

Desirable, Conservation-Oriented Reservoir Design and Operation

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ABSTRACT

Reservoirs supply water for domestic and industrial use as well as for recreational facilities. A majority of these reservoirs gradually lose their useful storage and utility due to sedimentation. The adverse effects of reservoir sedimentation can be mitigated by proper reservoir design and operation. Some of these mitigative measures are watershed management and soil conservation, retention of coarse sediments in upstream debris dams or sediment basins, reservoir drawdown and flushing, density-current flushing, venting of sediments through undersluices, and siphoning. Used with great success in other parts of the world, these measures make it possible to design considerably smaller reservoirs, because the need for sediment storage capacity is greatly reduced. The savings in the initial cost of a smaller reservoir may be more than sufficient to offset the extra cost of measures required. A desirable, conservation-oriented reservoir design and operation would also ensure a legacy of healthy water resources for future generations.

INTRODUCTION

Natural and man-made lakes and reservoirs in Illinois serve a multitude of purposes: municipal and industrial water supplies (especially in areas with poor ground-water resources such as the southern half of the state), water-based recreation, flood control, and low-flow augmentation through mandatory low-flow releases such as from Shelbyville, Carlyle, and Rend Lake. In recent decades, reservoir construction has been viewed as having serious adverse impacts on riverine ecology and environment for some distance upstream and downstream of the impounding structure. These concerns have mostly been engendered because of 1) continuing reservoir sedimentation, 2) seasonal stratification, 3) nutrient recycling from bed deposits affecting water quality, 4) lack of mandatory low-flow releases from most of the state reservoirs, and 5) downstream bed degradation and caving-in of banks. However, these are largely manifestations of conventional reservoir design and operation policies that do not address the environmental and conservation concerns. They also do not address the intergenerational equity considerations (treating both present and future generations fairly) that ordain that the design and operation avoid burdening future generations with a considerably degraded resource.

A good reservoir site should entail minimal adverse impact to existing wetlands and wildlife habitats. If some of them cannot be saved, mitigation measures such as creating compensatory wetlands and habitats can become an integral part of reservoir planning and design. Creation of a reservoir and minimization of level fluctuation through suitable operation provide opportunities for wetlands and habitat formation if the lands adjoining the lake waters are zoned for these and other purposes. The integrity of shoreline needs to be preserved by provision of erosion retarding brushes and grasses and restricting speed and proximity of motor boats.

The streams carry sediment and deposit most of it in the reservoir. Reduction in reservoir sedimentation or conservation of reservoir storage can be achieved either by lowering the stream sediment load or by reducing its deposition in the reservoir. Reduction in stream sediment load can be achieved by a sound watershed protection program which can be made an essential part of the planning, design, and operation. The economics may determine the acceptance and successful completion of such a program which may extend over a number of years and thus gradually decrease the stream sediment load. The effectiveness of soil conservation for large watersheds cannot be estimated with accuracy. Significant reduction in stream sediment load can initiate a new cycle of stream geometry adjustments in keeping with the new sediment regime.

The reduction in sediment deposition in the reservoir can be effectively and expeditiously pursued by controls and measures limited mostly to the dam and reservoir. A brief review of reservoir sedimentation in Illinois is followed by various storage conservation measures, and desirable reservoir design and operation.

RESERVOIR SEDIMENTATION

Reservoir sedimentation rates are usually based primarily on empirical relations which are calibrated using field measurements. Using the Upper Mississippi River Basin Commission (UMRBC, 1970) approach, the sediment yield of a stream is given by

$$Y = K * A^{-0.12} \quad (1)$$

where Y is average sediment yield in tons/year/square mile of watershed area, K is a regional constant for sediment potential, and A is watershed area in square miles. Reservoir capacity loss rate, S, in acre-feet (ac-ft) per year is

$$S = \frac{Y * A * TE}{2178 * \delta} = \frac{K * A^{0.88} TE}{2178 * \delta} \quad (2)$$

where TE is reservoir trap efficiency in percent, 2178 is a conversion constant, and δ is density of sediment in pounds per cubic feet or lb/ft³.

Trap Efficiency, TE

Trap efficiency can be estimated from Brune's curve (Brune, 1953), which correlates sediment trap efficiency of a reservoir to its capacity-inflow or C/I ratio. The curve is commonly used for reservoirs operated with overflow spillways. The trap efficiency equals the percent of incoming sediment retained in the reservoir. It decreases with years as C diminishes because of continuing sedimentation. For reservoirs with capacity equal to 1, 10, and 100% of average flow, the trap efficiency from the normal curve equals 46, 86, and 98%, respectively. Thus a small reservoir, storing only 1% of annual water inflow, stores 46% of incoming sediment load.

