feet followed by inches (in parentheses).

Table 4. Design capacity, C_0, and capital cost of a potential reservoir on Range Creek near Casey (03344500), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow[r]			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	119	430	984	517	1,084	1,762
	40	188	597	1,278	673	1,313	2,059
	50	244	699	1,418	780	1,440	2,190
25 †	25	77	344	885	403	953	1,655
	40	107	455	1,122	488	1,120	1,905
	50	131	518	1,222	546	1,209	2,005
10 †	25	55	323	863	335	917	1,631
	40	73	421	1,087	393	1,070	1,870
	50	88	476	1,180	437	1,150	1,963

† Achievab le by sediment reduction measures.

Table 5. Design capacity, C_0, and capital cost of a potential reservoir on Edwards River near Orion (05466000), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2 %	10	20	2$	10	20
From Brune's Curve	25		3,791	8,120		3,979	6,398
	40		5,132	9,576		4,799	7,102
	50		5,948	10,761		5,261	7,649
25 †	25		2,618	6,618		3,172	5,625
	40		3,206	7,213		3,590	5,937
	50		3,519	7,812		3,801	6,243
10 †	25		2,247	6,247		2,891	5,425
	40		2,632	6,639		3,182	5,636
	50		2,813	7,106		3,314	5,882

† Achievable by sediment reduction measures.
‡ For 2% draft rate, algorithm used with Brune's curve does not work because C_T is very small.

Table 6. Design capacity, Co, and capital cost of a potential reservoir on Bear Creek near Marcelline (05495500), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$ \times 10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	5,758	14,945	28,9466	5,156	9,443	14,545
	40	8,862	20,053	37,159	6,761	11,428	17,172
	50	10,888	23,576	41,029	7,707	12,705	18,349
25 †	25	3,255	10,135	23,433	3,623	7,363	12,654
	40	4,464	12,329	28,461	4,402	8,344	14,383
	50	5,231	13,866	30,262	4,857	8,998	14,979
10 †	25	2,012	8,892	22,191	2,704	6,776	12,211
	40	2,539	10,404	26,536	3,114	7,486	13,733
	50	2,861	11,495	27,892	3,348	7,979	14,192

† Achievable by sediment reduction measures.

Table 7. Design capacity, C_0, and capital cost of a potential reservoir on Sangamon River at Monticello (05572000), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$ \times 10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2‡	10	20	2‡	10	20
From Brune's Curve	25		17,192	36,925		10,339	17,099
	40		20,925	41,861		11,750	18,598
	50		23,272	44,461		12,597	19,366
25†	25		14,076	33,173		9,086	15,921
	40		15,924	35,976		9,839	16,805
	50		17,002	37,178		10,265	17,178
10†	25		13,181	32,278		8,710	15,634
	40		14,539	34,590		9,277	16,371
	50		15,297	35,473		9,586	16,648

† Achievable by sediraent reduction measures.

‡ For 2% draft rate, algorithm used with Brune's curve does not work because C_T is very small.

Table 8. Design capacity, C_0, and capital cost of a potential reservoir on Hurricane Creek near Roodhouse (05586500), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$ \times 10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	43	140	262	292	569	813
	40	77	198	470	404	692	1,141
	50	93	274	808	449	836	1,568
25 †	25	26	110	229	221	496	753
	40	42	149	417	289	589	1,065
	50	49	212	741	312	720	1,490
10 †	25	19	103	222	185	477	739
	40	31	138	406	243	563	1,048
	50	35	198	727	258	693	1,473

† Achievable by sediment reduction measures.

Table 9. Design capacity, C_0, and capital cost of a potential reservoir on Otter Creek near Palymra (05586800), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$ \times 10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	904	2,882	7,416	1,676	3,363	6,042
	40	1,576	5,002	15,970	2,334	4,723	9,857
	50	1,962	7,820	22,097	2,663	6,247	12,177
25 †	25	586	2,313	6,758	1,299	2,942	5,699
	40	926	4,038	14,913	1,700	4,137	9,430
	50	1,108	6,573	20,776	1,891	5,601	11,695
10 †	25	442	2,169	6,613	1,101	2,829	5,623
	40	703	3,816	14,690	1,445	3,995	9,339
	50	834	6,299	20,502	1,598	5,454	11,595

† Achievable by sediment reduction measures.

Table 10. Design capacity, C_0, and capital cost of a potential reservoir on Asa Creek at Sullivan (05591500), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	110	391	754	494	1,026	1,505
	40	175	737	1,394	645	1,486	2,168
	50	230	787	1,444	754	1,544	2,215
25 †	25	84	349	706	426	959	1,448
	40	126	664	1,316	535	1,397	2,095
	50	163	696	1,348	620	1,436	2,126
10 †	25	73	338	695	394	942	1,435
	40	109	647	1,299	493	1,376	2,079
	50	143	675	1,328	574	1,411	2,106

† Achieva ble by sediment reduction measures.

Table 11. Design capacity, C_0, and capital cost of a potential reservoir on Bluegrass Creek near Raymond (05593600), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	370	1,089	2,513	994	1,872	3,094
	40	665	1,711	5,262	1,398	2,452	4,874
	50	817	2,799	7,009	1,579	3,304	5,831
25 †	25	213	821	2,213	722	1,583	2,864
	40	348	1,269	4,781	958	2,050	4,593
	50	409	2,231	6,410	1,052	2,878	5,514
10†	25	147	756	2,147	585	1,507	2,812
	40	247	1,168	4,681	786	1,952	4,532
	50	285	2,107	6,287	854	2,780	5,447

† Achieva ble by sedirdent reduction measures.

Table 12. Design capacity, C_0, and capital cost of a potential reservoir on Seven Mile Creek near Mt. Vernon (05595800), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	475	1,331	2,430	1,148	2,110	3,031
	40	875	1,867	3,038	1,644	2,584	3,473
	50	1,101	2,179	3,380	1,884	2,838	3,708
25 †	25	269	906	1,950	825	1,678	2,653
	40	426	1,178	2,286	1,078	1,962	2,921
	50	509	1,316	2,451	1,195	2,095	3,047
10 †	25	160	798	1,842	614	1,557	2,563
	40	259	1,012	2,119	809	1,791	2,790
	50	303	1,111	2,245	885	1,894	2,889

† Achievable by sediment reduction measures.

Table 13. Design capacity, C_0, and capital cost of a potential reservoir on Crab Orchard Creek near Marion (05597500), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	447	1,472	2,945	1,109	2,241	3,408
	40	599	1,748	3,797	1,315	2,484	3,983
	50	703	1,939	4,348	1,444	2,644	4,330
25 †	25	314	1,226	2,664	902	2,008	3,205
	40	375	1,352	3,342	1,000	2,129	3,683
	50	415	1,443	3,780	1,061	2,213	3,972
10†	25	249	1,161	2,599	790	1,945	3,158
	40	273	1,251	3,241	834	2,033	3,614
	50	289	1,317	3,654	861	2,096	3,890

† Achievable by sediment reduction measures.

Table 14. Design capacity, C_0, and capital cost of a potential reservoir on Big Creek near Wetaug (05600000), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2 ‡	10	20	2	10	20
From Brune's Curve	25		1,736	3,501		2,474	3,789
	40		2,476	4,407		3,066	4,366
	50		2,939	5,068		3,403	4,762
25 †	25		1,113	2,716		1,896	3,244
	40		1,428	3,143		2,200	3,546
	50		1,603	3,478		2,358	3,774
10 †	25		922	2,525		1,695	3,103
	40		1,128	2,844		1,911	3,336
	50		1,232	3,108		2,014	3,522

† Achievable by sediment reduction measures.
‡ For 2% draft rate, algorithm used with Brune's curve does not work because CT is very small.

Table 15. Design capacity, C_0, and capital cost of a potential reservoir on North Fork Mauvaise Terre Creek near Jacksonville (05586000), for given values of T_E, T, and draft rates.

T_E (percent)	T (years)	Design Storage Capacity, C_0 (acre-feet)			Capital Cost ($\$\times10^3$)		
		Draft Rate Percent Annual Flow			Draft Rate Percent Annual Flow		
		2	10	20	2	10	20
From Brune's Curve	25	518	1,409	2,688	1,208	2,182	3,224
	40	845	2,318	5,416	1,610	2,946	4,962
	50	1,112	3,382	8,343	1,895	3,709	6,508
25 †	25	290	980	2,204	862	1,758	2,857
	40	416	1,594	4,629	1,064	2,350	4,502
	50	517	2,449	7,352	1,207	3,046	6,009
10 †	25	182	871	2,096	659	1,640	2,771
	40	249	1,426	4,462	789	2,198	4,400
	50	311	2,242	7,146	898	2,887	5,903

† Achievable by sediment reduction measures.

