MANAGEMENT OF IMPOUNDED RIVERS

(Part 2)

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and

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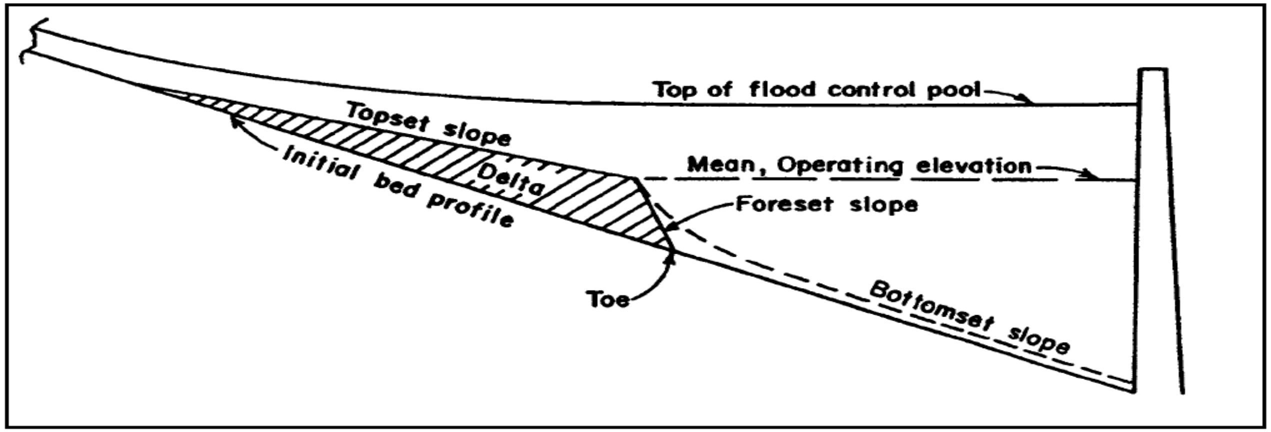
Why Sediment Deposit in reservoirs

- Natural river reaches are usually in a state of morphological equilibrium where the sediment inflow on average balances the sediment outflow. Sediment deposition occurs as the flow enters the impounded reach of a reservoir due to a decrease in flow velocity and drop in transport capacity of the flow.
- Coarse sediment is deposited first in the upper part of the reservoir, while finer sediment is transported further into the reservoir. The impounded reach will accumulate sediment and lose storage capacity until a new balance with respect to sediment inflow and outflow is again achieved.



Rate of Storage Loss

- The worldwide average annual rate of storage loss due to reservoir sedimentation is on the order of 0.5 to 1% of total storage capacity.
- This amounts to having to replace approximately 300 large dams on an annual basis worldwide, at an estimated cost of $ 9 billion just to replace existing storage capacity.
- 66 reservoirs in the United States had an average storage loss rate of 0.71%.
- 20 reservoirs in the China had an average storage loss rate of 2.26%.

Need for Sediment Management

- Reservoirs have traditionally been planned, designed, and operated on the assumption that they have a finite “life,” frequently as short as 100 years, which will eventually be terminated by sediment accumulation.
- Traditional approaches to sediment management have not considered the need for sustained use. As a result, reservoirs worldwide are losing storage capacity rapidly, possibly as fast as 1 percent per year (Mahmood, 1987).
- Sediment management in reservoirs is no longer a problem to be put off until the future; it has become a contemporary problem.
- In 1987 the U.N.’ World Commission on Environment and Development issued the report titled ***Our Common Future*** which proposed the concept of sustainable development as “Meeting the needs of the present without compromising the ability of future generations to meet their own needs.”

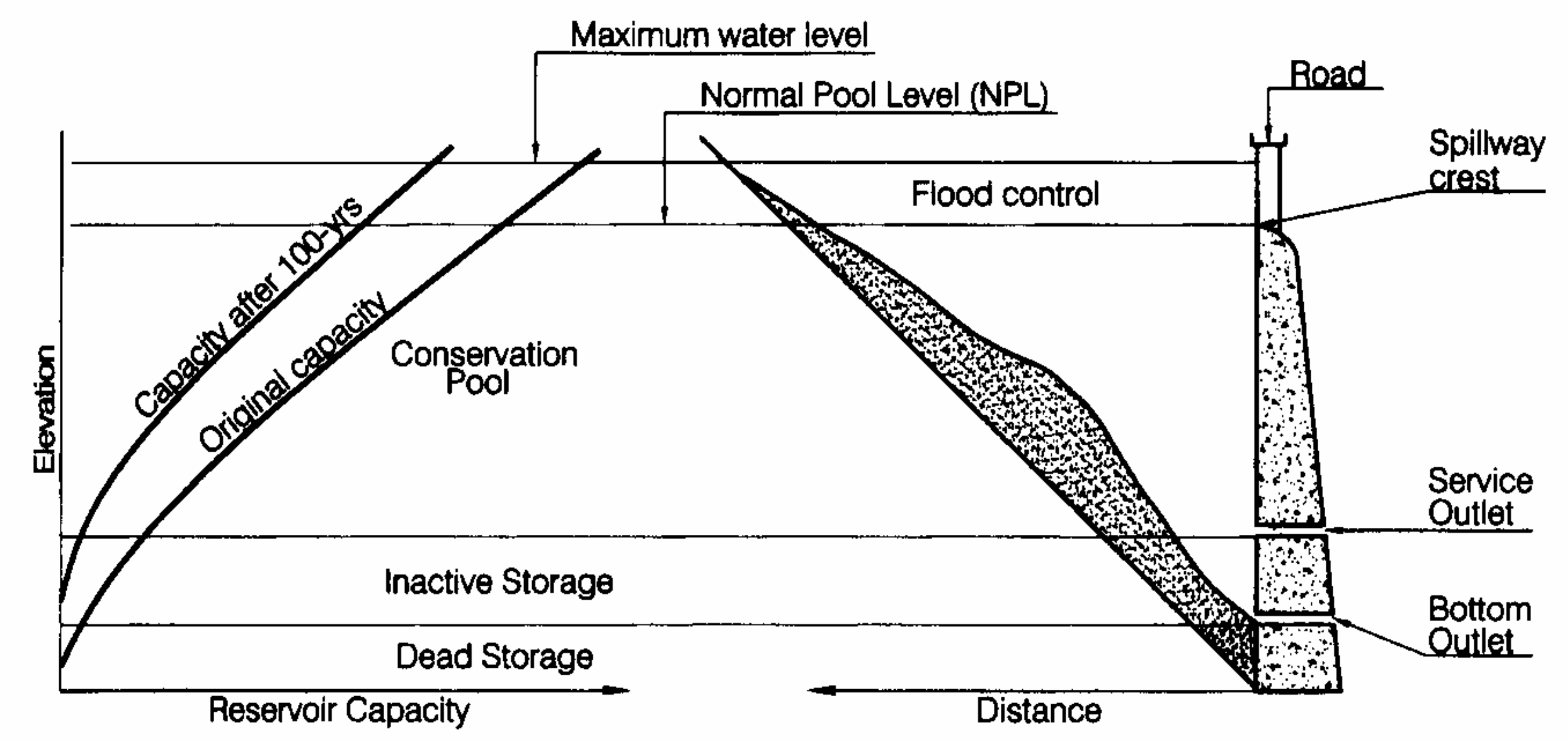
Concepts of Sustainable Development

- **New Projects:**

  The sustainability criteria suggested for new reservoirs is to design for a minimum of 1000 years of operation.

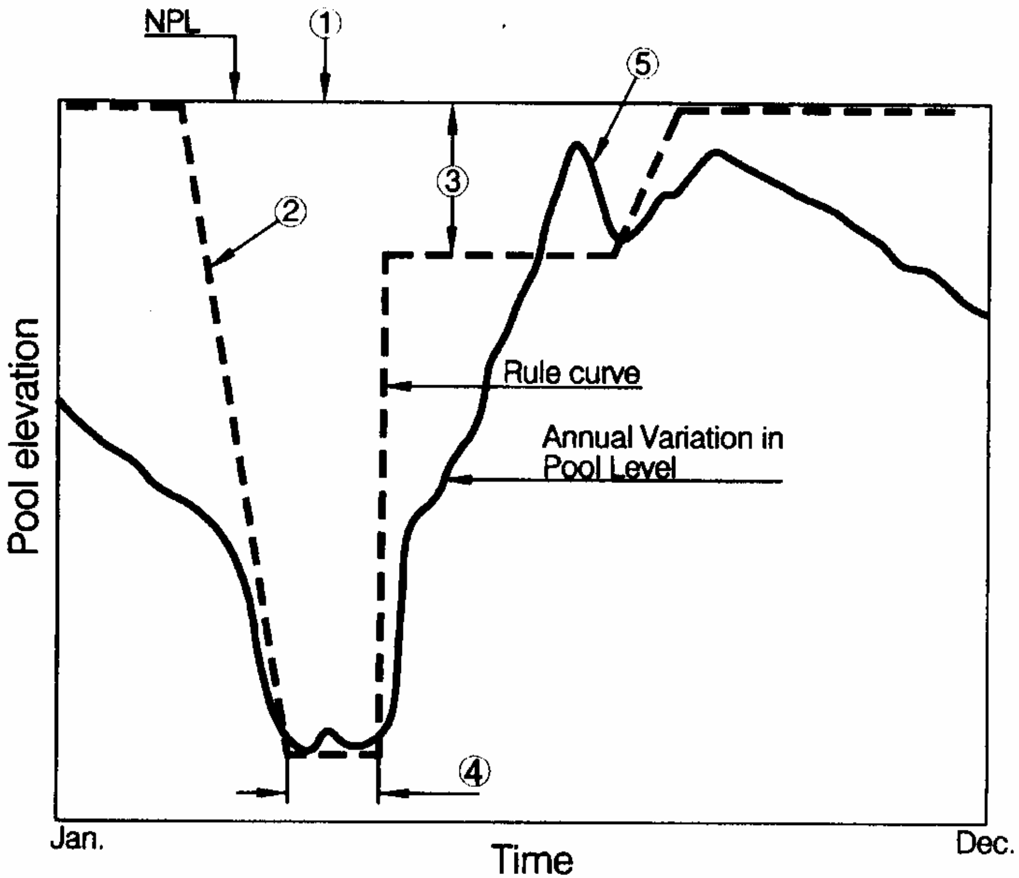
- **Existing reservoirs:**

  At existing reservoirs, sustainable sediment management should seek to balance sediment inflow and outflow across the impounded reach while maximizing long-term benefits.