Density of Sediment, δ

The density of sediment increases with time due to compaction under pressure of overlying sediments. Lane and Koelzer (1943) developed the following equation for estimating sediment density on the basis of age and grain-size distribution of the sediment:

$$\delta_T = \delta_1 + M \cdot \log T \quad (3)$$

where δ_T is density of sediment after T years of compaction, δ_1 is density at the end of the first year, and M is an adjustment constant for compaction. Values of δ_1 and M for different sediment types and reservoir operating conditions are given in Table 1.

The average density of the sediments at time T or δ_T , deposited during a period of $\Delta T = T - T_0$ years is given by (Singh and Durgunoglu, 1990a):

$$\bar{\delta}_T = \frac{1}{\Delta T} \sum_{t=1}^{100} \frac{1}{t^3} \sum_{i=1}^3 P_i (\delta_{i,1} + M_i \cdot \log t) \quad (4)$$

where P is percent weight distribution of the sediment constituents, T_0 is time for $t = 0$, t is time in years, and i is subscript 1, 2, or 3 for sand, silt, and clay, respectively.

The storage continuity equation for a reservoir with sediment deposition can be written as

$$C_0 = C_T + S \cdot \Delta T \quad (5)$$

where C_0 is initial or design storage at time T_0 , S is average annual reservoir capacity loss over ΔT time, and ΔT is time elapsed in years ($T - T_0$), and C_T is available reservoir capacity at time $t = T$. Finally, combining equations 2, 4, and 5, and dividing by the average annual inflow I, the storage continuity equation can be rewritten as

$$\frac{C_0}{I} = \frac{C_T}{I} + \frac{K \cdot A^{0.88} \cdot T E}{2178 \cdot I \cdot \bar{\delta}_T} \cdot \Delta T \quad (6)$$

Statewide Distribution of K Values

Sediment survey data for 118 reservoirs conducted by the State Water Survey personnel over the last 60 years were used in a computer algorithm to determine best-fit values of K, using one-year time steps. Particle-size distribution information available for 24 reservoirs was used in drawing percent contours to estimate sediment constituent percentages for other reservoirs. Calculated K values for the surveyed reservoirs are shown in Figure 1. K values are relatively high in western and southern Illinois. Most of the variation in K within a county or small region can be explained by variations in land slope, land use, and watershed size.

Future Reservoir Capacities and Yields

As-constructed, last survey, and future capacities for four reservoirs (Singh and Durgunoglu, 1990a) are given in Table 2. Capacities of Lake Decatur and Lake Vermilion were increased by 8,123 and 4,200 ac-ft, respectively, in 1956 and 1988 by raising normal pool levels by 3 and 5 feet, about the maximum levels consistent with structural safety and other impacts.

The reduction in capacities leads to yield reductions for supply systems using these reservoirs. The present and future yields for the reservoirs in Table 2 are given in Table 3 for drought recurrence intervals of 20 and 50 years, together with the water supply system demands (Broeren and Singh, 1989). Many municipalities use a 50-year drought

yield for assessing the adequacy of their reservoir for water supply needs. If the lake drawdown duration exceeds 6 to 12 months, the average annual demand during the drought may be 1.2 to 1.3 times the average year demand. In Table 3, M is the demand multiplier and RI is the recurrence interval in years, taken as 20 or 50 years.

Decatur's water supply system is inadequate to meet increased drought-induced demands even during a 20-year drought. Inter-State Water Company serving Danville and neighboring communities has adequate capacity to meet future demands because its capacity was more than doubled in 1988 by raising the pool level by 5 feet. Continuing sedimentation lowers reservoir yield year by year. The recycling by industries and sewer charges based on water use have helped greatly to slow down any increase in water demand. Adequacy of many supply systems can be insured if lake sedimentation can be drastically reduced.

STORAGE CONSERVATION

Dams are built to create reservoirs for storage of water and not for storage of sediment per se. Reservoir sedimentation reduces reservoir storage and its yield. It also causes bed degradation and caving-in of banks downstream of the dam, because water overflowing the spillway contains considerably less sediment. The sediments deposited in a reservoir carry pollutants and nutrients that are recycled into overlying waters, greatly reducing dissolved oxygen levels and causing algal blooms. The overflow spillway maintains and promotes stratification during summer and winter, greatly reducing the usable space for fish and recreation. From intergenerational equity considerations, the design and operation of a reservoir should keep it robust and healthy not only for the present generation but also for future ones, without unduly impacting the quantity and quality of the resource.

Mitigation Methods for Storage Preservation

Methods for controlling or reducing reservoir sedimentation can be considered under two broad categories:

1. Reducing sediment inflow to the reservoir. This can be achieved by:
 - a. watershed management and soil conservation,
 - b. retention of coarse sediments in upstream debris dams or sediment basins,
 - c. bypassing of heavily sediment-laden flows, and
 - d. trapping and retention of sediments by a vegetative screen.
2. Reducing sediment entrapment in the reservoir. Some methods are:
 - a. reservoir drawdown and flushing,
 - b. density current flushing,
 - c. venting of sediments through undersluices,
 - d. reservoir operation policy and design for sediment control,
 - e. siphoning, and
 - f. dredging of sediments.