SUMMARY

It is imperative to design and operate new dams and retrofit existing dams so as to minimize the sedimentation in the reservoirs they create. This will greatly prolong the useful reservoir life, improve the reservoir water quality, reduce the downstream bed degradation, and follow the principles of intergenerational equity (treating both present and future generations fairly). The misconception that all reservoirs and their construction are inimical to the environment, has been cultivated largely by continuing reservoir sedimentation, seasonal lake stratification, nutrient recycling from bed deposits affecting water quality, lack of suitable mandatory low-flow releases from many reservoirs to maintain aquatic habitat and stream integrity, and downstream bed degradation and caving in of banks. However, these conditions are largely manifestations of conventional reservoir design that uses overflow spillways, and operation policies that do not address environmental and conservation concerns.

An extensive literature review shows that the objective of drastically reducing reservoir sedimentation can be achieved by three methods: reducing the sediment input to a reservoir, minimizing the sediment entrapment in it, and rehabilitating reservoir storage capacity. The application of these methods is not mutually exclusive, and a variety of actions and measures can be used to achieve the objective. The measures that can be used with these methods are listed below.

1. Reducing sediment inflow to the reservoir:
   a. Watershed management and soil conservation
   b. Constructing a check or debris dams upstream to retain relatively coarse sediments
2. Reducing sediment deposition in the reservoir:
   a. Venting density currents through bottom outlets or undersluiees
   b. Flood flushing through bottom outlets or undersluices
   c. Drawdown flushing to evacuate new and old settled deposits
3. Rehabilitating reservoir storage capacity:
   a. Siphon dredging - easily implemented and very effective for small to medium reservoirs
   b. Flushing and emptying through undersluices
   c. Dredging of sediments and their disposal - rather costly

The above measures, together or individually, can reduce the sediment entrapment in a reservoir up to 10 to 20% of that with an overflow-spillway reservoir.

The planning for minimal reservoir sedimentation should start with the integration of suitable sediment reduction measures in the dam design and reservoir operation. The plan of operation should be adhered to after the project is completed. Any change or modification may be made later if the actual operation so indicates.

Regardless of the plan of operation, the dams should be equipped with bottom outlets. For more efficient operation of the bottom outlets, the following guidelines can be used in dams and reservoir design, retrofitting, and operation:

- lower the head on the sluices
- locate the sluices as deep as possible
- build wider sluices
- increase the duration of flushing
- maintain steeper reservoir bottom slope
- maintain sufficient outlet capacity to release flood waters
- flush towards the end of the high-flow season
- consider time required to refill the reservoir during flushing
- flush intermittently (to allow sediments to move closer to dam)
- flush under pressure no more than 10 minutes (to avoid damage to outlet structures)
- use free-flow flushing if possible
- flushing is more efficient if the reservoir is at least half empty

By coupling sediment entrapment reduction measures and proper reservoir operation, sediment trap efficiency can be reduced to 25% and even 10%. Then only 25 or 10% of the inflowing sediment load will be retained in the reservoir. These efficiencies can be compared with 94, 86, and 77% for capacity-inflow ratio C/I = 0.30, 0.10, and 0.05, respectively, using Brune's curve for reservoirs with overflow spillways. Considering potential reservoirs at 12 gaging stations on small and medium streams in various parts of Illinois (table 3), design storages in acre-feet and capital cost in thousand dollars are given in table 16 for a 50-year design drought and trap efficiency from Brune's curve as well as set value of 25 and 10% with sediment entrapment reduction measures, and draft rate equal to 10% of average annual inflow. Average reduction in C_0 is 32 and 40% (from those with Brune's curve) with trap efficiency of 25 and 10%, respectively, and corresponding capital cost reduction of 21 and 27%, respectively. For other combinations of trap efficiencies, design drought, and draft rates, information can be developed from tables 4-15.

Table 16. Design capacity, C_0, and capital cost of potential reservoirs (T = 50 years, and draft rate = 10% mean annual flow).

Station ID	Drainage Area (sq mi)	Design Storage, C_0 (acre-feet)			Capital Cost ($ x 10^3)		
		Brune's T_E	T_E = 0.25	T_E = 0.10	Brune's T_E	T_E = 0.25	T_E = 0.10
03344500	7.6	699	518	476	1,440	1,209	1,150
05466000	155	5,948	3,519	2,813	5,261	3,801	3,314
05495500	349	23,576	13,866	11,495	12,705	8,998	7,979
05572000	550	23,272	17,002	15,297	12,597	10,265	9,586
05586500	2.3	274	212	198	836	720	693
05586800	61.1	7,820	6,573	6,299	6,247	5,601	5,454
05591500	8.1	787	696	675	1,544	1,436	1,411
05593600	17.3	2,799	2,231	2,107	3,304	2,878	2,780
05595800	21.1	2,179	1,316	1,111	2,838	2,095	1,894
05597500	31.7	1,939	1,443	1,317	2,644	2,213	2,096
05600000	32.2	2,939	1,603	1,232	3,403	2,358	2,014
05586000	21.9	3,382	2,449	2,242	3,709	3,046	2,887
Total		75,614	51,428	45,262	56,528	44,620	41,258
Average Reduction			32%	40%		21%	27%

Therefore, the adoption of sediment entrapment reduction measures and suitable reservoir operation will result not only in smaller, less costly reservoirs, but also in reservoirs whose utility after T years will be sustained well for many years to come. Additional benefits include improved reservoir water quality and considerable reduction in downstream bed degradation and caving in of banks. Capital cost savings with sediment entrapment reduction measures should be more than adequate to meet extra costs attributable to such measures.

ANNOTATED BIBLIOGRAPHY

[1] Ackers, P., and G. Thompson. 1987. Reservoir Sedimentation and Influence of Flushing. In *Sediment Transport in Gravel-Bed Rivers,* edited by C.R. Thorne, J.C. Bathurst, and R.D. Hey. John Wiley and Sons, Ltd., pp. 845-868.

Sediment studies can be integrated with economic and operational studies of the project to develop an acceptable flushing routine to conserve reservoir storage. Reservoir sedimentation leads to storage and yield loss, increased upstream flooding, blockage of intakes, abrasion of turbines, and impact on downstream regime. Sluicing through low-level outlets is examined in the framework of operational and economic criteria, taking into account reservoir-level changes and loss of output from hydropower. For sluicing to be effective, the capacity of sluice should exceed annual discharge with the reservoir drawdown.

[2] Baurne, G. 1984. "Trap-dams": Artificial Subsurface Storage of Water, *Water International,* Vol. 9, pp. 2-9.

For arid and semi-arid regions with sufficient yearly rainfall, subsurface storage of water can be achieved by constructing a low dam (also to act as subsurface dam) and filling the storage space with sand and gravel carried by the high flows. These trap dams can supply water to small communities. Dams of this or similar type existed in Libya and presently exist in South and East Africa.

[3] Bhowmik, N.G., W.P. Fitzpatrick, J. Helfrich, and E.C. Krug. 1988. *Lake Dredging in Illinois and a Preliminary Assessment of Pre-dredging Conditions at Lake Springfield.* Illinois State Water Survey Contract Report 453.

[4] Binger, W.V. 1972. Tarbela Dam Project, Pakistan. *Journal of the Power Division,* Proceedings of the ASCE, 98(PO2), pp. 221-245.

The Tarbela Reservoir on the Indus River in Pakistan has a storage capacity of 9.3 million acre-feet (MAF) and an annual inflow of 64 MAF. High flows occur during midsummer from a combination of snow melt and monsoon rains. The Indus River gradient is steep (8 ft per mile) and flow velocities are extremely high. The reservoir will be silted soon. As long as use of the irrigation release and power intakes continues, the channels leading to them will be self-cleaning.

[5] Blind, H. 1985. Design Criteria for Reservoir Bottom Outlets. *Water Power and Dam Construction,* July, pp. 30-32.

Provision of bottom outlets is generally necessary and a significant component of dam design. Possible arrangements for bottom outlets depend on the multiplicity of purposes to be served. In dimensioning the capacity and positioning of bottom outlets, the following factors need to be considered: occasional increased discharge through the bottom outlets, withdrawal of substantial quantities of water during certain periods, flexibility in controlling reservoir storage, providing rapid drawdown during emergencies, and to performing essential repairs.

[6] Bolton, P. 1984. Sediment Deposition in Major Reservoirs in the Zambezi Basin. In *Challenges in African Hydrology and Water Resources* (Proc. of the Harare Symp.), IAHS Publ. No. 144, pp. 559-567.