- *Dead storage* is the volume that is below the invert of the lowest-level outlet and which cannot be drained by gravity.
- *Inactive storage* is the lower part of the conservation pool that is normally not used.
- *Active* or *conservation storage* is the volume that can be manipulated for beneficial use, but excluding flood storage. It lies above the minimum operating level and below the bottom of the flood storage pool.
- *Live storage is* the total volume below full reservoir level less dead storage.
- *flood storage is* the upper portion of the pool dedicated to flood detention.

Reservoir Operation

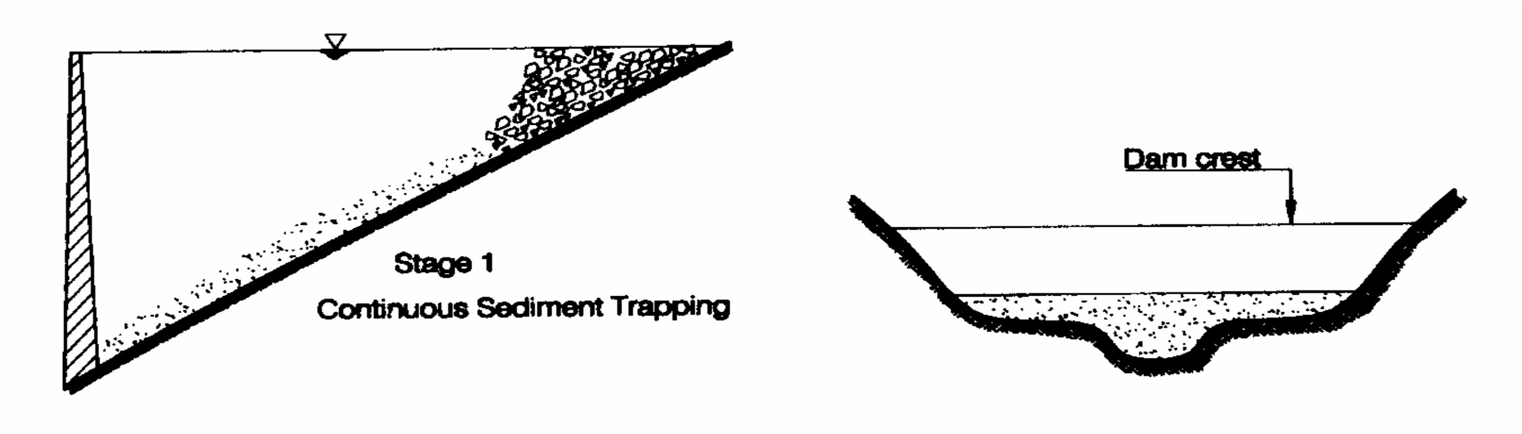


1) Top of gates
2) Guide curve for maximum pool level
3) Flood control storage
4) Drawdown period for sediment flushing
5) Flood detention and release

Stages of Reservoir Life

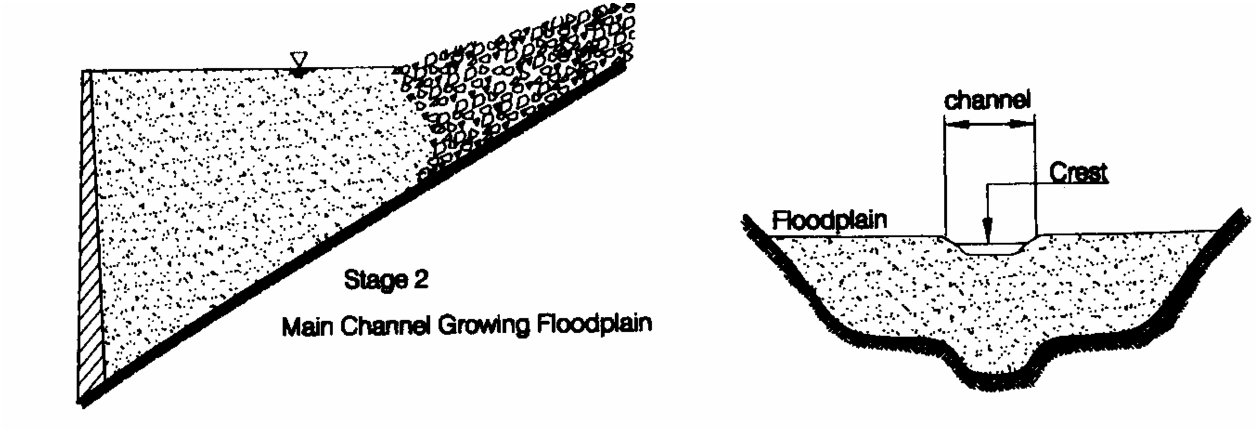
- Reservoir life can be described in geomorphic terms as a **three-stage process**.

Stage 1 – Sediment Trapping



- Coarse bed material load is deposited as soon as stream velocity diminishes as a result of backwater from the dam, creating delta deposits at points of tributary inflow.
- Most finer sediments are carried further into the reservoir by either stratified or nonstratified flow and accumulate downstream of the delta deposits. These finer sediments first fill in the submerged river channel, after which continued deposition produces horizontal sediment beds extending across the width of the pool.

Stage 2 – Main Channel and Growing Floodplain

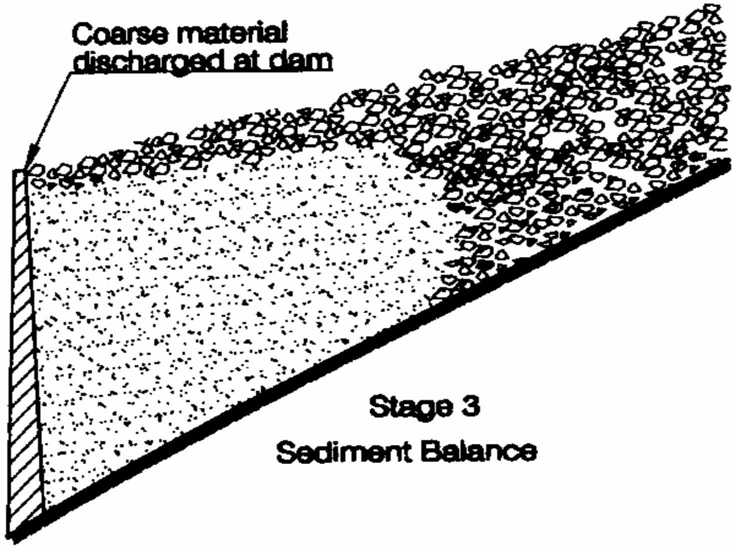


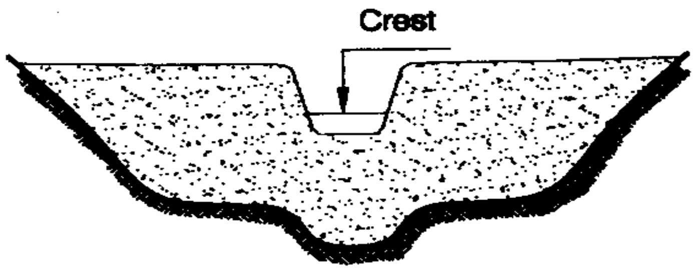
- When sedimentation reaches the spillway crest, the reservoir transits from continuous deposition to a mixed regime of deposition and scour. A main channel will be maintained by scour, and its base level will be established by the spillway. Sediment deposition continues on floodplain areas, causing the floodplain elevation to rise above the spillway elevation.

Stage 2

- Sediments will be deposited in both channel and floodplain areas during impounding. Scouring during drawdown will remove sediment from the channel but not the flood plains, which will gradually rise in elevation as sediment continues to accumulate. .