Reducing Sediment Inflow to the Reservoir

The intent of watershed management and soil conservation measures is to substantially reduce erosion and thereby decrease the sediment input to the streams. Conservation measures applied to areas contributing excessive sediment result in a significant reduction in sediment input to the lake. These measures include contour farming and terracing, stripcropping, crop rotation, no-till farming, grassed drainage ways, gully erosion

control, and stabilization of banks and of critical areas by their return to grasslands or forests. Conservation measures take years to implement and require an efficient planning agency, as well as farmers and other landowners willing to pay for them. The efficiency of watershed management in reducing sediment inflow to a reservoir varies from a low of 5% to a high of 40% (Bruk, 1985; Mahmood, 1987).

Debris dams, low dams built across the main sediment-contributing tributaries, can control the sediment inflow into the downstream reservoir. These dams retain the coarse fraction of the sediment and help in reducing backwater deposits in the main reservoir. The sediments can be removed every two to three years during low-flow periods and used to raise nearby lands.

A sediment basin constructed at the entrance of a stream into a reservoir can be considered for reducing sediment input into the reservoir. The sediment basin is created by constructing a low dam in the upper part of the reservoir. However, unless the dam is designed for extreme floods, it can be washed into the reservoir together with the contents of the basin. Limited storage of the basin may be filled with sediments in 10 to 30 years. A sediment basin at the head of a reservoir may appear as landfill after some years and detract from the esthetics of the reservoir.

A large part of flood flows carrying abundant sediment can be bypassed through a channel, tunnel, or pipes, significantly reducing silting in the reservoir. Pipelines can be anchored in a low submerged weir near the stream/lake interface, can be placed along or partially embedded in the lakebed, and can discharge downstream of the dam under a full head of water. This technique has been successfully applied in Italy (Roveri, 1981).

A vegetative screen at the head of the reservoir, whether artificial or natural, serves to reduce the velocity of incoming flow and to cause sediment deposition. As an example, the growth of tamarisk (salt cedar) along the Pecos River above Lake McMillan, New Mexico, resulted in a reduction of sediment deposition in the lake (Stevens, 1936). Capacity loss during 20 years with tamarisk was only 14% of that in the previous 20 years. The vegetation lowers the water supply to the lake by as much as 10%. A suitable vegetative screen should be chosen for a particular area on the basis of climate, soil, and flow conditions. It can, however, increase water elevations upstream of the vegetation and thus increase the potential flood damages.

Reducing Sediment Entrapment in the Reservoir

The efficiency of drawdown of reservoir water level for flushing some sediments and/or inducing erosion of deposited sediments depends on reservoir bed topography, locations and capacities of bottom outlets, sediment characteristics, reservoir operation, duration of flushing, and flushing discharge. Flushing flows carve out a deep channel in the reservoir, which approaches the pre-dam width of the stream or river with periodic flushing. The sediment flushing may be resorted to before formation of considerable valley deposits. The outlet gates will require protection against abrasion by high sediment concentrations and blockage by sediment deposits.

According to Wunderlich and Elder (1973), "...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." According to Bell (1942), "...lives of many of them

(reservoirs) may be substantially increased by making use of the transporting power of density currents. If the maximum benefit is to be obtained from the use of stratified flows as transporting agents, they should be put to work as soon as possible after storage has begun in a new reservoir." Venting sediments from the very beginning does not allow them to stabilize, and it maintains the bottom slope of the reservoir for efficient use of density currents (Singh, 1987). In the Iril Emda Reservoir in Algeria, between 45 and 60% of the annual incoming sediment was vented during the period 1953 to 1958 (Duquenois, 1959). For the Fengjiashan Reservoir in northwest China, because of density current flushing, the ratio of sediment outflow to sediment inflow for 14 flood events ranged from 23 to 65% according to the nature of flood and sediment characteristics of the inflow (Bruk, 1985). Provision of multi-level, multiple outlets improves the venting efficiency of the density currents.