Sediment deposition in two large lakes in Africa (Kariba and Cabora Barsa) was estimated using available fragmentary data. Such estimates were made to identify the possible implications for future reservoir operation and for long-term regional planning. Sediment deposition in Lake Kariba will have negligible effect on its storage capacity for many centuries, but for Lake Cabora Bassa the effect may be appreciable within a few decades.

[7] Bruk, S. 1985. *Methods of Computing Sedimentation in Lakes and Reservoirs.* UNESCO, Paris.

The contents of this report were contributed by a team of six experts. The report provides a summary of recent developments in the study of lake and reservoir sedimentation and in practical computation methods. It also recommends appropriate and feasible methods to prevent or reduce silting of reservoirs during their operation. The use of methods for recovering lost reservoir storage is also discussed along with ecological, environmental, and economical considerations.

[8] Brune, G.M. 1953. Trap Efficiency of Reservoirs. *Transactions of AGU,* 34(3).

More than 40 records of reservoir trap efficiency and the factors affecting it are analyzed. The reservoir capacity-inflow ratio (C/i) is found to offer the best correlation. Other factors that may affect trap efficiency are the timing of venting and sluicing operations, and the type of reservoir. In general, trap efficiency increases with the *C/I* for normally ponded reservoirs. However, desilting basins have much larger trap efficiencies, and values for semi-dry reservoirs are lower than values for normally ponded reservoirs.

[9] Carranza, C, and J.E. Walsh. 1985. Environmental Evaluation of Lake Dredging Projects in the Northeast. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc, October 16-19, 1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 132-138.

The engineering of inland lake dredging has developed accepted standard practices for dredging, and dredged material contaminant area design, construction, and operation. Dredging projects need to economically dispose of dredged materials near the dredge site, but environmental restrictions currently limit this option, and resale of these material has not usually proven feasible. Should the dredged materials fail the EPA toxicity test for upland disposal, it is a foregone conclusion that dredging will not be considered feasible.

[10] Committee on Erosion and Sedimentation. *Research Needs in Erosion and Sedimentation,* American Geophysical Union, Hydrology Section.

Erosion and sedimentation are important problems in environmental and water quality studies, watershed management, reservoir planning, and dredging and disposal of the dredged material. Sediment yield prediction equations based on the universal soil loss equation and the use of delivery ratio suffer from various assumptions and approximations. Several topics warrant in-depth investigation: sediment deposition patterns in reservoirs, formation of deltas in backwaters, degradation processes downstream of the dam, reservoir sedimentation and reduction in productivity of the water body, recycling of nutrients from bottom sediments, and the role of sedimentation as a eutrophication agent.

[11] Cooke, G.D., E.B. Welch, A. Spencer, and P.R. Newroth. 1986. *Lake and Reservoir Restoration.* Butterworth Publishers, Storeham, MA.

When properly conducted, sediment removal is an effective lake management technique. Also considered are the purposes of sediment removal, environmental concerns, appropriate depth of sediment removal, sediment removal techniques, suitable lake conditions for dredging, and dredge selection and disposal area design. Dredging projects are usually successful, but those designed to control internal nutrient cycling may have mixed results because of incomplete pre-evaluation or removal of too little sediment.

[12] Copp, R.S., and H.K Horstman. 1985. Restoration of Lake Accotink. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc., October 16-19,1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 122-126.

Lake Accotink is a 62-acre recreational lake in a suburban area of Fairfax County, Virginia. Sediment deposition has decreased the lake volume to 25% of the original volume. The lake restoration plan developed includes 153,000 m^3 of sediment dredging and construction of an upstream sedimentation basin with a capacity to hold 196,500 m^3 of sediment. This basin will trap the sediments originating from upstream channel erosion. Dredging permits are required if wetlands are involved.

[13] Dai, J., W. Chen, and B. Zhou. 1980. A Preliminary Study on Sediment Evacuation from a Reservoir with Siphon Devices. *Proceedings of the International Symp. on River Sedimentation,* Beijing, China, March 24-29, Vol. 2, pp. 763-772.

Siphon dredges can help dispose of and use the sediments in small- and medium-sized reservoirs. The amount of water to remove the sediment is reduced to a minimum, the operation is flexible, and unit dredging cost is very low. A "dust pan" dredge head with a scraper and nozzles was attached to the siphon pipeline for the Tianjiawan Reservoir, Shanxi Province, China. The siphon pipe is connected to the reservoir outlet by a valve chamber under water. Eleven reservoirs in three provinces of China have siphon dredges installed in them. Not only incoming sediment can be evacuated this way, but depleted reservoir storage capacity can also be recovered.

[14] Dawes, J.H., and M. Wathne. 1968. *Cost of Reservoirs in Illinois.* Illinois State Water Survey Circular 96.

An empirical expression for project cost of single or multipurpose reservoirs in Illinois was developed, including construction cost, engineering services, contingencies, and land costs. This empirical expression, which reflects 1968 conditions, correlates the project cost to reservoir storage capacity and land cost, and should be used for comparison and screening alternatives.

[15] Deo, S.R. 1981. A Case Study of the Economic Benefits of Reclaiming Lake Paradise, Mattoon. In *Proceedings of a Round Table on Reclaiming and Managing Lakes in Illinois,* Illinois Institute of Natural Resources, October 10-11,1980, pp. 121-125.

The economics of a lake reclamation program are important to every community considering such a project. Lake Paradise supplies water for the city of Mattoon in east-central Illinois. Dredging of sediments to regain lost capacity was found to be economical, reducing water treatment costs due to improved water quality, enhancing recreation, and increasing water supply. The dredged sediment was found useful for increasing crop yields and had a value of $\$1/yd^3$ for use as topsoil.

[16] Dillon, M.M., Limited. 1972. *Mohawk Lake Study, Brantford, Ontario, Grand River Conservation Authority.* Project No. 6939-01, M.M. Dillon, Limited, Consulting Engineers and Planners, Cambridge, Ontario.

Mohawk Lake in Ontario (drainage area 1,647 acres) was found to be heavily sedimented with an estimated 220,000 yd^3 of sediment. A biological study recommended removal of all sediments to restore the lake for recreational use. Draining of the lake through the city of Brantford retention pond was recommended for an open excavation dredge at a cost of $\$2.40\text{-}2.76/yd^3$ (1972 estimate). Costs of acquiring a disposal site are not included in these unit costs.

[17] Engineering News Record. September 18, 1986, and December 24, 1990 issues.

[18] Evrard, J. 1980. Consideration sur l'Alluvionnement dans les Ouvrages Hydrauliques d'Electricite de France. *Seminaire International d'Experts sur le Derasement des Retenus,* Tunisia.

A siphon was installed at the Rioumajou Dam, France to evacuate sediment-laden water from the reservoir. The siphon straddles the 21-m high gravity arch dam. The entrance of the siphon is located between the water intake and bottom sluice. The siphon operates automatically when the spillway functions. The diameter varies from 400 to 450 mm. The siphon can discharge 1 m^3/sec with a carrying capacity of 15 kg of sediment. The installation cost was amortized almost within one year.

[19] Fan, J. 1986. Turbid Density Currents in Reservoirs. *Water International,* IWRA, Vol. 11, pp. 107-116.

[20] Fan, J. 1991. Chinese Experiences with Reservoir Desiltation. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 7.2.1 to 7.2.30.

Delta deposition and deposits due to density currents, as well as the impacts on reservoirs are discussed. The process of delta formation in the backwater region of a reservoir is analyzed. Methods of reservoir desiltation, outlined from the Chinese experiences, include flood flushing, drawdown flushing, flushing and emptying, and density current venting. Empirical formulas for estimating floodplain slope and bottom slope of the main channel are developed for estimating the storage capacity for long-term use.

[21] Fan, J. 1991. Density Currents in Reservoirs. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 3.1.1 to 3.1.27.

Release of sediments with the density currents from the Sanmenxia Reservoir was investigated. The plunge point, where the turbid discharge plunges beneath the clear reservoir, gradually moves downstream as bed levels rise due to sedimentation. The sediment concentration released by density currents through the outlets depends on the topographic features of the reservoir, the magnitude of incoming flood peak, incoming silt discharge and its sediment characteristics, the outlet elevation, discharge capacity of outlets, flushing discharge, reservoir water level, length of reservoir, etc.

[22] Fan, J. 1991. Sediment Yield in River Catchments in China. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 1.2.1 to 1.2.22.

Siltation near the dam can cause increased sediment concentration at the water intakes and abrasion of the impellers and other hydraulic structures. Though there is significant yearly variation in sediment load in the Yangtze River basin, it was found that peak sediment concentrations were maintained over a longer time than the peak flow in the loess regions. An empirical equation was developed to estimate sediment yield from a flood using basin and regional factors.