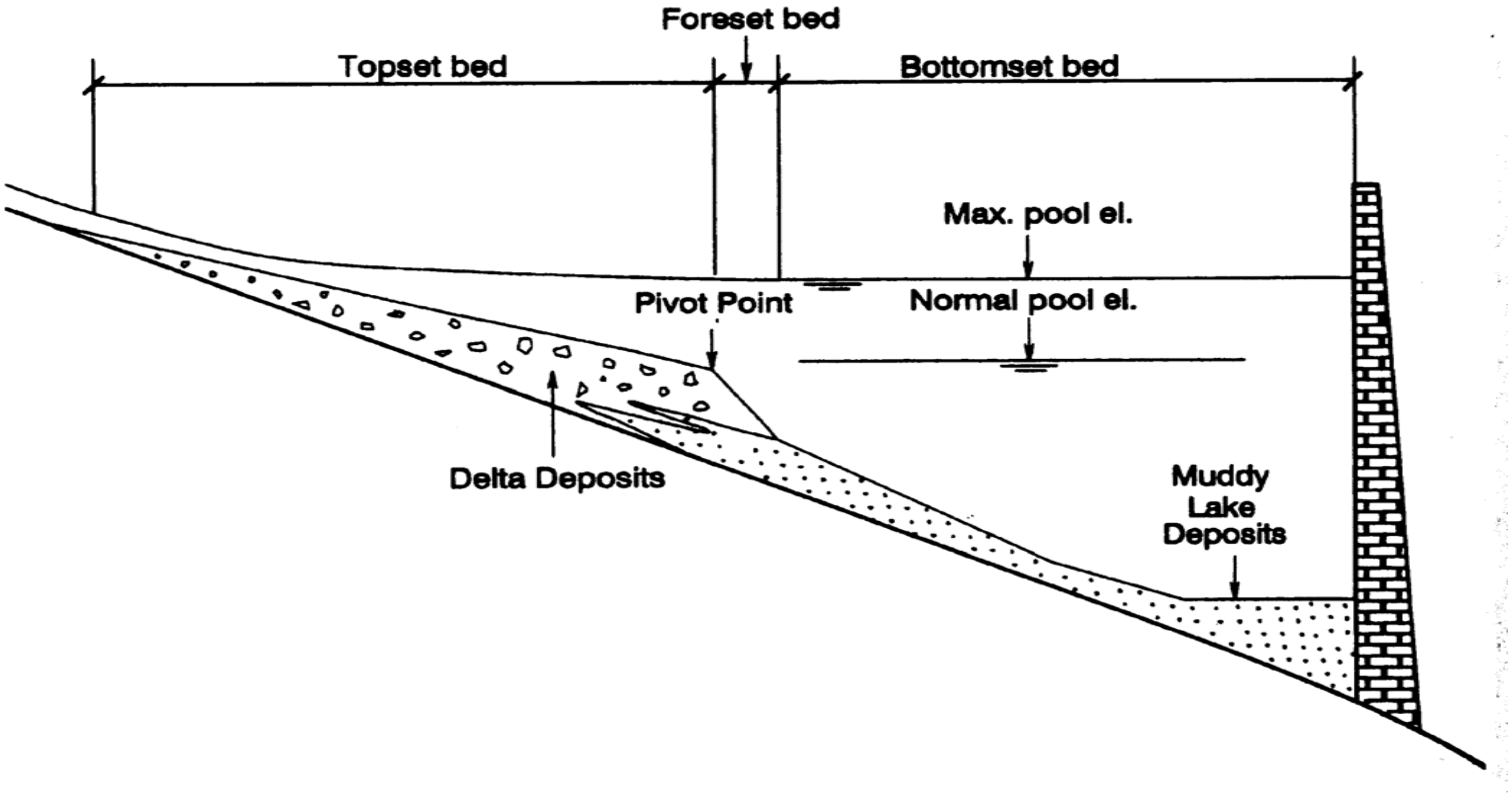
Stage 3 – Sediment Balance





- Sediment inflow and outflow are essentially in full long-term balance when the amount and grain size distribution of sediment entering the reservoir is balanced by the material passing the dam.
- Sediments of all sizes may accumulate upstream of the dam during smaller events, but major floods can wash out large volumes of accumulated sediment.

Deposition Zones



The longitudinal deposition zones in reservoirs may be divided into three main zones:

1. **Topset bed**
2. **Foreset deposit**
3. **Bottomset bed**

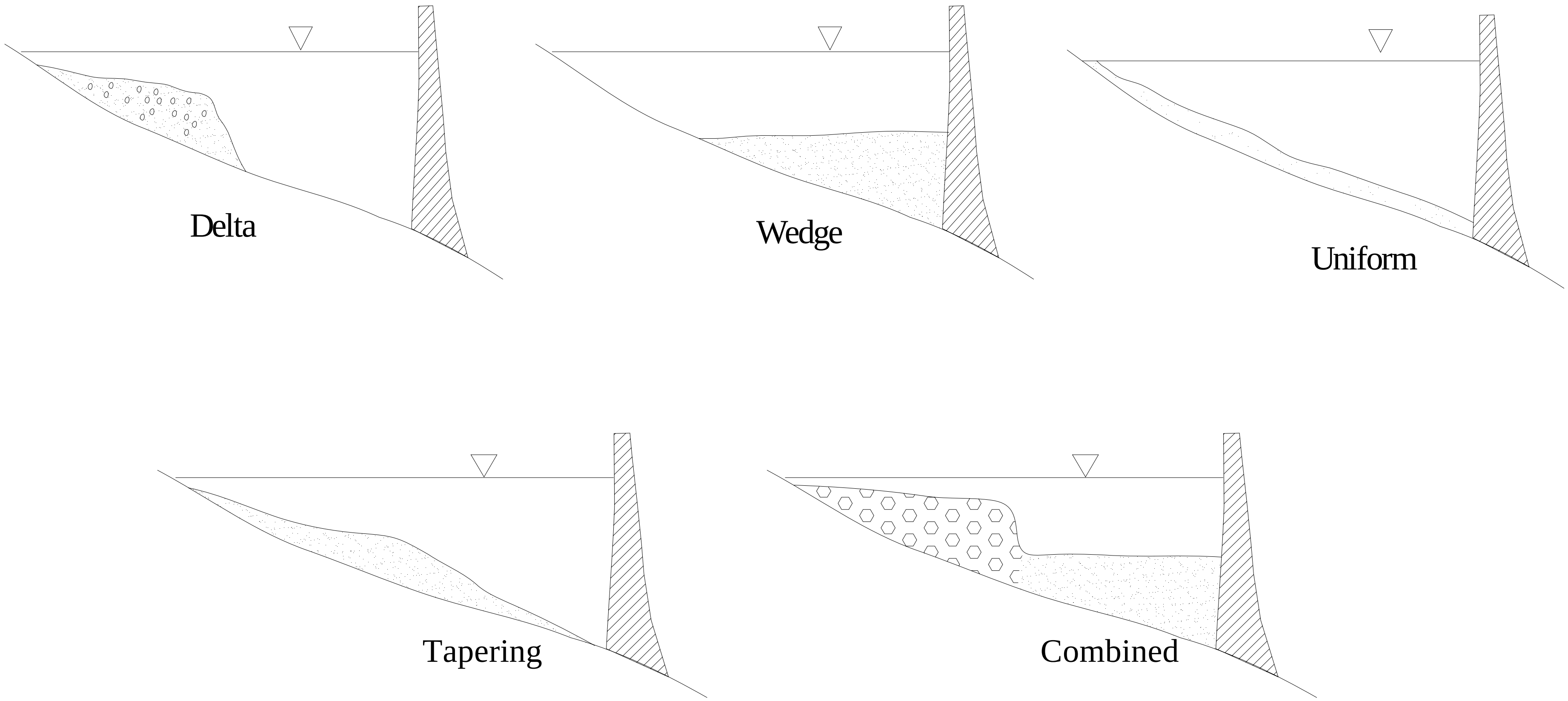
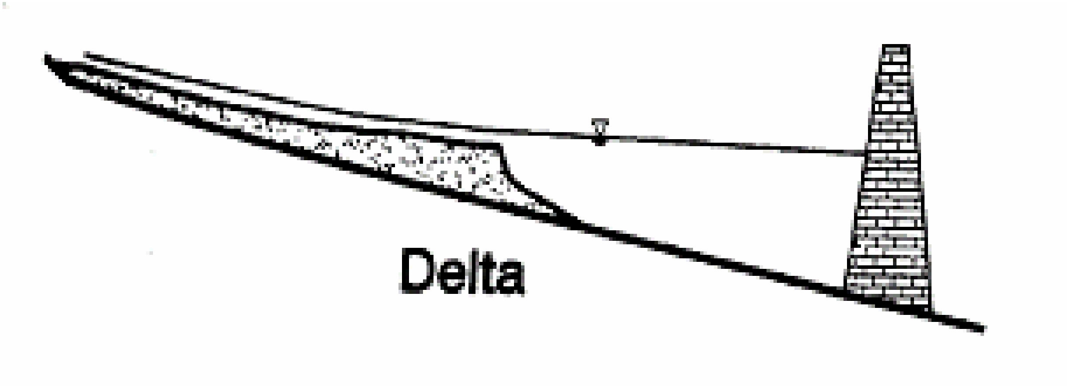


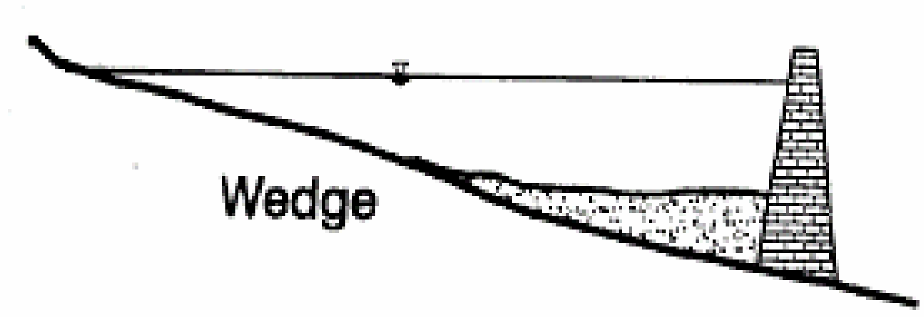
Fig. 7.11 Longintudinal patterns of sediment deposition in reservoir.

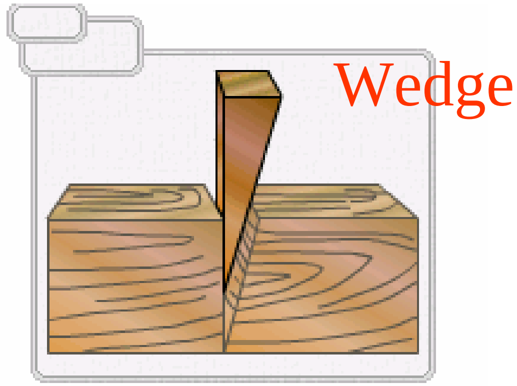
Longitudinal Deposit Geometry



- **Delta deposits** contain the coarsest fraction of the sediment load, which is rapidly deposited at the zone of inflow. It may consist entirely of coarse sediment (d > 0.062 mm) or may also contain a large fraction of finer sediment such as silt.