Sediment sluicing is distinct from sediment flushing because most of the sediment load entering a reservoir is released downstream before it has time to settle. The sluices can be incorporated in the design of the impounding structure or dam. The total capacity of these sluices should be in the range of 0.3 to 1.0 times the maximum daily flood inflow. Models can be used to identify the most suitable size and locations for the sluices. Frequent venting of sediments may be resorted to during the high-inflow season when the excess flows may all be routed through the sluices. The operation greatly reduces sediment entrapment and reservoir surcharge (which causes flooding of low lands around and upstream of the reservoir). It reduces downstream bed degradation and caving-in of banks, and practically eliminates the hypolimnetic zone. The technique of venting sediments through undersluices has been used in Spain since the sixteenth century to keep the reservoirs relatively free of sediment deposits (Wegmann, 1927). The Zuni Reservoir near Black Rock, New Mexico, was 80% filled with sediment by July 1931 when a 4-foot by 6-foot sluice was installed (Brown, 1943). In about three months, 800,000 cubic yards of sediment were sluiced out of the reservoir. The Sanmen Gorge Dam, the most downstream dam on the Yellow River in China, and the power plant were completed in 1960. In the first 1.5 years of operation, 90% of the actual sediment load of 2.1 billion tons per year was trapped in the reservoir. The Chinese began sluicing through the dam in 1962 (Robinson, 1981). A diversion tunnel and some penstocks were converted to sluiceways in 1965. Additional diversion outlets, plugged after construction, were reopened in 1970, and power generation was reduced to one third of what had been planned. The trap efficiency with these measures has been reduced from 90% to less than 20%.

The goal of reservoir operation and management should be not only to meet the design purposes, but also to entrap the least incoming sediment that is economically and practically feasible. About 80 to 90% of annual sediment load enters the reservoir during flood season, and lowering pool levels in this season increases the efficiency of sediment venting operation. Use of such an operation on the Heisonglin Reservoir, located on a tributary to the Yellow River in China, reduced the annual sediment load trapped from 706,000 to 122,000 cubic yards (Zhang et al., 1976) and reduced the trap efficiency to 17%. The maximum through-flow of the sediment was attained.

According to Bruk (1985), "Siphon dredging for desilting reservoirs differs from ordinary dredging in exploiting the hydraulic head difference between the upstream and downstream water levels at a dam as the source of motive power for suction dredging." The simplest successful type of device is the hydraulic siphon installed at the Rioumajou Dam in

France (Evrard, 1980). The siphon pipe varies from 16 to 18 inches in diameter and can discharge 35 cubic feet per second (cfs) with 33 pounds of sediment. A siphon dredger was installed at the Tianjiawan Reservoir in China (Brak, 1985) in 1975. During June 1977 to June 1978, it removed 0.42 million cubic yards when the inflow was only 0.39 million cubic yards. The suction pipe is about 22 inches in diameter; the suction head has scrapers, nozzles, and a rotating cutter. The outflow slurry had a sediment concentration of 15.6% by volume.

Sediment flushing, sluicing or siphoning in the case of new reservoirs allows venting up to 80% of incoming sediment, slightly lowers the sediment concentration in the outflow water (as compared with the inflowing water to the reservoir) thus greatly minimizing bed degradation and inhibiting initiation of a new erosion cycle in the tributaries downstream to meet the lowered bed levels in the main stream. The stream sediment load in the downstream reach is still less than that without the dam. In the case of existing reservoirs with considerable storage lost to sedimentation, flushing of the old sediments may be based on the quantity of sediments, acceptable sediment concentrations with flushing or sluicing discharges, and nearness to a major stream or river.

Dredging is an expensive means of restoring the storage capacity of a reservoir. Various designs of dredgers are available. The usual ratio of water to sediment by volume is 8:1 to 10:1. In the case of wide reservoirs, hydraulic dredging can more efficiently recover overbank deposits than flushing. Dredging may be done at fixed intervals for small- or medium-sized reservoirs. It can also be an ongoing operation for some large reservoirs.

DESIRABLE RESERVOIR DESIGN AND OPERATION

By combining the parameters in front of ΔT into a single variable β , Eq. 6 can be rewritten as

$$\frac{C_0}{I} = \frac{C_T}{I} + \beta * \Delta T \quad (7)$$

where β denotes an average annual capacity loss over a period of ΔT years as a fraction of average annual inflow I , and is a function of trap efficiency TE , C/I , watershed area, K , sediment density δ_T , and l . $\beta * \Delta T = 0$ indicates no storage loss and useful storage C_T after ΔT years equals the initial design storage C_0 . A progressive increase in $\beta * \Delta T$ makes C_0 progressively higher than C_T . The reservoirs are designed with a useful life of, say, ΔT years such that C_T will be able to meet the water demands fully in the last year of this period. Reduction in storage loss can be achieved by reducing β , leading to initial smaller design storage. This can be achieved by improved watershed management (resulting in reduction in K) and by reducing trap efficiency through sediment venting measures.