[23] Fan, J., and G.L. Morris. *Reservoir Sedimentation I: Delta and Density Current Deposits,* and *Reservoir Sedimentation II: Reservoir Desiltation and Long-Term Capacity.* Unpublished notes.

The Chinese have implemented structural and operational procedures to maximize sediment discharge from the impounded reaches of a river, thereby reducing, arresting, or reversing reservoir sedimentation at many sites. Floods can be routed through reservoirs under hydraulic conditions that minimize or prevent sediment deposition in the reservoir. Selecting the time for flushing and emptying, and predicting the time and duration of flushing for evacuating sediments are the most important problems in reservoir operation. Methods to estimate sediment evacuation with different methods are explained.

[24] Gavrilovic, Z. 1988. The Use of an Empirical Method (Erosion Potential Method) for Calculating Sediment Production and Transportation in Unstudied or Torrential Streams. In *International Conf on River Regime* (edited by W.R. White), pp. 411-422.

The Erosion Potential Method is presented for estimating erosion in catchment areas and its transportation to a river section. It is based on identified situation and erosion interactions, topographic features, and general climatic characteristics. The method requires some field investigation. Erosion is classified in terms of its severity. Sediment load transport is estimated from the sediment retention coefficient based on basin characteristics such as basin length and difference in mean basin elevation and that at the discharge site.

[25] Gibbons, H.L., Jr., and S.C. Wagner. 1986. Restoration of Lake Ballinger. In *Lake and Reservoir Management, Volume II,* (Proceedings of the Fifth Annual Conf. and International Symposium on Applied Lake and Watershed Management, November 13-16, 1985, Lake Geneva, WI), North American Lake Management Society, pp. 277-280.

Lake Ballinger is a 100-acre eutrophic lake in Mountlake Terrace, Washington. The lake's very poor water quality characteristics have been brought about by excessive nutrient loadings from the watershed and internal cycling of phosphorus during periods of hypolimnetic anoxia. Two sedimentation basins were established as well as the construction of a hypolimnetic injection/siphon withdrawal system to enhance dissolved oxygen levels and remove phosphorus-rich hypolimnetic waters.

[26] Gill, M.A. 1988. Planning the Useful Life of a Reservoir. *Water Power and Dam Construction,* May, pp. 46-47.

A method is developed for computing loss of reservoir capacity because of sedimentation during a given period or the useful life of the reservoir. It incorporates variation in weights of the constituents (clay, silt, and sand) using empirical relations developed by Lane and Koelzer for the effect of consolidation with time on the specific weights of the sediments. An example is also included.

[27] Hanson, M.J., and H.G. Stefan. 1985. Shallow Lake Water Quality Improvement by Dredging. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc., October 16-19,1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 162-171.

Lake improvement methods for shallow lakes are limited in number and effectiveness. High turbidity and high productivity are related to sediment resuspension and nutrient recycling, which are effectively reduced by dredging. Criteria for a rational selection of a dredging project are: problem assessment, required dredging depths, duration, selection of disposal area, and project costs. A case study of the Fairmont dredging program is presented together with the reservoir's past performance prior to dredging.

[28] Heede, B.H., and J.G. Mufich. 1973. Functional Relationships and a Computer Program for Structural Gully Control. *Journal of Environmental Management,* Vol. 1, pp. 321-344.

It is suggested that flood-retarding structures like check dams, usually used in gully control, decreased original sediment yield by 50% or more. Cost estimates are given for various types of check dams with varying heights. Maintenance is about 1% of the installation cost. Design recommendations are made to attain certain objectives.

[29] Hitzhusen, F., B. MacGregor, and D. Southgate. 1984. Private and Social Cost-Benefit Perspectives and a Case Application on Reservoir Sedimentation Management. *Water International,* Vol. 9, pp. 181-184.

A comparative private and social cost-benefit perspective for sediment management in developing countries is considered. The Valdesia Dam, used as an example, was constructed to decrease the Dominican Republican's dependence on imported oil by providing hydropower. However, sedimentation has been a continuous concern at the reservoir. The condition has been worsened by deforestation. Incorporating the off-site effects of erosion yields substantially increased estimates of the net benefit of soil conservation.

[30] Horstman, H.K., and R.S. Copp. 1985. Different Dredging Techniques for the Restoration of Two New Jersey Lake Systems. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc., October 16-19, 1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 127-131.

Etra Lake and Sylvan Lake are relatively small, shallow lakes in New Jersey and both have extensive macrophyte growth. Sediment removal, in combination with other measures, was determined to be the best restoration technique in both cases. Dredging methods were selected on the basis of cost-effectiveness, disposal site locations, outlet structures, sediment characteristics, etc. Dredging costs were high, especially because of disposal costs. Both dredging projects were designed to integrate the development of the existing and proposed recreational facilities within the surrounding public park lands.

[31] Hsu, R.L., and M.C. Hsu. 1988. Dredging Program for Shihmen Reservoir. *Sixth Congress, Asian and pacific Regional Division of the International Association for Hydraulic Research,* July 20-22, Kyoto, Japan, pp. 229-235.

The Shihmen Reservoir completed in 1963, is located on the Tahan Creek in Taiwan, and serves multiple purposes: irrigation, hydropower, water supply, and flood control. The dam is 133 m high, with reservoir storage of 309 x 10^6 m^3, and average inflow volume of 1,336 x 10^6 m^3. Reservoir sedimentation reached 79.5 x 10^6 m^3 in less than 1 year. Upstream sand-retaining dams were built to reduce sediment inflow to the main reservoir. Sediment was also flushed through the spillway, tunnels and outlets. A reservoir-dredging program was also started. Dredging cost per cubic meter is estimated as \$6.27/m^3 (1987). Because of the high cost of operation, dredging was confined to clearing the power intakes.

[32] Hwang, J. 1985. Study and Planning of Reservoir Desilting in Taiwan. *Water International,* 10(1), pp. 7-13.

Streams on the island of Taiwan are generally short and steep, many with high sediment loads. To store runoff water in the wet summer season for later use, many reservoirs have been constructed. Because of heavy stream sediment loads, the reservoirs will be silted in 5 to 20 years. One possible approach to prolong useful reservoir life is to flush the sediments in the reservoir periodically by using valve-controlled sluices. Prototype experiments with flushing have been effective in Jensenpei Reservoir.

[33] Jaggi, A.L., and B.R. Kashyap. 1984. Desilting of Baira Reservoir of Baira Siul Project. *Irrigation and Power,* India, October, pp. 375-380.

The Baira Siul Project, Himachal Pradesh, India, uses combined flows of the Siul, Baira, and Bhaledh tributaries of the Ravi River for generating hydropower. The reservoir started operating in 1981. Reservoir sediments in the first 18 months were estimated as 0.45 million m^3. Model studies indicated that a D-shaped undersluice tunnel could flush 0.21 million m^3 of sediment in about 21 hours with 100 m^3/sec discharge. Desilting operations were undertaken to remove the sediments and about 377,543 m^3 of sediment was flushed in 31 hours. The authors suggest desilting be carried out preferably in April/May with flows exceeding 100 m^3/sec. A desilting period of about 24 hours once a year was found to be sufficient.

[34] Jain, R.K. 1971. Peaking-Station Layouts on Himalayan Rivers. *Water Power,* Vol. 23, pp. 218-223.

Some sedimentation is unavoidable in hydropower stations, and raising the barrage height may be necessary to compensate for the live storage lost. The extent of this raising can, however, be limited by lowering the water level in the forebay during high flows in the river, consequently lowering the reservoir level and narrowing the barrage — both factors are conducive to less sediment entrapment. A suitable operation requires correct estimation of the intake level, possible replacement of silt excluder bay by a settling basin, and preferable location of the powerhouse near the power channel head.

[35] Jordaan, J.M. Jr. 1971. Protection of Offtake Works against Silting-Up, Caledon-Welbedacht Dam. *Proceedings of the 14th Congress,* IAHR, Vol. 5, Paris, pp. 107-1 to 107-4.

A model investigation was carried out for deflecting river sand and silt away from water-supply intakes and directing them to the five sluices with gates in the Welbedacht Dam, South Africa. Venting of sediments through the gates could be improved by providing two deflector groins or walls upstream of the dam to induce a meander pattern. The flow carrying sediments is thus deflected well away from the sills of the intake structures.

[36] Jowett, I. 1984. Sedimentation in New Zealand Hydroelectric Schemes. *Water International,* Vol. 9, pp. 172-176.