Longitudinal Deposit Geometry





- **Wedge-shaped deposits** are thickest at the dam and become thinner moving upstream. This pattern is typically caused by the transport of fine sediment to the dam by turbidity currents. Wedge-shaped deposits are also found in small reservoirs with a large inflow of fine sediment, and in large reservoirs operated at low water level during flood events, which causes most sediment to be carried into the vicinity of the dam.

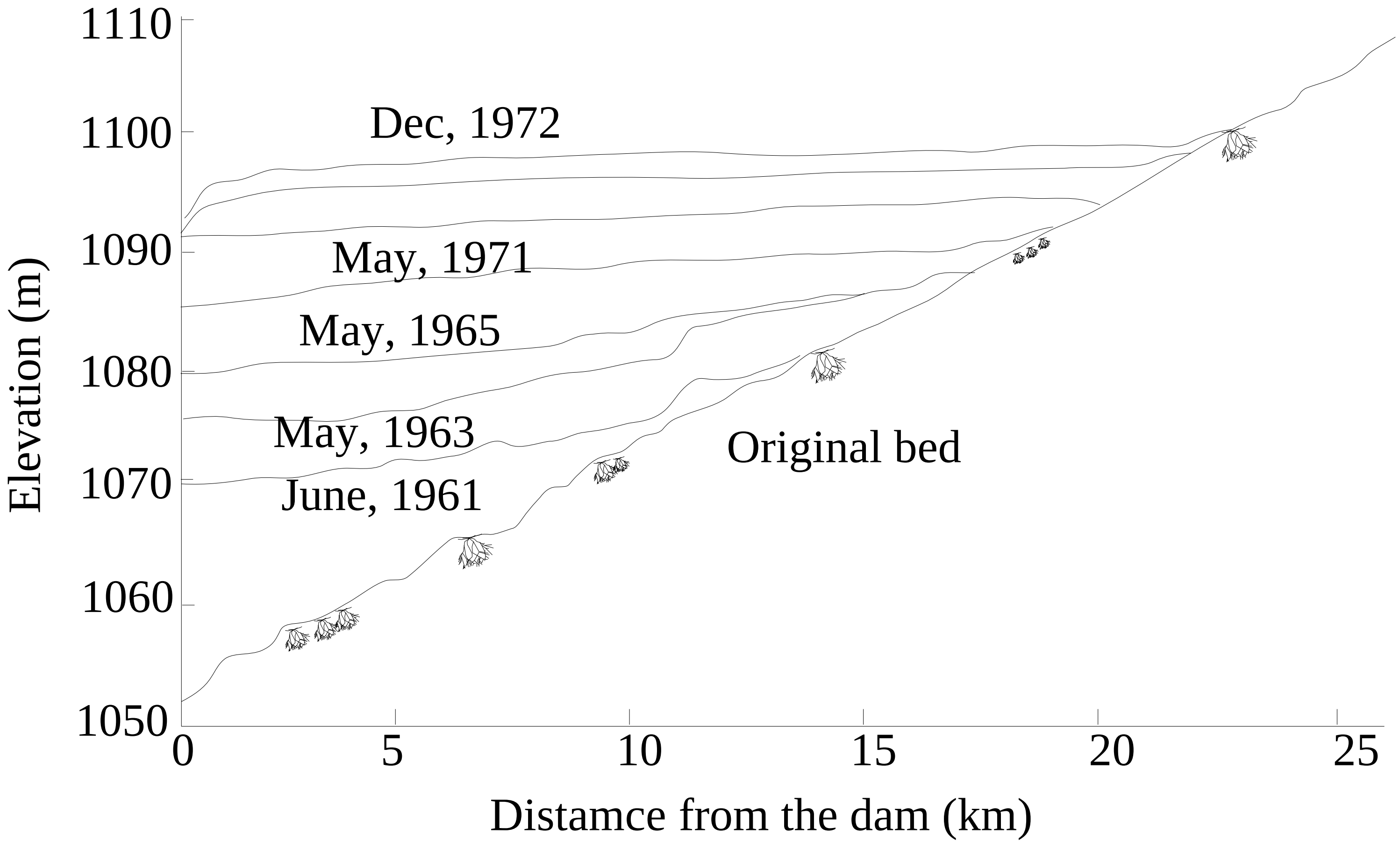
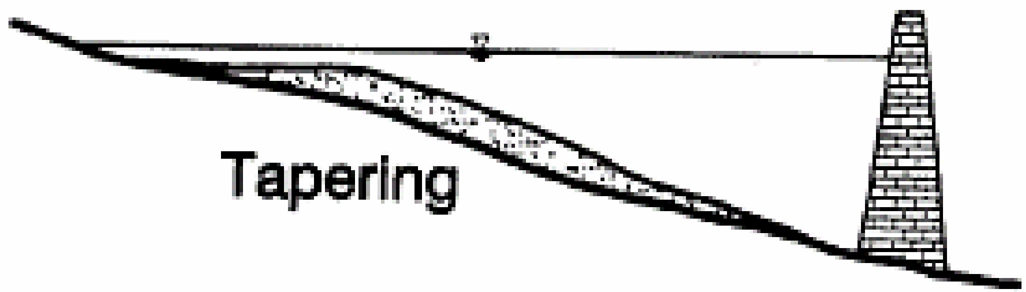


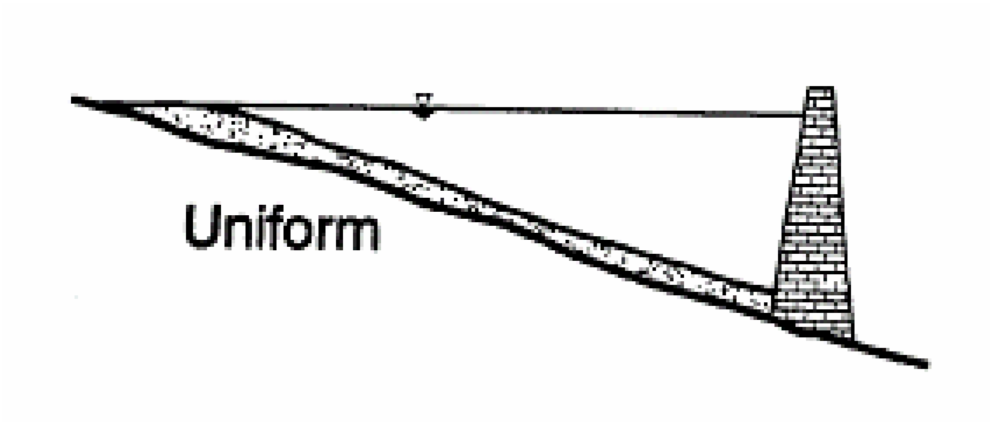
Fig. 7.12 Profile of the Bajiazui Reservoir on the Puhe River showing a wedge shape deposit (after IRTCES, 1985).

Longitudinal Deposit Geometry



- **Tapering deposits** occur when deposits become progressively thinner moving toward the dam. This is a common pattern in long reservoirs normally held at a high pool level, and reflects the progressive deposition of fines from the water moving toward the dam.

Longitudinal Deposit Geometry



- **Uniform deposits** are unusual but do occur. Narrow reservoirs with frequent water level fluctuation and a small load of fine sediment can produce nearly uniform deposition depths.

A general rule the reservoir sedimentation pattern can be predicted with the following formula (IRTCES, 1985):

- V/W > 0.3 Delta pattern
- V/W< 0.3   Wedge shape pattern

- in which V is the storage capacity of the reservoir in (m3) and W is the amount of water flowing into the reservoir during a flood season in (m3).