Economic analyses were performed (Singh and Durgunoglu, 1990b) for a reservoir with conventional overflow spillway as well as one with sediment entrapment reduction measures that reduce trap efficiency to 25 and 10%, respectively. Design periods of 10, 25, and 50 years were considered. The results are shown in Figure 2 for a reservoir designed to supply water at a rate of 5% of average annual inflow and two K values of 1,200 and 3,500. The initial design storage C_0 and cost decrease with decreased trap efficiency, and the decrease gets more pronounced with increased erodibility factor K and increased T . The cost savings resulting from incorporation of trap-efficiency reduction

measures will usually be ample to cover the costs of integrating such measures in design and construction. After T years, the reservoir with reduced trap efficiency will continue to provide more water supply, recreation, and aquatic habitat than a reservoir with conventional overflow spillway.

Incorporating Trap-Efficiency Reduction Measures

The relative efficiency and desirability of one or more sedimentation reduction measures depends on reservoir and watershed characteristics, reservoir location on the stream system, and the severity of sediment and water quantity and quality problems to be addressed. Building a check or debris dam upstream of the reservoir can be economical for retaining a large part of coarse sediments upstream of the check dam. These sediments can be vented downstream of the reservoir through flushing pipes or removed every three to five years during dry conditions by crawler tractors. Provision of gated undersluices in the dam near the reservoir bed level helps in reservoir drawdown flushing, venting density currents carrying high sediment loads, and venting of excess water together with sediment during medium-to-high flows. The water vented through the sluices mostly comes from the deeper water in the reservoir or from the hypolimnetic zone. Installation of a maneuverable siphon system can be economical and efficient for small- to medium-sized reservoirs. Typical installations of sediment entrapment reduction measures are shown in Figure 3 for two cases: one with check dam, flushing pipes, and undersluices; and the other with a siphon passing through a bottom outlet or straddling the dam.

Up to 80% or more of the sediment entering a reservoir can be vented through properly designed undersluices during high-flow periods (Singh and Durgunoglu, 1986). This can be done frequently during the high-flow season, which accounts for 80 to 90% of the annual sediment inflow. Benefits of such an operation would be a drastic reduction in the sediment retained in the reservoir, practical elimination of hypolimnetic zone in the reservoir, improved lake water quality, increased recreational and habitat space, and significant reduction in downstream bed degradation and bank caving.

There may be some concerns about permissibility of measures to reduce sedimentation in the reservoir under FWPCA 401, 402, and 404. Section 401 permit applies to construction of dam and reservoir. If the sediment concentration in the outflowing water is somewhat less than that of the inflowing water, it should not be a concern at all. No new effluents and dredged materials are added. Section 402 may not apply because no discharge of pollutants is involved. Section 404 applies to permits for discharge of dredged or fill material, and poses no problems for venting of incoming sediments (which have not become "fill" yet). However, if venting of old sediments from the existing reservoirs is contemplated, factors such as allowable sediment concentrations, downstream effects, and nearness to a major stream may be considered in the permitting process.

CONCLUSIONS

The following conclusions are drawn from this study:

1. Measures to achieve minimization of sedimentation in the reservoir and withdrawal of hypolimnetic waters or their aeration are needed for an environmentally desirable and conservation-oriented reservoir design and operation.

2. The savings in the initial cost of a smaller reservoir may be more than sufficient to offset the extra cost of mitigative measures required.
3. Reservoirs with sediment-entrapment reduction measures can be used to a greater extent beyond their design life than those with conventional design.
4. Reduction in sediment entrapment in the reservoir is synonymous with more sediment available to flow downstream. This will significantly alleviate downstream bed degradation, caving-in of banks, and initiation of a new cycle of erosion in tributaries entering the affected downstream reach.
5. Venting of sediment with bottom waters improves reservoir water quality not only because of reduced retention of pollutants adsorbed on the sediment particles and their subsequent recycling into the overlying waters, but also due to venting and/or siphoning of hypolimnetic waters with low dissolved oxygen levels. This increases space for recreation and habitats.
6. Reservoir sedimentation adversely affects water supply and other uses. Minimization of sedimentation allows the optimal use of the reservoir.
7. An environmentally desirable, conservation-oriented reservoir design and operation are necessary to ensure a legacy of healthy water resources for future generations.

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Table 1. Values of δ_1 and M Used for Estimating Average Density of the Compacted Sediment Deposits*

| Reservoir Operation | Sand | | Silt | | Clay | |
|---|------------|---|------------|-----|------------|------|
| | δ_1 | M | δ_1 | M | δ_1 | M |
| Reservoir always or nearly always submerged | 93 | 0 | 65 | 5.7 | 30 | 16.0 |
| Normally moderate reservoir drawdown | 93 | 0 | 74 | 2.7 | 46 | 10.7 |
| Normally considerable drawdown | 93 | 0 | 79 | 1.0 | 60 | 6.0 |
| Reservoir normally empty | 93 | 0 | 82 | 0.0 | 78 | 0.0 |

* After Lane and Koelzer (1943).