In New Zealand, small hydroelectric schemes in catchments with high annual sediment loads have encountered problems associated with sedimentation, such as loss of operating storage, damage to turbines, degradation of bed downstream, and aggradation upstream with increased flood levels. In 1969, the Mangahao plant was closed for three weeks during flushing of sediment from the reservoir, and 880,000 m^3 of silt, or 75% of the old sediment, was flushed out. Water used during flushing does reduce potential power generation.

[37] Kabell, T.C. 1984 Sediment Storage Requirements for Reservoirs. In *Challenges in African Hydrology and Water Resources* (Proc. of the Harare Symp.), IAHS Publ. No. 144, pp. 569-576.

Reservoir sedimentation, serious problem in Zimbabwe, leads to diminished draft or even total loss of live storage capacity. Improved conservation and land use measures do help but take many years to implement. Due to a lack of sediment data in Zimbabwe, it is proposed to include a provision for sedimentation based on the mean annual runoff from the drainage basin in the dam and reservoir design.

[38] Khan, S.M. 1985. Management of River and Reservoir Sedimentation in Pakistan. *Water International,* 10(1), pp. 18-21.

Water is the mainstay of Pakistan's economy for irrigation, electric power, and industrial production. The Mangla and Tarbela reservoirs are silting up at the rate of 42,000 and 10,900 acre-feet annually. Scientific land management can reduce the siltation rate by 30%. Various organizations are working in isolation to carry out proper land management activities, but there are several major problems. These include no central coordinating organization; lack of trained personnel, research and monitoring facilities; noninvolvement of the people; and faulty implementation.

[39] Kirschner, R.J. 1985. Lake Restoration as a Stimulus for Comprehensive Environmental Management. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc., October 16-19,1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 344-348.

A lake restoration project not only enhances water quality but also stimulates environmental improvements. Substantial improvements in lake aquatic quality occurs as a result of the restoration, which includes wastewater diversion, watershed management, fisheries management, and dredging. Other environmental concerns can be integrated and addressed by the restoration in a more effective and economical way.

[40] Knaus, R.M., and R.F. Malone. 1984. An Historical Overview of Successful Lakes Restoration Projects in Baton Rouge, Louisiana. In *Lake and Reservoir Management* (Proc. of the Third Annual Conf. of the North American Lake Management Soc., October 18-20,1983, Knoxville, TN), U.S. Dept. of Agriculture and U.S. Environmental Protection Agency, Washington, D.C., pp. 412-415.

The five-lake system comprising 300 acres in Baton Rouge had massive fish kills on a regular basis over the past 50 years. To correct the hypertrophic conditions in the lakes, 490,000 m^3 of lake-bottom material was dredged out at a cost of $3 million from November 1981 to May 1983. Some projects associated with lake restoration and rehabilitation are sewerage correction and rehabilitation, engineering studies, road improvement, and recreational uses of the lake area.

[41] Krumdieck, A., and P. Chamon. 1979. Sediment Flushing at the Santa Domingo Reservoir. *Water Power and Dam Construction,* December, pp. 25-30.

Results of site and model tests show that judicious operation of outlets in a concrete arch dam will fully maintain the useful storage volume of the reservoir. The volume of water required for flushing is minimized, making the procedure efficient and inexpensive. To ensure the flow through bottom outlet structures when the entrance is covered by sediment, each outlet includes a 0.8-m diameter siphon. Flushing operations during high flow are the most effective. After four years of construction, flushing and emptying operations at Santo Domingo Reservoir removed 50 - 60% of deposited sediments in the first four days. Only 5 - 10% of sediment remained in the reservoir after three weeks of operation.

[42] Lee, M.T., and K.L. Guntermann. 1976. A Procedure for Estimating Off-Site Sediment Damage Costs and an Empirical Test. *Water Resources Bulletin*, 12(3), pp. 561-575.

Research conducted to develop a methodology for estimating agricultural off-site sediment damage costs includes an empirical estimate of such damages for the watershed. The economics of off-site damage costs are discussed on a theoretical basis for the procedures developed. A detailed methodology is described for estimating five different types of off-site damages commonly associated with rural watersheds. The excess annual cost of a reservoir due to reduced useful life is also considered.

[43] Lembke, W.D., J.K. Mitchell, J.B. Fehrenbacher, and M.J. Barcelona. 1983. Dewatering Dredged Sediment for Agriculture. *Transactions of the ASAE,* pp. 805-813.

A study was conducted to determine the feasibility of using lake-bed sediments for agricultural production, to investigate the effectiveness of subsurface drains in dewatering hydraulically placed sediment, and to investigate the tile outlet terraces for storing sediments. Dredging and disposal of dredged material from Lake Paradise near Mattoon, Illinois, were investigated. The hauled sediment plots produced significantly higher crop yields, the quality of return flow was generally very good, and a combination of outlet terraces and sand filters worked very well in dewatering sediments.

[44] Lin, J.J, and C.M. Wu. 1991. Hydraulic Model Studies of Tien-Lun Reservoir Desiltation. *Proceedings of the 5th Federal Interagency Sedimentation Conference,* Las Vegas, NV, March 18-21, pp. 7-9 to 7-14.

The Tien-Lun Dam Project, the most significant desilting achievement of coarse sediments in Taiwan, illustrates the benefits that can be derived from hydraulic model studies. Prototype operation verified the results expected from model studies to create suitable hydraulic sediment flushing conditions. Hydraulic flushing is an efficient technique for the removal of sediment deposits. A set of desilting capacity equations is suggested for preliminary estimates of desilting efficiency.

[45] Lohnes, R.A., and T.A. Austin. 1985. Restoration of Blue Lake, Iowa: A Case Study. In *Lake and Reservoir Management: Practical Applications* (Proc. of the Fourth Annual Conf. and International Symp. of the North American Lake Management Soc., October 16-19, 1984, McAfee, NJ), U.S. Environmental Protection Agency, Washington, D.C., pp. 157-161.

Blue Lake, 48 km south of Sioux City, Iowa, is one of four oxbow lakes on the floodplain of the Missouri River, and it provides important recreational resources for western Iowa and eastern Nebraska. The four lakes have poor water quality and limited water quantity. Blue Lake was the first oxbow lake at which management recommendations were implemented. Water quality of the lake during dredging was not significantly impaired.

[46] Long, Y., and Q. Zhang. 1981. Sediment Regulation Problems in Sanmenxia Reservoir. *Water Supply and Management,* 5(4/5), pp. 351-360.

Sanmenxia Reservoir and Dam were completed in 1960 on the Yellow River in China. During the filling period, backwater deposits extended upstream and into tributaries with remarkable rapidity. To reduce sedimentation in the reservoir, sediment sluicing should be carried out under large discharges by lowering the water stage during large floods. The sediment outflow hydrograph should be suitable for downstream flows. Coarse-grained sediments may be sluiced off only during large floods.

[47] Lovell, L.A., L. Lowe III, and W.V. Binger. 1972. Tarbela Dam Construction Reaches Half-Way Mark, Parts One and Two. *Water Power,* pp. 317-325, and pp. 355-365.

The Tarbela Dam is the world's largest fill dam, built across the Indus River in Pakistan. The alluvium in the Indus Valley is up to 700 ft deep. Sediment sampling data indicate an annual sediment load of 230,000 ac-ft; 90% is transported by flows exceeding 170,000 cfs. The reservoir capacity is only one-seventh of the mean annual discharge. Under these conditions, the reservoir will act as a sediment trap and most of the design capacity (9.3 million ac-ft) will be lost in 50 to 60 years.

[48] Mahmood, K. 1987. Reservoir Sedimentation: Impact, Extent, and Mitigation. *World Bank Technical Paper 71,* The World Bank, Washington, D.C.

This monograph presents a review of the worldwide extent, impact, methods of prediction, and mitigation of reservoir sedimentation. Annual sediment yields from the world's major rivers are given along with the worldwide distribution of runoff and sediment load. Mechanics of sediment entrainment, transport, and deposition in reservoirs, and methods of predicting and mitigating reservoir sedimentation are also discussed.

[49] Maiding, X., and Z. Ren. 1980. Methods of Sluicing Sediment from Heisonglin Reservoir and its Utilization Downstream. *Proceedings of the International Symp. on River Sedimentation,* Beijing, China, March 24-29, Vol. 2, pp. 717-726.

Heisonglin Reservoir, Shanxi Province, China, is a small reservoir for irrigation and , flood control. The average annual runoff is 14.36 million m^3 and sediment load is 690,000 tons. The reservoir lost 19% of its capacity in the first three years of operation. An operation — "storing clean water and discharging muddy water, and diverting flood for irrigation and warping," was adopted. Within 17 years of this operation, 61 million m^3 of muddy water and 13 million tons of sediment have been released through the reservoir. This operation method has been widely adopted in North China.