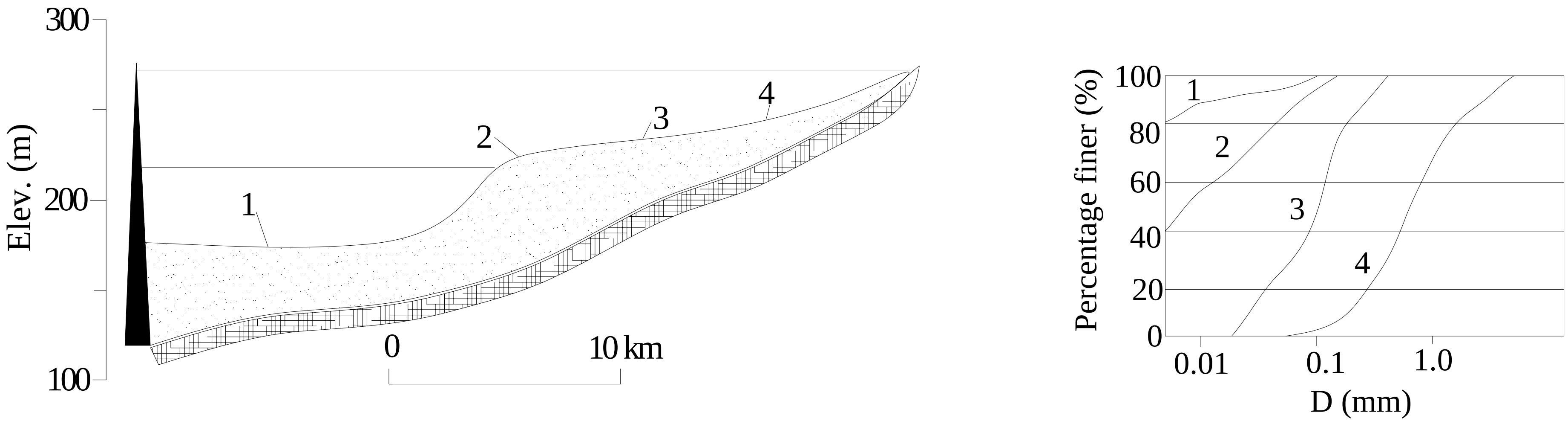
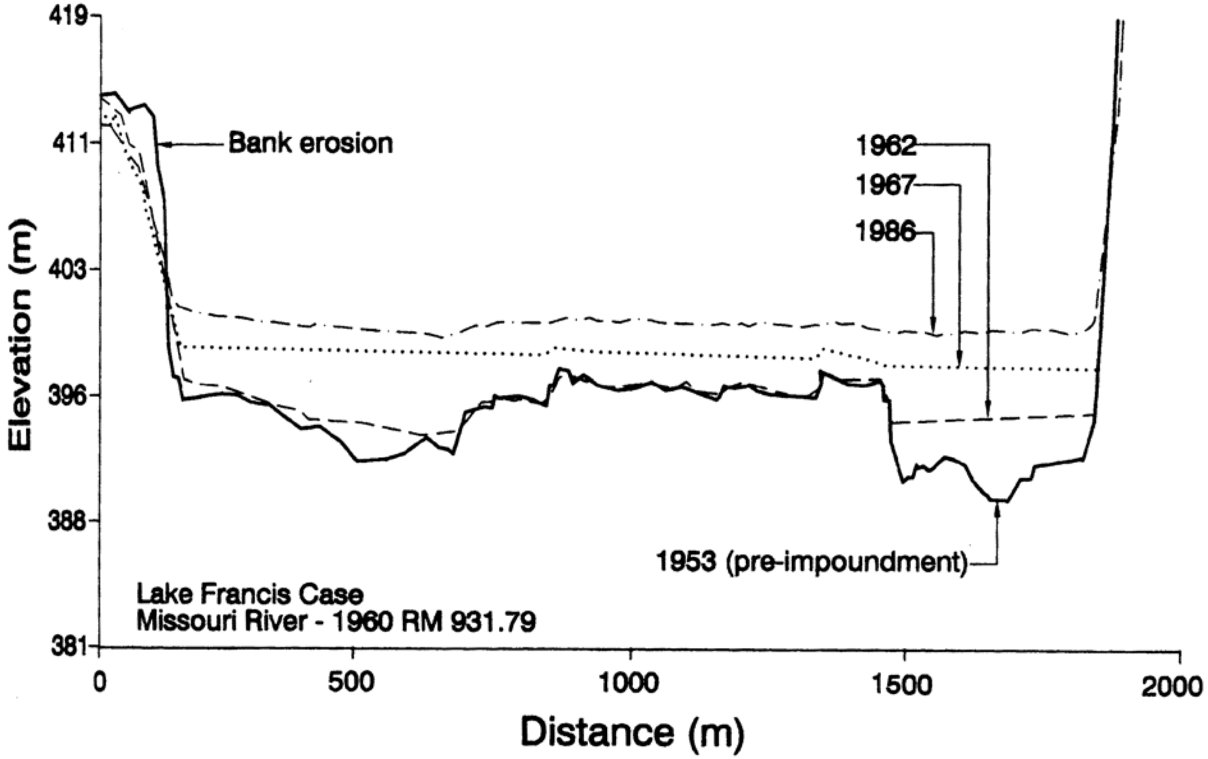


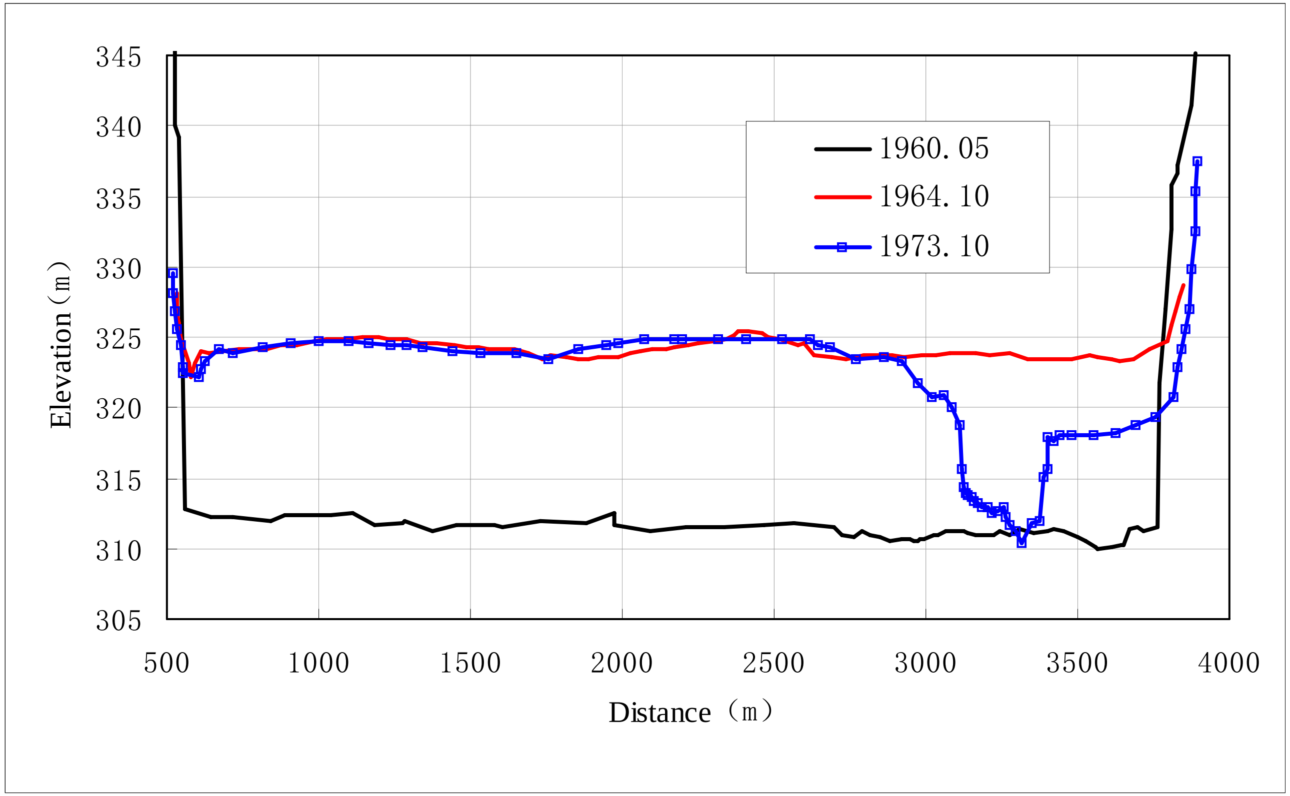
Fig. **7.13** (a) Complex longitudinal profile of the Sakuma Reservoir in Japan (after 24 years of operation); (b). Grain size distributions of deposits at different sites in the reservoir (after Okada Tsuyoshi & Baba Kyohei, 1982)

Lateral Deposition Patterns



- Sediment deposition of Lake Francis Case on the Missouri River. Sediment deposition is initially focused in the deepest part of the reservoir cross section, crating a nearly-horizontal surface regardless of the original cross section shape.

Lateral Deposition Patterns

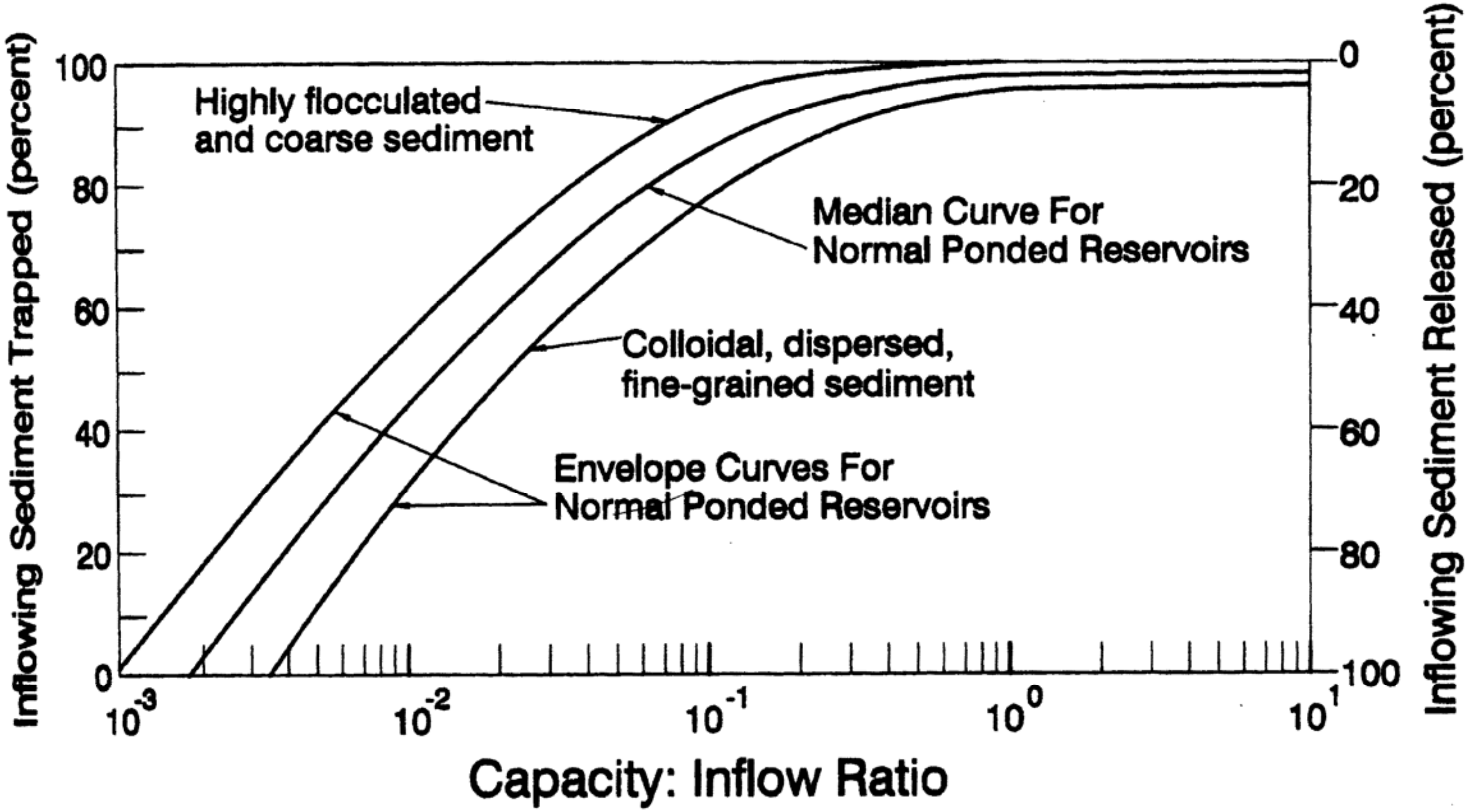


- Sediment deposition of Sanmenxia Reservoir on the Yellow River.
- A narrow channel is formed during scouring of the reservoir.
- 淤积一大片，冲刷一条线。