Table 2. Future Capacities of Some Illinois Reservoirs

| Reservoir Name | Area (mi ²) | As-Constructed | | Last Survey | | Estimated Future Capacities | | | |
|------------------|-------------------------|----------------|-------|-------------|--------|-----------------------------|-------|-------|-------|
| | | Year | Cap. | Year | Cap. | 2000 | 2010 | 2020 | 2030 |
| Lake Taylorville | 131.3 | 1962 | 9406 | 1977 | 7914 | 6045 | 5296 | 4580 | 3893 |
| Lake Decatur | 925.0 | 1922 | 19738 | 1983 | *18800 | 16552 | 15285 | 14057 | 12868 |
| Lake Pittsfield | 11.1 | 1961 | 3580 | 1985 | 2760 | 2307 | 2015 | 1730 | 1450 |
| Lake Vermilion | 298.0 | 1925 | 8514 | 1988 | *8106 | 7414 | 6881 | 6397 | 5964 |

Capacities are in acre-feet.

* denotes capacities considering raises in normal pool.

Table 3. Present and Future Demands and Yields of Reservoirs

| Reservoir Name | Demand or Yield | M or RI | Demand or Yield for the Years (mgd) | | | |
|------------------|-----------------|---------|-------------------------------------|-------|-------|-------|
| | | | 1990 | 2000 | 2010 | 2020 |
| Lake Taylorville | Demand | 1.0 | 2.55 | 2.53 | 2.51 | 2.54 |
| | | 1.3 | 3.31 | 3.29 | 3.26 | 3.30 |
| | Yield | 20 | 7.12 | 6.45 | 5.59 | 4.88 |
| | | 50 | 5.19 | 4.73 | 4.33 | 3.93 |
| Lake Decatur | Demand | 1.0 | 26.03 | 28.24 | 30.31 | 32.27 |
| | | 1.3 | 33.84 | 36.72 | 39.40 | 41.95 |
| | Yield | 20 | 31.16 | 29.30 | 28.24 | 26.48 |
| | | 50 | 28.58 | 26.16 | 24.71 | 23.66 |
| Lake Pittsfield | Demand | 1.0 | 0.44 | 0.43 | 0.43 | 0.44 |
| | | 1.2 | 0.52 | 0.51 | 0.51 | 0.52 |
| | Yield | 20 | 1.87 | 1.71 | 1.56 | 1.43 |
| | | 50 | 1.39 | 1.28 | 1.19 | 1.08 |
| Lake Vermilion | Demand | 1.0 | 8.04 | 7.81 | 7.69 | 7.80 |
| | | 1.3 | 10.45 | 10.16 | 9.98 | 10.14 |
| | Yield | 20 | 20.18 | 19.62 | 19.06 | 18.50 |
| | | 50 | 19.02 | 18.46 | 17.75 | 17.19 |

M = Demand multiplier

RI = Recurrence interval in years (20 or 50)