[50] Makkaveev, N.I. 1970. Effect of Major Dam and Reservoir Construction on Geomorphological Process in River Valleys. Translated from *Geomorfologiya,* No. 2, pp. 28-34.

The construction of reservoirs disrupts naturally occurring processes forming river valley relief. A dam increases the local base level, causing regressive accumulation of sediments propagating upstream. Waves, currents, gravitational processes, and seasonal level fluctuations develop a singular shore relief. Riverbed erosion develops below the dam and is propagated downstream with gradual reduction in bed retrogression. Examples are given for several Russian reservoirs.

[51] McKeogh, E.J. 1981. Sedimentation Control in Indian Reservoirs. *International Water,* Vol. 33, pp. 41-43.

The Central Water and Power Research Station at Pune, India, has been involved in the design and model testing of the desilting systems of two hydroelectric power plants. One system is the water conductor system of a hydroelectric project in Himachal Pradesh, the other a settling/flushing tank for the Trisuli barrage in Nepal. Hydroelectric power plants may require removal of 90% of the sediment load. The Baira Siul hydroelectric project in Himachal Pradesh is designed for 90% removal of sediment of 0.2 mm at a discharge of 28.32 m^3/sec. During flushing the discharge was 20% of the gross inflow to each desilting basin unit. The Trisuli plant had sediment ejectors installed but removed only 63% of coarse sediment and 27% of medium silt. Model studies for a settling tank showed that flushing efficiency of 87.5-95% could be achieved in 45 minutes.

[52] Mikhalev, M.A. 1971. Control of Silting in Reservoirs on Mountain Rivers. *Proceedings of 14th Congress.* IAHR, Vol. 5, Paris, pp. 101-1 to 101-4.

The reservoir, used as an example, is formed by an arch dam 54 m high, with intakes placed 44 m above the canyon bottom, and an overflow spillway 47 m high. The reservoir had a total storage of 15 x 10^6 m^3 at 51 m normal pool but 80% was silted in the first eight years. Laboratory-tested flushing procedures were incorporated in the reservoir operation. Calculations showed that several days' sluicing during floods was sufficient to wash out several years of sediment accumulation. Useful reservoir life can be extended to 80-100 years. Stopping operation for a few days each year is economically justifiable considering the alternative costs of sediment removal.

[53] Miltz, D., and D.C. White. 1987. Sedimentation and the Economics of Selecting an Optimum Reservoir Size. *Water Resources Research,* 23(8), pp. 1443-1448.

An easily reproducible methodology is developed for the economical selection of an optimal reservoir size given an annual sedimentation rate. The optimal capacity is that at which the marginal cost of additional storage capacity is equal to the dredging costs avoided by having additional storage capacity available to store sediment. The cost implications of misestimating dredging costs and sediment deliveries are also investigated.

[54] Moglen, G.E., and R.H. McCuen. 1990. Economic Framework for Flood and Sediment Control with Detention Basins. *Water Resources Bulletin,* 26(1), pp. 145-156.

Detention basins intended to control channel erosion must be considerably larger than basins designed to control peak discharge rates. In order to increase the economic value of detention basins for water quality control, it is necessary to increase the detention time of flood runoff. It appears that the benefit function and the trap efficiency relationship are the weak links in the development of accurate production functions for water quality control. Sediment-control benefits are usually small compared to the flood-control benefits.

[55] Morris, G.L. 1991. A Global Perspective of Sediment Control Measures in Reservoirs. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 5.1.1 to 5.1.31.

If reservoirs are to represent renewable sources of water supply, techniques for sediment management will necessarily become one of the principal design and operational features at both existing and future reservoirs. Reservoir storage conservation techniques have been developed and applied at a small but growing number of reservoirs worldwide. These techniques mostly consist of reducing sediment yield from the basin, sediment routing through or around the impounded reach, and sediment removal. Examples are included.

[56] Morris, G.L. 1991. Sedimentation and Sediment Control Strategies: Loíza Reservoir, Puerto Rico. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 7.1.1 to 7.1.21.

The Loiza Reservoir in Puerto Rico has a drainage area of 534 km^2 and delivers 80 mgd of water for municipal use. Since its completion in 1953, the original reservoir capacity has been reduced by 43% because of sedimentation. Two strategies are being implemented to arrest sedimentation: 1) hydraulic flushing of sediments during floods, and 2) limited dredging to remove the coarse materials that cannot be flushed out. The expected cost of complete implementation is estimated as $5 million in contrast to development of a new reservoir 100 km away, with costs exceeding $250 million.

[57] Morris, G.L. 1991. Use of HEC-6 One-Dimensional Model for Reservoir Sedimentation Studies: Program Capabilities and Utilization at Loíza Reservoir, Puerto Rico. Course Material for: *Workshop on Management of Reservoir Sedimentation,* June, New Delhi, India, Conducted by Water and Power Consultancy Services (India) Limited, pp. 6.1.1 to 6.1.8.

Computer models, which simulate the transport, deposition, and scour of sediment in a river-reservoir system, are valuable tools in the analysis of sediment control alternatives for reservoirs. Particularly useful is the U.S. Army Corps of Engineers one-dimensional HEC-6 model released in 1991. Several basic considerations in the modeling of sediment control strategies are described. The enhanced HEC-6 model is used to simulate reservoir drawdown and sediment routing at the Loiza Reservoir in Puerto Rico.

[58] Nelson, R.W., J.R. Dwyer, and W.E. Greenberg. 1987. Regulated Flushing in a Gravel-Bed River for Channel Habitat Maintenance: A Trinity River Fisheries Case Study. *Environmental Management,* 11(4), pp. 479-493.

Loss of flushing flows in the Trinity River below the dams and higher sediment production from extensive land disturbance on erodible soils have practically filled the pools and buried stream riffles, thus highly impacting benthic invertebrates and fish habitats. For maintaining habitats, controlled one-time peak flows or annual maintenance peak flows have been proposed to flush the spawning gravel and scour the banks, deltas, and pools. The technical feasibility of such flows depends on associated mechanical and structural measures needed for water supply and hydroelectric facilities maintenance and sediment control dams on tributaries.

[59] Paul, T.C., and G.S. Dhillon. 1988. Sluice Dimensioning for Desilting Reservoirs. *Water Power and Dam Construction,* May, pp. 40-44.

One successful solution to the problem of reservoir sedimentation is the hydraulic flushing of sediment deposits through low-level sluices. Flushing is more effective with lower head on the sluice, greater flushing discharge, wider sluice, deeper setting of the sluice, longer duration of flooding, and steeper bottom slope. Very successful experiences in the USSR, China, Venezuela, Taiwan, India, and Iran are briefly described. The literature review indicates desirability of flushing at least once a year, intermittent operation, and free-flow conditions during flushing.

[60] Peterson, S.A. 1979. Dredging and Lake Restoration. In *Lake Restoration*, (Proceedings of a National Conf., EPA-400/5-79-001), U.S. Environmental Protection Agency, Office of Water Planning and Standards, Washington, D.C., pp. 105-114.

Positive and negative aspects of dredging freshwater lakes are addressed, including sediment composition, toxic substances, primary productivity, disposal area, etc. Types and uses of grab, hydraulic cutter head, and special purpose dredges are described. Results of selected dredging projects demonstrate that sediment removal can improve water quality and fish habitats. Dredging costs depend on a number of variables. For selected projects, they vary from $1.34/m^3 in the Great Lakes region to $5.63/m^3 in the northeast.

[61] Peterson, S. A. 1982. Lake Restoration by Sediment Removal. *Water Resources Bulletin*, 18(3), pp. 423-435.

A review of more than 60 projects and five case histories shows that sediment removal achieves enhanced fish production, removal of nutrient-rich sediment, and removal of toxic or hazardous materials. Disadvantages of dredging include cost, temporary phosphorus release from sediments, increased phytoplankton productivity, noise, lake drawdown, and temporary reduction in benthic fish food organisms. Sediment removal is recommended for deepening and for long-range reduction of phosphorus release from sediments. Environmental problems associated with sediment removal by dredging are also discussed.

[62] Pitt, J.D., and G. Thompson. 1984. The Impact of Sediment on Reservoir Life. In *Challenges in African Hydrology and Water Resources* (Proc. of the Harare Symp.), IAHS Publ. No. 144, pp. 541-548.