Reservoir Releasing and Trapping Efficiency

- The sediment release efficiency of a reservoir is the mass ratio of the released sediment to the total sediment inflow over a specified time period. It is the complement of trap efficiency:

  Release efficiency = 1- trap efficiency

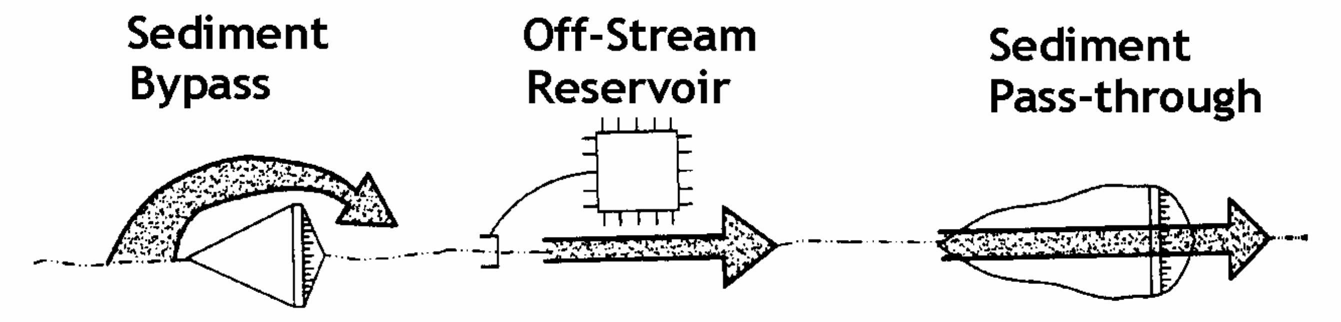


- Brunce (1953) developed an empirical relationship for estimating long-term trap efficiency in normally impounded reservoirs based on the correlation between the capacity to inflow ratio (C:I) and trap efficiency observed in Tennessee Valley Authority reservoirs in the southeastern United States. This is probably the most widely used method for estimating the sediment retention in reservoirs, and gives reasonable results from very limited data: storage volume and average annual inflow.

Management Strategies

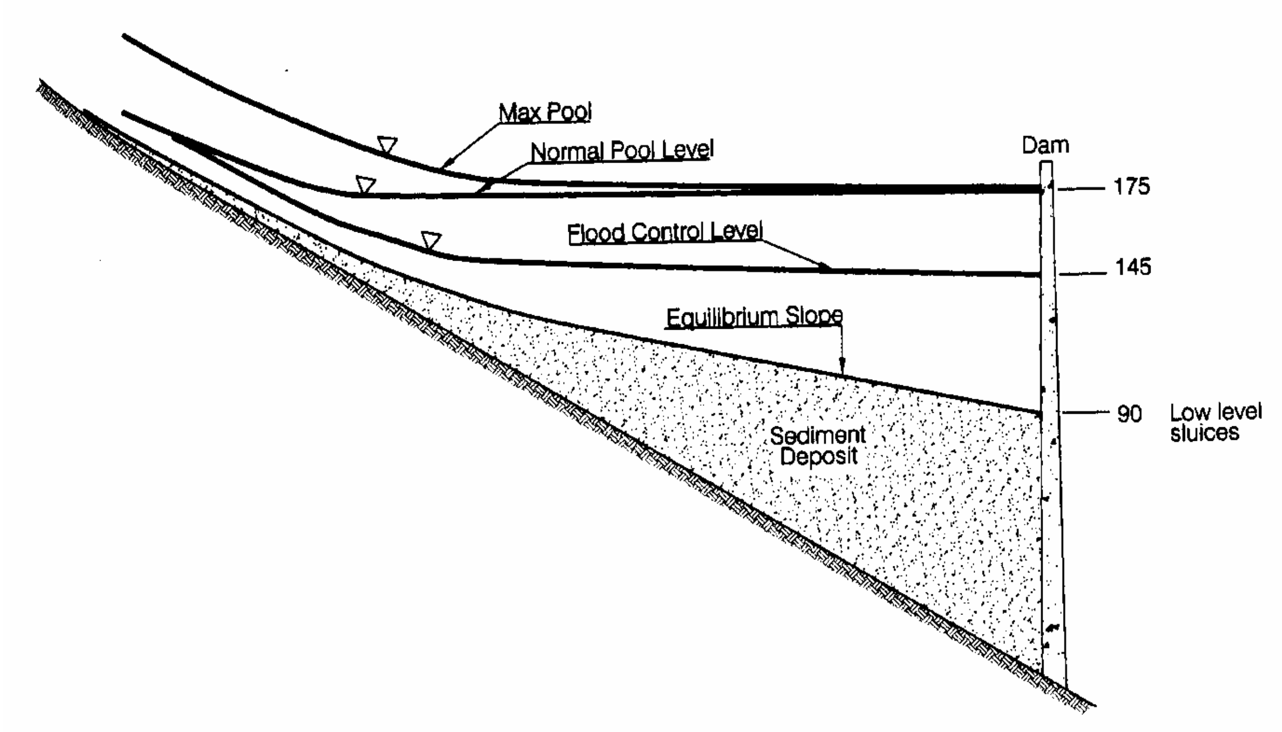
1 .Sediment Routing

- Sediment routing techniques seek to identify the sediment-laden portion of the inflow, and to manage it differently than clear water inflow to prevent, minimize, or focus sediment deposition.
- Sediment routing focuses on either minimize deposition or balancing deposition and scour during flood periods.



- Sediment routing techniques may be classified into the following categories:
  - Sediment bypass
  - Off-stream reservoir
  - Sediment pass-through

Sediment Pass-through By Seasonal Drawdown



Partial drawdown at the Three Gorges Project on the Yangtze River in China

- Under partial drawdown, the reservoir is maintained at a lower pool elevation during the flood season to increase flow velocity and decrease detention time and sediment trapping.
- A flood control and sediment routing level of 145m will be maintained during the wet season and a normal pool level of 175 will be maintained during the remainder of the year to provide increased head for power generation.