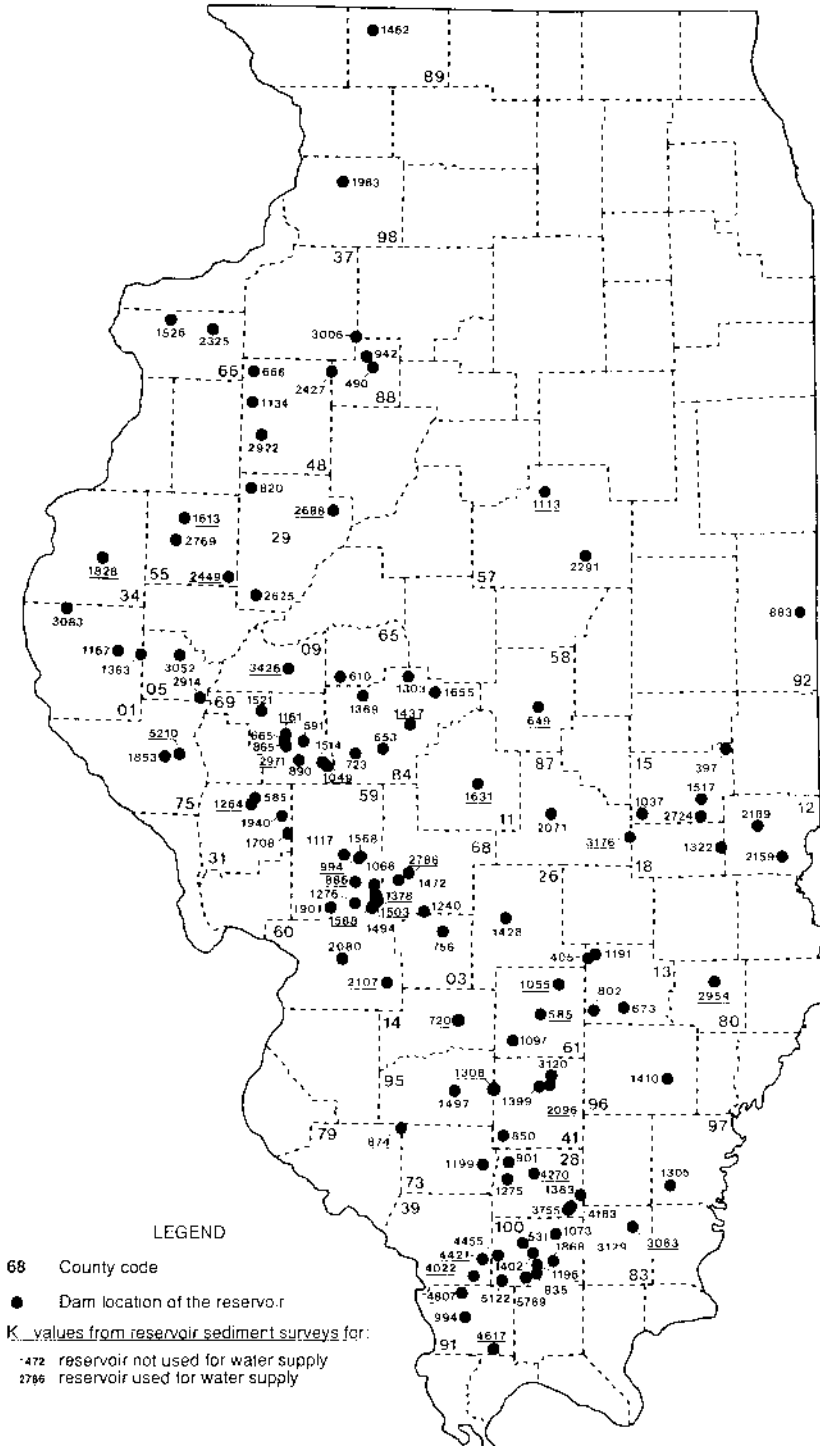


Figure 1. Calculated K values for the surveyed reservoirs

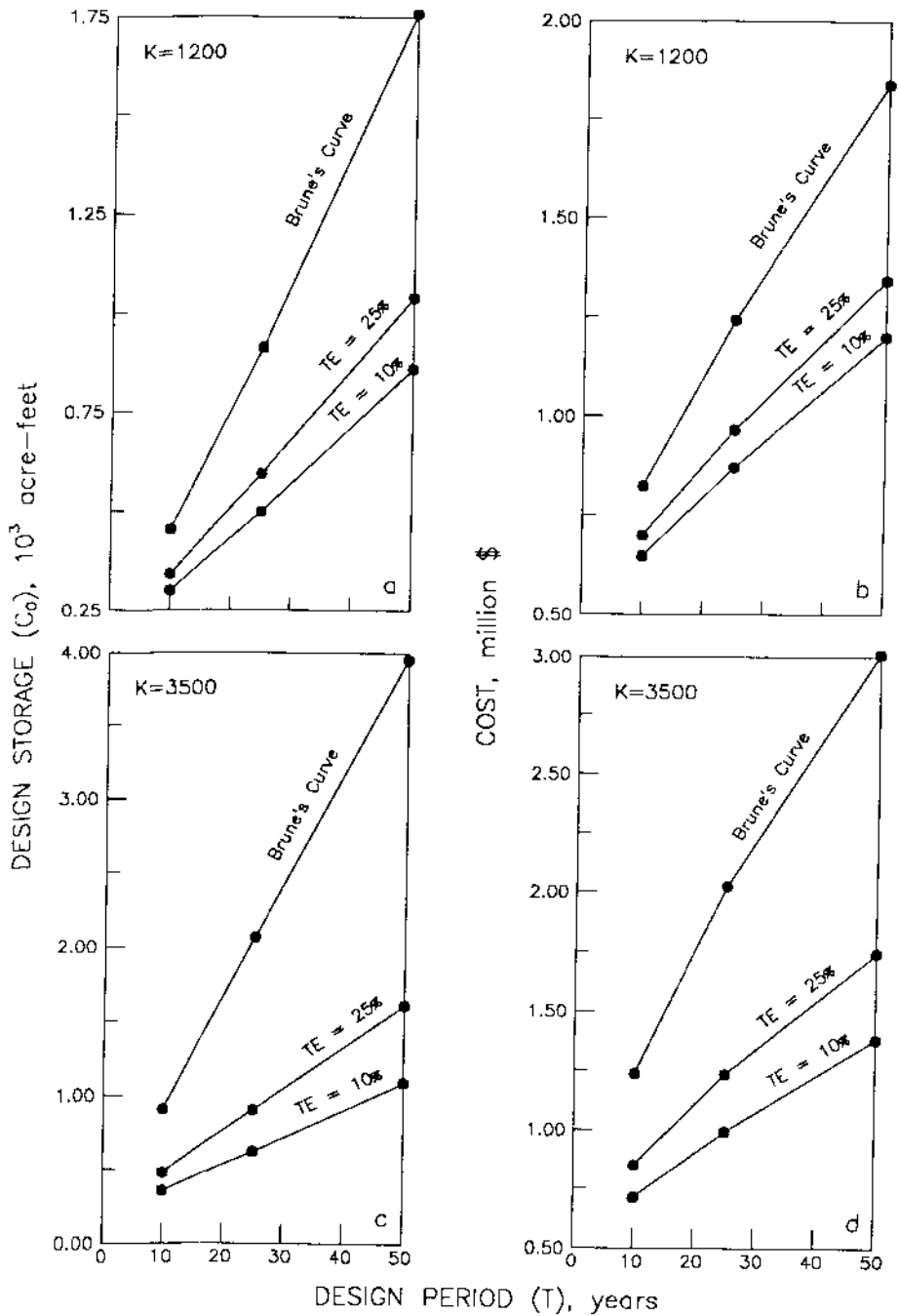


Figure 2. Design storage and cost versus design period for various trap efficiencies and K-values for draft rate of 5% of average annual flow, Indian Creek at Wanda, Illinois