Many reservoirs have become inadequate because much of their storage has been filled by sediment. For small capacity-inflow ratio reservoirs, it will be necessary to consider sediment venting, especially if reservoir half-life is less than 20 years. Studies to prove the viability of sediment sluicing require good field data and should include reviewing case studies, mathematical modeling at both a simple and detailed level, and physical modeling. The model can scan a range of sluicing scenarios and indicate what is acceptable from an operational view point. Sediment sluicing is often used. The real proof of the efficiency of sluicing finally lies in the operation of the prototype. Sufficient flexibility should therefore be included in the design. Sluicing examples are given for Bhatgarh Dam in India, Old Aswan Dam in Egypt, Sanmenxia Reservoir in China, and La Pena Dam in Spain. Some guidelines are suggested for flushing and operating low-level outlets.

[63] Rausch, D.L., and H.G. Heinemann. 1975. Controlling Reservoir Trap Efficiency. *Transactions of the American Society of Agricultural Engineers*, pp. 1105-1113.

Detention time in a reservoir can be decreased with the use of bottom withdrawal sluices. To reduce the quantity of sediment-associated nutrients, the minimum reservoir trap efficiency that will meet the downstream water-quality requirements should be used. Conventional overflow spillways are conducive to discharge of rather clean surface waters and retain sediment- and nutrient-laden waters. Reduction in trap efficiency reduces sediment and nutrient content, improves water quality for fishery and recreational use, increases useful reservoir capacity, and reduces downstream bed degradation. Design features of a bottom-withdrawal siphon spillway are also illustrated.

[64] Roberts, W.J. 1981. Dredging in Illinois. In *Proceedings of a Round Table on Reclaiming and Managing Lakes in Illinois,* Illinois Institute of Natural Resources, October 10-11, 1980, pp. 56-59.

A cutter head dredge was used to remove sediments from the Carlinville reservoir (built in 1937). A spoil area adjacent to the lake was compartmentalized into three basins to permit maximum deposition of silt before returning water to the lake. Another successful lake dredging was accomplished in Oakland, Coles County. During the 32 years of its life, the lake had lost half of its storage capacity. The overall costs came to about $2.60/yd^3.

[65] Robinson, A.R. 1981. Erosion and Sediment Control in China's Yellow River Basin. *Journal of Soil and Water Conservation,* May-June, pp. 125-127.

The Lower Yellow River in China experiences enormous sediment loads and flooding. In its last 450 miles, the riverbed is 10 to 30 ft above the surrounding countryside. The average sediment concentration of a river is 2.5 pounds per cubic foot. Average erosion loss is 12 tons per acre. The 320-ft Sanmen Gorge Dam, built on the Yellow River in 1960, entrapped 90% of incoming annual sediment load (2.1 billion tons). Sluicing through the dam was resorted to in 1962 to reduce sediment deposition by opening diversion tunnels, converting some penstocks to sluiceways, and unplugging diversion outlets. The sediment entrapment was reduced to 20% or less. Soil conservation measures are also being applied in the watershed area.

[66] Roovers, M. 1989. The Removal, Treatment and Use of Sediment from Reservoirs. *Water Power and Dam Construction,* March, pp. 45-48.

A system for sediment removal and disposal, developed in Belgium, is described. It is suitable for dredging to 150 m depths and does cause turbidity in the reservoir. Protective measures considered for controlling reservoir sedimentation include watershed management, bypassing heavily sediment-laden flows, and construction of small upstream dams. Curative techniques are dredging and sediment flushing. The costs of these two types of solutions can be analyzed in terms of cost of dredging and disposal and cost of water losses in flushing.

[67] Schnitter, N.J. 1979. Roman Dams. *Water Supply and Management,* Vol. 3, pp. 29-39.

Roman dams, built mostly in north Africa and the Middle East many centuries B.C., varied in height from about 5 to 40 m. Some of them still exist today and are used for irrigation and water supply. Some dams built for water supply had intake towers. The water was admitted through small openings at various levels and left at the bottom in a pipe through the dam. Some dams were built to divert water for irrigation and some for retaining sediments to develop arable lands. Two dams are of the arch type, with lateral support from the valley sides.

[68] Scott, J.T., Jr. 1989. *Lease Shares and Farm Returns 1988.* AE-4567. Department of Agricultural Economics, University of Illinois at Urbana-Champaign.

This report documents the returns to Illinois landowners and farm operators and shows the relative investments and inputs each is putting into the business and the share of production and returns received by each. The history of average land price per acre given here was used in determining the current project cost of reservoirs in Illinois.

[69] Shalash, S. 1983. Degradation of the River Nile. *Water Power and Dam Construction,* 35(7), pp. 37-43.

One of the effects of construction of the Aswan High Dam has been the bed degradation of the Nile River. In 1956, Fathy stated that the degradation would extend about 56 miles below the dam and each following barrage, and that it would stop in 86 years (year 2058). Moustafa estimated maximum degradation, 8.5 m, below the dam by 1986. Degradation has been only 1.37 m from 1964 to 1973 and the period to reach equilibrium is estimated as 50 years.

[70] Sharma, H.D., and H.R. Sharma. 1977. Sediment Problems at Intakes for Hydropower Plants. IAHS, Publ. No. 122, pp. 330-337.

One of the essential requirements for hydropower intake is that water withdrawn should be essentially sediment-free as far as possible. Large quantities of sediments entering the intakes damage power canal, turbine blades, and auxiliaries. Sediment excluders can be provided at barrages in controlling sediment entry to the intakes. Sediment basins can be used that can be cleaned out by mechanical means or flushing. Suitable mitigatory measures can be integrated in the design and operation of hydroschemes to minimize sediment problems. Different solutions to sediment problems at intake structures are discussed for high-sloped northern Indian hydropower plants.

[71] Shen, H.W. 1991. *Application of Research to Sediment Management.* A keynote speech presented to the Fifth Federal Interagency Conference on Sedimentation, Las Vegas, Nevada.

[72] Shresta, A.K., and A.E. Wannick. 1989. Construction of the Marsyangdi Project in Nepal. *Water Power and Dam Construction,* March, pp. 33-38.

Construction work on the Marsyangdi hydropower project in Nepal began in 1986. The river transports an annual bed load and suspended load of 5.2 and 26.7 million tons. Model tests were carried out in Germany to integrate suitable sediment management in the project design. During floods, the coarse bed load will be transported over the weir downstream into the riverbed. Coarse sediments above the settling basin will be sluiced downstream. For sand-sized sediments, the settling basin (400 m × 75 m × 12 m deep) designed to retain 100% of sediment, will be flushed regularly.

[73] Singh, K.P. 1987. Lake Sedimentation Reduction Techniques. *Public Works,* September, pp. 99-102.

Increased erosion due to land use changes and provision of overflow spillways in the reservoirs have greatly increased sedimentation in them. Watershed erosion control measures can help in reducing erosion, but they require considerable time and expense on the part of farmers. Significant reduction in reservoir sediment-entrapment efficiencies can be achieved by venting sediments with water through the undersluices during high inflows, providing siphon spillways, and passing density currents, carrying high quantities of sediments, through the bottom outlets. Coarse sediments can be retained behind low dams upstream.

[74] Singh, K.P., D.F. Sefton, and R.P. Clarke. 1984. Economic Returns and Incentives of Lake Rehabilitation: Dlinois Case Studies. In *Lake and Reservoir Management* (Proc. of the Third Annual Conf. of the North American Lake Management Soc., October 18-20, 1983, Knoxville, TN), U.S. Dept. of Agriculture and U.S. Environmental Protection Agency, Washington, D.C., pp. 405-411.

Frequent inflows of nutrient and sediment-laden water to small- and medium-sized lakes in Illinois contribute to problems of hypolimnetic oxygen depletion, algal blooms, dense macrophyte growth, inorganic turbidity, and siltation. In-lake techniques such as aeration/destratification, groundwater/surface water blending, shoreline stabilization, and algal control are some of the essential management tools. A recreational benefit assessment procedure was developed for evaluating lake management strategies.

[75] Singh, K.P., and A. Durgunoglu. 1988. *An Improved Methodology for Estimating Future Reservoir Storage Capacities: Application to Surface Water Supply Reservoirs in Illinois.* Illinois State Water Survey Contract Report 446.

A methodology is developed for determining the future storage capacities of water supply reservoirs in Illinois for the next 10 to 40 years based on the available data from reservoir sedimentation surveys.

[76] Singh, K.P., and A. Durgunoğlu. 1990. Economic Design and Storage Conservation by Reduced Sedimentation. *Journal of Water Resources Planning and Management,* 116(1), pp. 85-98.

A mathematical model has been developed for estimating the design storage capacity of a reservoir by using the expected water demand, storage loss due to sedimentation, and physical and hydrological characteristics of the watershed. Suitable mitigative measures can be incorporated in dam design and reservoir operation to substantially reduce sediment entrapment in the reservoir. Economic analyses for different storage maintenance measures are performed for a site in Illinois for several water demand levels and useful lives of the reservoir.