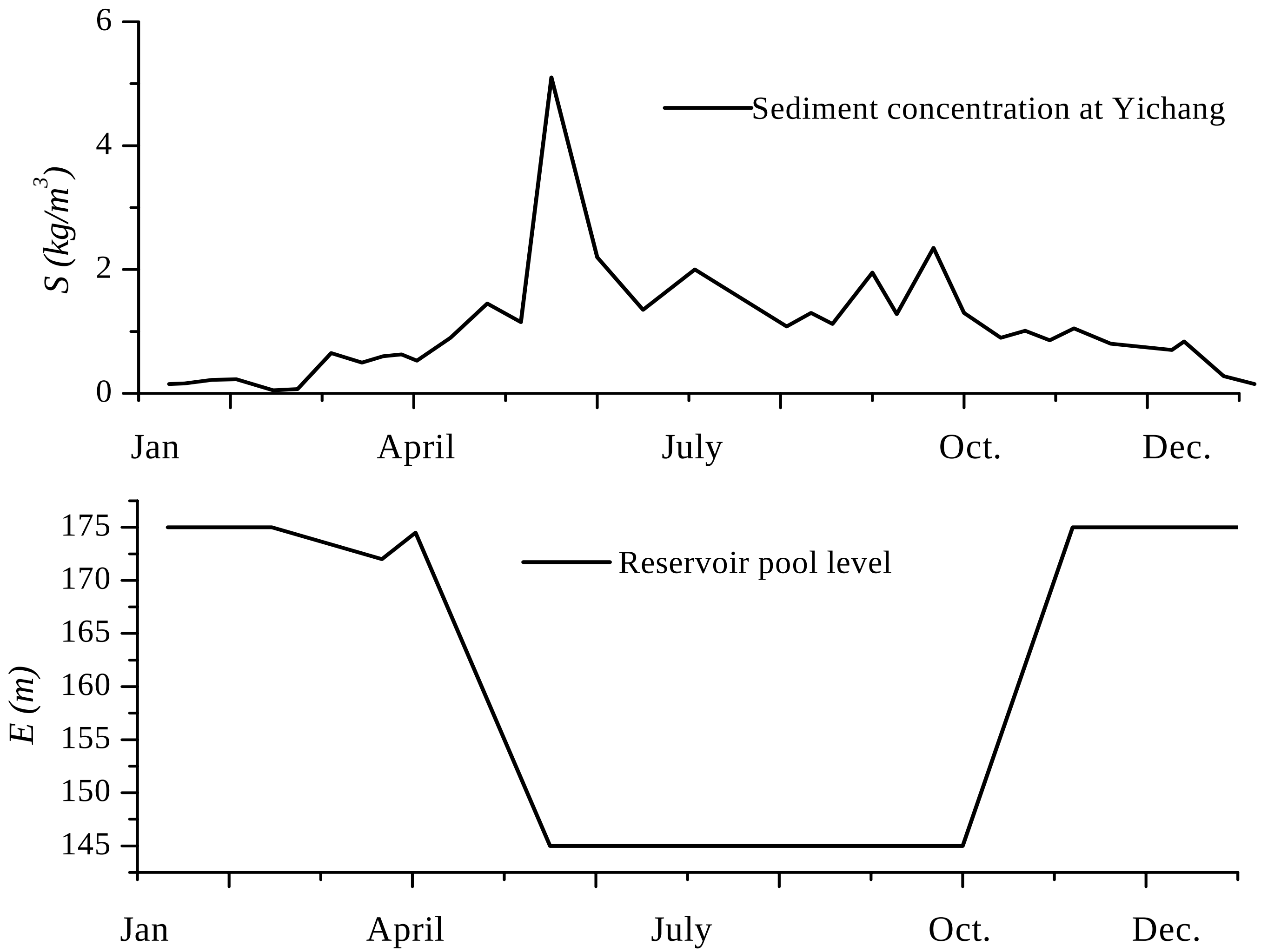
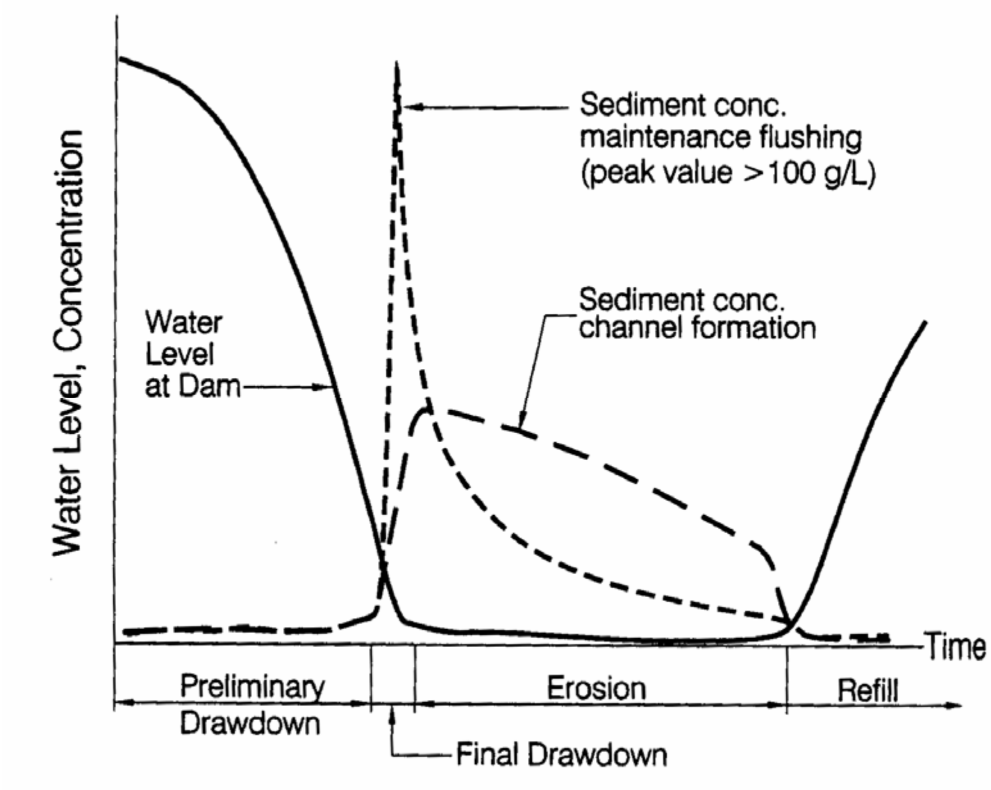


Fig. 7.18 Typical variation process of sediment concentration at the dame site of TGP and the operation scheme of pool level for sedimentation control

2. Drowdown Flushing

- Hydraulic flushing involves reservoir drawdown by opening a low-level outlet to temporarily establish riverine flow along the impounded reach, eroding a channel through the deposits and flushing the eroded sediment through the outlet.
- There two key features that distinguish flushing from sediment routing. Flushing operations:
  - remove previously deposited sediment, and
  - the timewise pattern of sediment release below the dam differs significantly from sediment inflow.

Flushing procedures



- Each flushing event has three distinct stages: drawdown, erosion, and refill.

- A large volume of accumulated sediment will be released during a short period of time, generating extremely high sediment concentrations.

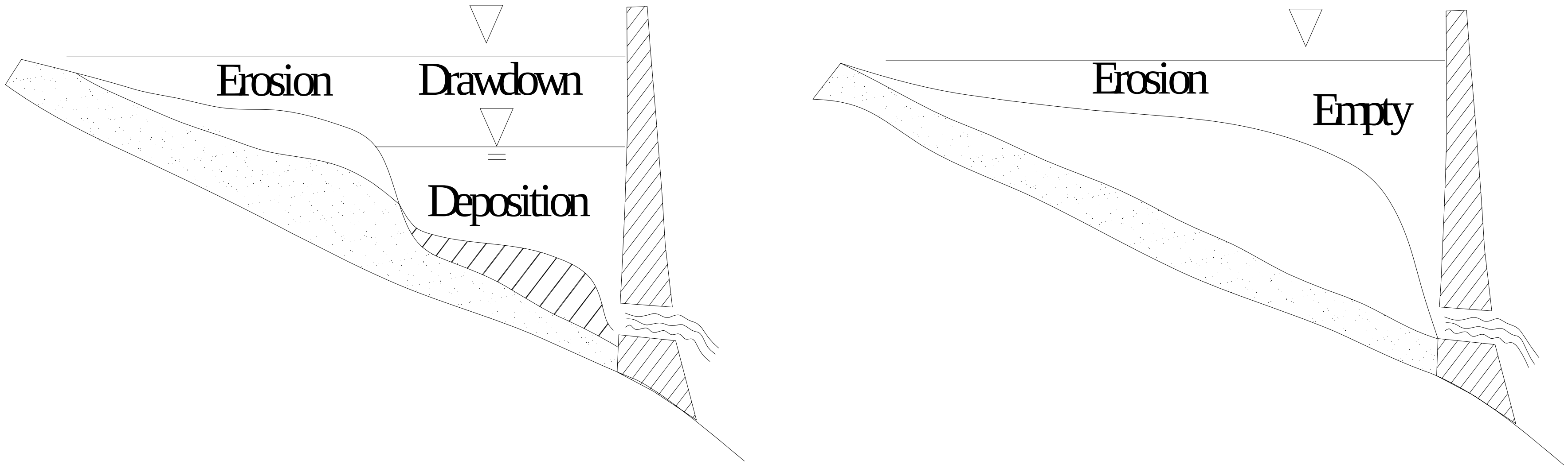
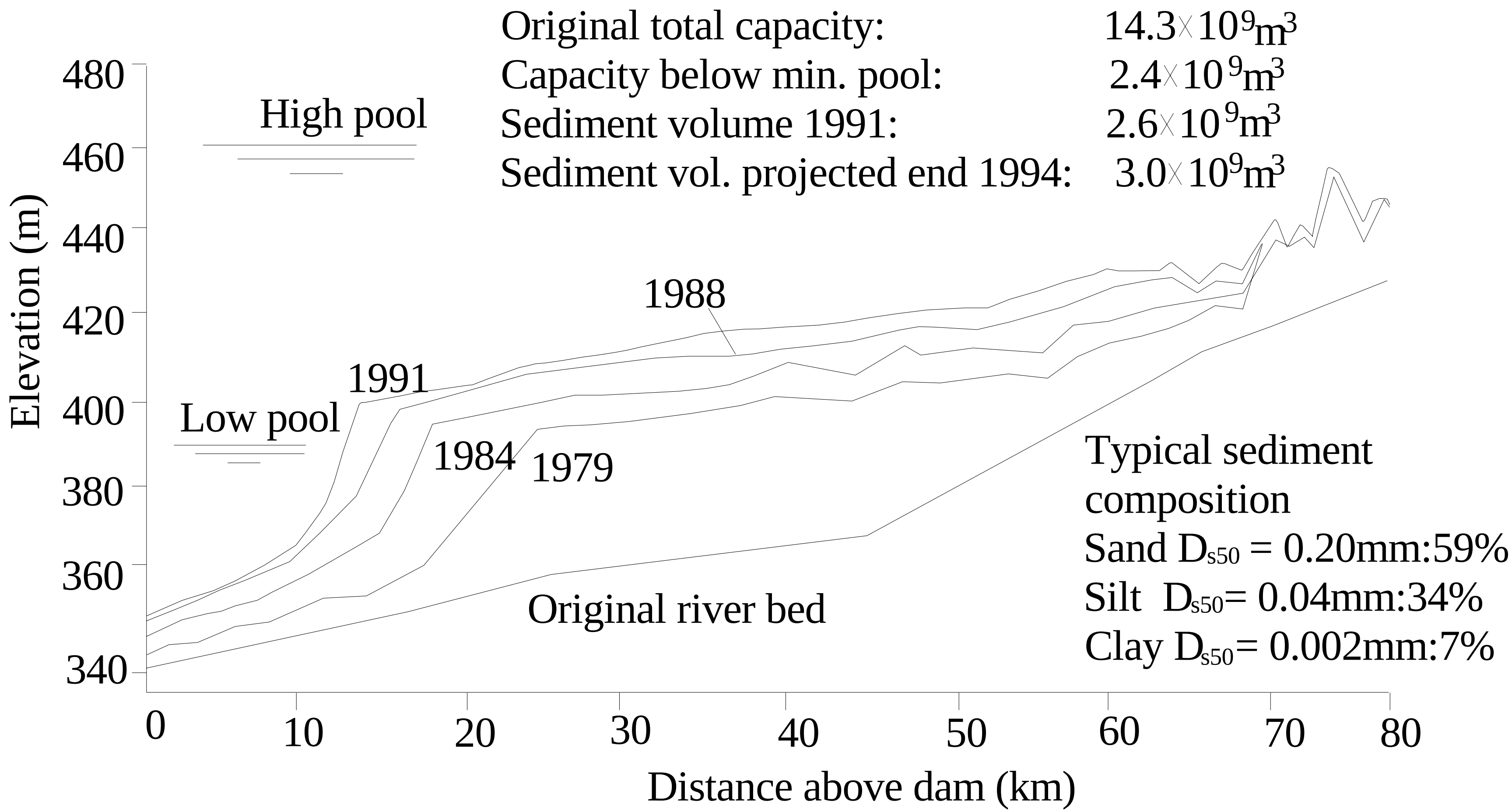