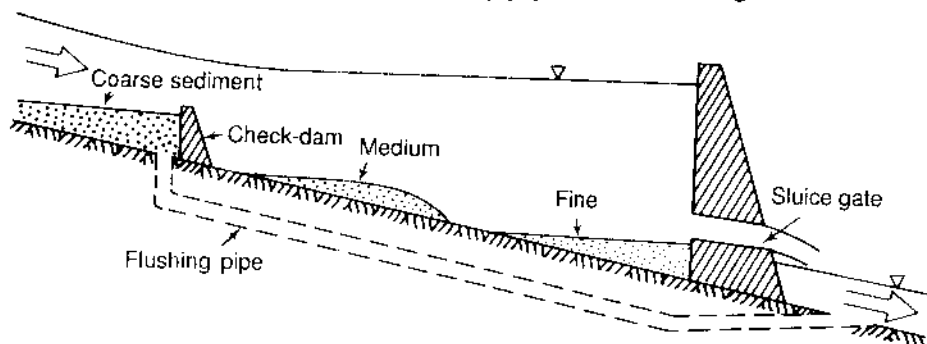
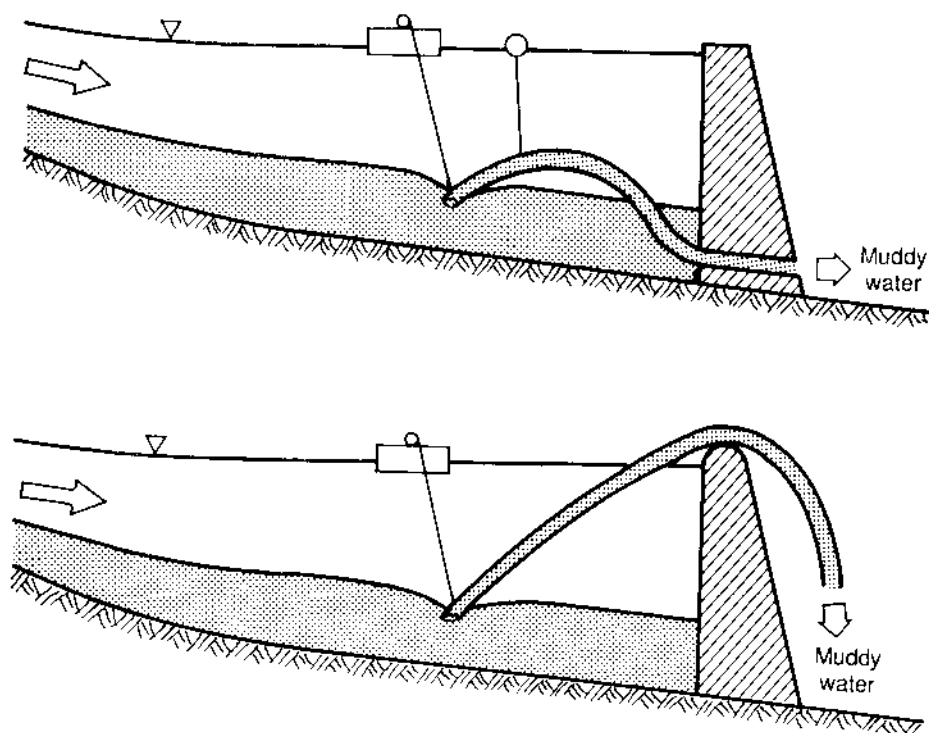
(a) Check-dam, flushing pipe, and sluice gate**(b) Siphoning**

Figure 3. A schematic representation of typical installations of sediment entrapment reduction measures