[77] Singh, K.P., and D.F. Sefton. 1985. Economical and Effective Measures for Lake Protection and Lake Management. *Public Works,* September, pp. 132-137.

Lake protection, restoration, and management measures can be classified under preventive and ameliorative categories. Preventive measures include drainage basin alterations, land treatments, and interception of nutrients and sediments before they reach the lake. Ameliorative measures include harvesting of macrophyte biomass, aeration/destratification, dredging; hypolimnetic drainage, lake drawdown, and lakebottom sealing. Calculation of benefits and costs for different techniques provides an indication of the economic feasibility of these measures. A mix of economical and practical measures can protect the existing lakes and prolong their useful life.

[78] Singh, K.P., and J.R. Adams. 1980. *Adequacy and Economics of Water Supply in Northeastern Illinois, 1985-2020.* Illinois State Water Survey Report of Investigation 97.

[79] Stutz, R.O. 1967. The Bitsch Hydroelectric Scheme, Part I. *Water Power,* November, pp. 445-454.

The glacier-fed streams in Switzerland carry high discharges during summer but have negligible flow during winter. Large quantities of sand and gravel are brought down each year by the glaciers. For the Bitsch hydroelectric scheme on the Massa River, annual sediment load is estimated as 550,000 m^3, of which about 25% is sand and gravel. Various alternatives of flushing these sediments from the reservoir were investigated. Sediment scouring can be done through sluices, under pressure or under free-flow conditions. It can be initiated when the Massa River flow reaches 25 to 30 m^3/sec. Yearly flushing of large sediments through undersluices interrupts operation for a few days.

[80] Stutz, R.O. 1967. The Bitsch Hydroelectric Scheme, Part II. *Water Power,* December, pp. 487-493.

The great concentration of materials to be evacuated by the flushing sluices during the scouring operations in the Bitsch Reservoir in Switzerland made it necessary to improve the Massa riverbed downstream of the dam to its junction with Rhone River. The upstream gradient of 5.5% is sufficient to move the materials, but downstream the gradient was only 0.8%. An improvement in the carrying conditions was achieved through an artificial canal with longitudinal gradient of 1.5%. The form of the channel was improved through hydraulic studies in the laboratory.

[81] Terstriep, M.L., M. Demissie, D.C. Noel, and H.V. Knapp. 1982. *Hydrologic Design of Impounding Reservoirs in Illinois.* Illinois State Water Survey Bulletin 67.

[82] Turner, D.J. 1971. Dams and Ecology. *Civil Engineering,* September, pp. 76-80.

Major problems associated with construction of dams are the piling of silt behind the dam and reduction in waterborne nutrients downstream. Aswan High Dam in Egypt has caused a great loss in sardine catch in the eastern Mediterranean. Other environmental problems are anticipated with projects in Southeast Asia, Canada, and the United States. Generally dams and reservoirs raise agricultural production and provide recreation, water supply, and hydropower. There are some unique solutions available to minimize ecological impacts and thus increase the benefits from water resources projects.

[83] Turner, T., and V. Fairweather. 1974. Dredging and the Environment: The Plus Side. *Civil Engineering,* ASCE, October, pp. 62-65.

Most new dredges are hydraulic and do not cause the severe turbidity in the dredged areas associated with mechanical dredges. Investigations are done to determine how and where to dispose of excavated material and how to control the quality of return flow. The dredged material can be used in improving environment by creating wildlife refuges and recreational areas with good fishing and boating. Many dredging projects thus ultimately benefit society.

[84] University of Wisconsin at Madison. 1974. Sedimentation and Sediment Control. In *Environmental Analysis of the Kickapoo River,* A Report to the U.S. Army Corps of Engineers from the Center for the Biotic Systems, Institute for Environmental Studies, IES Report No. 28, pp. 99-116.

There are a large number of tributaries to the Kickapoo River impoundment, hence, the development of sediment deltas. Topset and foreset slopes were used in estimating delta deposits. The sediment deposition within the reservoir was modeled using depth-capacity and depth-area curves. It is recommended to keep the impoundment level 5 ft above the normal pool level of 840 ft. Delta sedimentation can be reduced with lower lake levels during high runoff periods.

[85] Water and Water Engineering. 1972. The Hendrick Verwoerd Dam of the Orange River Project, South Africa. *Water and Water Engineering,* 76(919), pp. 317-323.

The Hendrick Verwoerd Dam formed the largest artificial lake (1972) in South Africa. It is a multipurpose project serving irrigation, urban and industrial water supply, and hydropower. The average silt load of the Orange River is 0.46% of the river's flow volume. Present estimates indicate that the reservoir will lose half of its capacity to sedimentation in the next 120 years. An effective way of combating siltation is to prevent the soil from being washed off the land and constructing sediment storage dams upstream of the main reservoir.

[86] Wegmann, E. 1927. *The Design and Construction of Dams.* John Wiley and Sons, Inc., New York, New York, 740 p.

[87] White, W.R., and R. Bettess. 1984. The Feasibility of Flushing Sediments through Reservoirs. In *Challenges in African Hydrology and Water Resources* (Proc. of the Harare Symp.), IAHS Publ. No. 144, pp. 577-587.

Sediment yields from drainage basins in tropical and subtropical regions of the world are usually high, and reservoir storage is filled up with sediments in relatively less years than in less humid areas. One solution to this problem is to use excess runoff from the drainage basin to flush sediments through the reservoir. Sediment flushing was used at Kamativi Dam in Africa with great success. With sufficient capacity low-level outlets, a state of dynamic equilibrium is reached, which provides adequate water supplies for an indefinite period. This operation is feasible if the water yield of the reservoir is less than the annual river flow.

[88] Wu, CM. 1973. Sedimentation Damage of Hydraulic Structures in Taiwan. *Proceedings of the International Symp. on River Mechanics,* IAHR, January 9-12, pp. A14-1 to A14-12.

Sedimentation damage sustained by hydraulic structures in Taiwan is severe, mainly due to dynamic and erosive forces exerted by turbid waters. Abrasive erosion of concrete surfaces in diversion tunnels and stilling basins and cavitational erosion in high-head sluiceways are common occurrences. The Wuchieh Dam, drainage area 501 sq km, had its dead storage of 18 million m^3 completely filled up in six years. The reservoir life is about one-tenth of the worldwide average because of severe erosion of the watersheds.

[89] Wu, CM. 1988. Reservoir Sedimentation Desilting by Sluicing. *Proceedings of the 6th Congress of the Asian and Pacific Regional Division,* IAHR, 20-22 July, Kyoto, Japan, pp. 191-198.

The loss of reservoir storage capacity is a worldwide concern. Sluicing of excess sediment deposits through the use of a desilting tunnel at Gen-Shan-Pei Reservoir in Taiwan has demonstrated its wider applicability. The overall conclusion derived from the results of prototype and model studies on sediment sluicing is that the judicious use of desilting tunnel can have very efficient desilting results in small- and medium-sized reservoirs with heavy fine-sediment loads. The sluicing operation involves conversion of the reservoir into a riverine situation. Gen-Shan-Pei Reservoir has been kept practically free of sediment since 1955.

[90] Wu, CM. 1991. Reservoir Capacity Preserving Practice in Taiwan. *Proceedings of the 5th Federal Interagency Sedimentation Conference,* Las Vegas, Nevada, March 18-21, pp. 10-75 to 10-81.

The prevailing measures for preserving reservoir capacity in Taiwan may be classified into measures minimizing sediment deposition, maximizing sediment flow through the reservoir, and recovering storage capacity. Sediment deposition is minimized by conservation measures, vegetative screens, and check dams. Maximum sediment flow through a reservoir is achieved, for example, by providing gated spillways. Recovery of storage is attained by dredging, flushing of deposited sediments, and siphoning.

[91] Wu, D. 1984. The Sedimentation Problem Water Conservancy in China. *Water International,* Vol. 9, pp. 177-180.

Inadequate conservation of soil and water leads to high erosion rates particularly in loess plateaus and hills in the Yellow River basin in China. It causes sedimentation in river channels and aggradation of bed, endangering navigation. Protective levees along the river are often breached. In about ten years, the sedimentation reduces reservoir capacities by 10 to 80%. The backwater effect has worsened flood conditions upstream, raised groundwater levels, and increased salinization. Irrigation canals require costly maintenance. Abrasion of turbine blades necessitates their replacement every one to two years. Conservation measures and sluicing of sediments are needed to deal with the problems.

[92] Wunderlich, W.O., and R.A. Elder. 1973. Mechanics of Flow through Man-made Lakes. In *Man-made Lakes: Their Problems and Environmental Effects.* AGU Monograph 17, pp. 300-310.