Fig. 7.14 Plan and thalweg profile of flushing operations illustrating longitudinal patterns of sediment redistribution during a flushing event: (a) drawdown flushing causes erosion in the upper part of the reservoir and redeposition near the dam, with pressure flow through the bottom outlets; (b) emptying flushing results in erosion in the whole reservoir, with free flow through bottom outlets



•**Fig. 7.17** Advancement of delta deposits toward Tarbela Dam ,
•Indus River , Pakistan (after Lowe and Fox, 1995)

3. Emplty Flushing

Fig. 7.15 (a) Sefid-Rud Reservoir in Iran is emptied for empty flushing; (after Sharifi Forood & Mohammad Ghafouiri, 2007)

Fig. 7.15 (b) Local people row boats in the fluid mud of the emptied reservoir and capture the fishes (after Sharifi Forood & Mohammad Ghafouiri, 2007)

4) Dredging

- Dredging has for a long time been used for small reservoir sedimentation management. There are different dredging methods in reservoir management, including mechanical dredging and dumping outside of the reservoir and agitating with jets and transporting with current to the downstream of the reservoir.
- Various dredgers have been used: dredge boat; agitating dredger; dipper dredger; hauling scraper; excavator and bulldozer; and trailer dredger.

Jet ship used for sediment flushing

A close look of the jet ship

A close look of the jet ship

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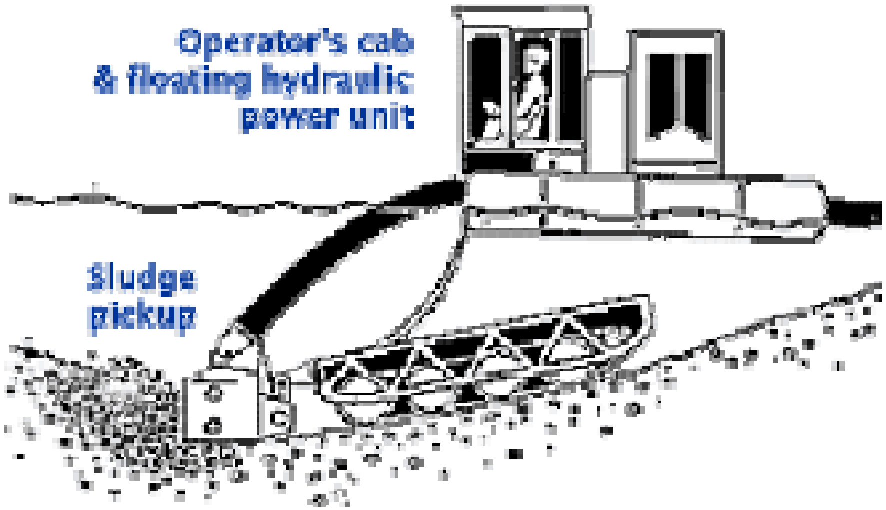
- Sediments are fed into a dredge pump by means of adjustable 8-foot helical augers equipped with cutter blades to break up solids. The slurry can then be pumped up to 2,500 feet away into a pre-designated spoil area.



5. Density currents

- A density current is a relative motion that takes place in the reservoirs between two fluid layers that have slightly different densities.
- The density flows occurred in reservoirs generally involve only slight differences in the densities of the upper and lower layers.

Since the density difference is small, the reservoir water creates a large buoyancy effect within the inflow liquid, so that the effective gravity of the flowing liquid is greatly reduced. Usually g' is defined as effective gravity given by:

$$g' = g\frac{\Delta\rho}{\rho}$$

in which $\Delta\rho$ is the density difference between the upper and lower liquids. Many formulas describing open-channel flow apply also to density currents once g is replaced by g'. In a density current, the Froude number remains the key parameter but its form is modified (Qian et al., 1998):

$$Fr' = \frac{U_c}{\sqrt{g'h'}}$$

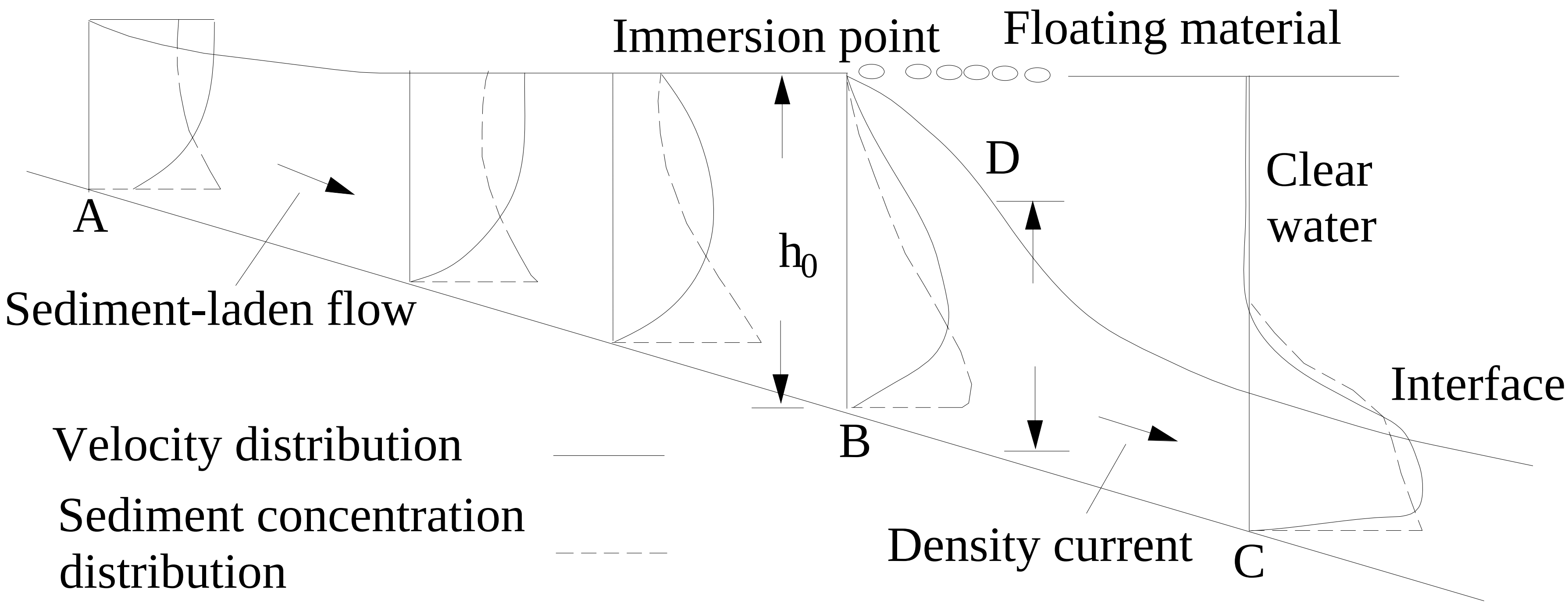


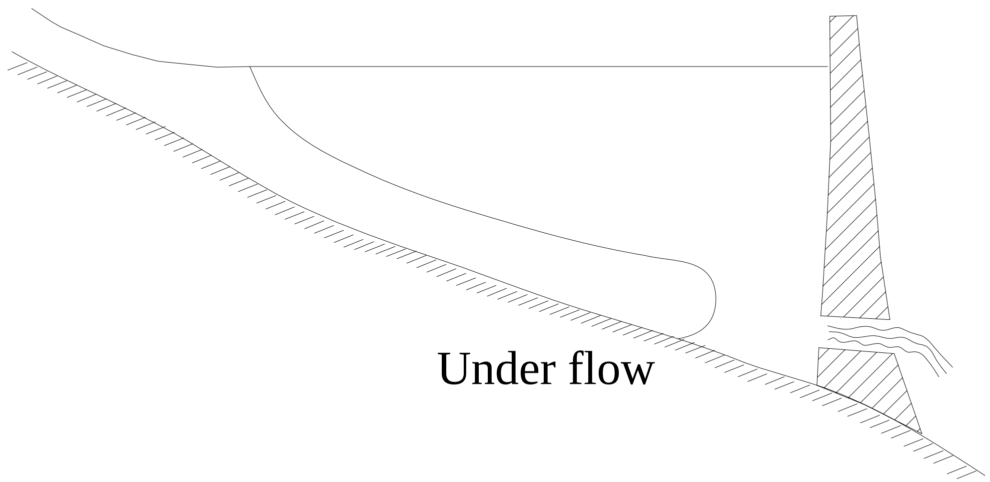
Fig. 7.19 Velocity and sediment concentration profiles varying along the reservoir during the transition from an open-channel flow to a density current (after Qian et al., 1998)

Data from both flume experiments and field observations show that the critical condition for the formation of a density current is (Fan, 1959):

$$\frac{q^2}{\frac{\Delta\rho}{\rho'} g h_0^3} = 0.6$$

in which q is the discharge per unit width and h_0 is the depth at the immersion point.

From the above equation, if the water level upstream of the dam remains constant, an increase of the inflow discharge would cause the immersion point to move downstream; an increase in the density difference between the inflow and the reservoir water would cause the point to move upstream.



Density current may pass through the reservoir, without ever completely mixing with the epilimnial or hypolimnial waters, and flows out of the reservoir if the bottom outlets are open.

Maintaining a density flow needs a continuous supply of inflow sediment suspension and a force to overcome any resistance it encounters. If the inflow ceases to supply dense fluid so that it no longer forms a density current at the immersion point, the already formed density current downstream would soon stop moving