Reservoir Sedimentation and Its Control

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International Workshop on Management of Flood Control and Disaster Mitigation
June 17-30 2010, Beijing, China
Why need reservoirs? Functions
Reservoir sedimentation & its control
Sedimentation and dam design
Typical cases—arrangement of structures
Summary
Why do we need reservoirs? Because ……

Functions: Flood Control, Irrigation, Water Supply, Hydropower, Navigation, Recreation etc.

Source: Adapted from ICOLD 1998

Distribution of existing large dams by region and purpose
The total number of reservoirs with dam height over 15m is 49697. They are distributed in over 140 countries. The total water storage capacity is 18640.6 GM³ and the total hydropower installation is 728.5 GW.
Why need reservoirs? Functions

Number of dams in top 20 countries (height over 15m)
# Why need reservoirs? Functions

## The four biggest hydropower installation countries (GW)

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>82.7</td>
</tr>
<tr>
<td>USA</td>
<td>75.5</td>
</tr>
<tr>
<td>Brazil</td>
<td>67.1</td>
</tr>
<tr>
<td>Canada</td>
<td>64.0</td>
</tr>
</tbody>
</table>

## The four biggest hydropower generation countries by 2002 (TWh)

<table>
<thead>
<tr>
<th>Country</th>
<th>Generation (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>353</td>
</tr>
<tr>
<td>USA</td>
<td>308.8</td>
</tr>
<tr>
<td>Brazil</td>
<td>300</td>
</tr>
<tr>
<td>China</td>
<td>280</td>
</tr>
</tbody>
</table>
Why need reservoirs? Functions

The six biggest water storage capacity reservoirs (GM³)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reservoir Name</th>
<th>River</th>
<th>Water storage capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>Bratskoye Reservoir</td>
<td>The Angara River</td>
<td>169.3</td>
</tr>
<tr>
<td>Egypt and Sudan</td>
<td>Aswan High Dam Reservoir</td>
<td>The Nile River</td>
<td>162</td>
</tr>
<tr>
<td>Zambia and Zimbabwe</td>
<td>Lake Kariba</td>
<td>The Zambezi River</td>
<td>160</td>
</tr>
<tr>
<td>Ghana</td>
<td>Volta Lake</td>
<td>The River Volta</td>
<td>148</td>
</tr>
<tr>
<td>Canada</td>
<td>Manicouagan Reservoir</td>
<td>Manicouagan River</td>
<td>142</td>
</tr>
<tr>
<td>Venezuela</td>
<td>Guri Reservoir</td>
<td>Caroni River</td>
<td>135.7</td>
</tr>
</tbody>
</table>

(Source: http://www.ilec.or.jp/database/index/idx-lakes.html)
## Why need reservoirs? Functions

The highest dams for various styles in the world (m)

<table>
<thead>
<tr>
<th>Country</th>
<th>Dam Style</th>
<th>Height (existing)</th>
<th>Under construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>Concrete gravity dam</td>
<td>285</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>Arched concrete dam</td>
<td>271.5</td>
<td>292 (China)</td>
</tr>
<tr>
<td>Russia</td>
<td>Earth rock dam</td>
<td>335</td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>Concrete gravity arch dam</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>concrete-faced rockfill dam</td>
<td>187</td>
<td>233(China)</td>
</tr>
<tr>
<td>Colombia</td>
<td>RCC Gravity Dam</td>
<td>188</td>
<td>216(China)</td>
</tr>
<tr>
<td>Canada</td>
<td>Concrete buttressed dam</td>
<td>214</td>
<td></td>
</tr>
</tbody>
</table>
### The world’s 8 greatest Hydropower Stations:

<table>
<thead>
<tr>
<th>Country</th>
<th>Hydropower Stations</th>
<th>River</th>
<th>Total installed capacity (MW)</th>
<th>Elect. generation (Twh /year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Three Gorges</td>
<td>Yangtze River</td>
<td>18200/22400</td>
<td>84.68/104</td>
</tr>
<tr>
<td>Brazil and Paraguay</td>
<td>Itaipu</td>
<td>Parana River</td>
<td>12600</td>
<td>71</td>
</tr>
<tr>
<td>USA</td>
<td>Grand Coulee</td>
<td>Columbia River</td>
<td>10830</td>
<td>20.3 (initial stage)</td>
</tr>
<tr>
<td>Venezuela</td>
<td>Guri</td>
<td>Caroni River</td>
<td>10300</td>
<td>51</td>
</tr>
<tr>
<td>Brazil</td>
<td>Tucurui</td>
<td>Tocantins River</td>
<td>8000</td>
<td>32.4 (initial stage)</td>
</tr>
<tr>
<td>Canada</td>
<td>La Grande Stage II</td>
<td>La Grande River</td>
<td>7326</td>
<td>35.8</td>
</tr>
<tr>
<td>Russia</td>
<td>Sayano-Shushensk</td>
<td>Yenesei River</td>
<td>6400</td>
<td>23.7</td>
</tr>
<tr>
<td>Russia</td>
<td>Krasnoyarsk</td>
<td>Yenesei River</td>
<td>6000</td>
<td>20.4</td>
</tr>
</tbody>
</table>

### Why need reservoirs? Functions
Why need reservoirs? Functions

Current exploitation degree of the world

- Over 60%, France, Switzerland, USA, Canada
- In developing countries, the exploitation degree is relatively lower.

<table>
<thead>
<tr>
<th>Country</th>
<th>Actual as % of economic potential</th>
<th>Hydro as % of total electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Switzerland</td>
<td>91</td>
<td>80</td>
</tr>
<tr>
<td>United States</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>Canada</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td>Norway</td>
<td>56</td>
<td>100</td>
</tr>
<tr>
<td>Brazil</td>
<td>33</td>
<td>91.7</td>
</tr>
<tr>
<td>India</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>Indonesia</td>
<td>32</td>
<td>14</td>
</tr>
<tr>
<td>China</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>World total</td>
<td>36</td>
<td>&lt;19</td>
</tr>
</tbody>
</table>

Sources: World Energy Conference, UN, MIT Energy Lab, Paul Scherrer Institute
Why need reservoirs? Functions

- **Hydropower advantage—Energy:**
  - World-wide, about 20% of electricity generated by hydropower
  - Norway produces more than 99% of its electricity with hydropower; Brazil, New Zealand and Canada use hydropower for over 60% of their electricity
  - Long lifetime, 50 plus years
  - Usable for base load, peaking, and pumped storage applications
Hydropower advantage—Low cost:

- Low operating and maintenance costs
- The cost of hydropower per kwh is about 50% the cost of the nuclear, 40% the cost of fossil fuel, and 25% the cost of natural gas.

Why need reservoirs? Functions

Average Power Production Expense per KWh

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Maintenance</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil-Fueled Steam</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Gas Turbine</td>
<td>3.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Why need reservoirs? Functions

- **Hydropower advantage——Environment:**
  - Hydropower is clean and leaves behind no waste.
  - Hydropower is one of the electricity sources that generate the fewest greenhouse gases, i.e. 60 times less than coal-fired power plants and 18 times less than natural gas power plant.
  - Real low carbon energy.
Why need reservoirs? Functions

- Hydropower advantage—Renewable: Hydropower is the leading source of renewable energy. It provides more than 97% of all electricity generated by renewable sources.

- Recreation: Reservoirs formed by dams provide many water-based recreational opportunities including fishing, water sports, boating, and water fowl hunting.
Why need reservoirs? Functions

- Land use—inundation and displacement of people
- Impacts on biodiversity
  - aquatic ecology, fish, plants, mammals
- Water chemistry changes
  - mercury, nitrates, oxygen
  - bacterial and viral infections
- Safety
  - seismic risks
  - structural dam failure risks
- Impacts on natural hydrology
  - increase evaporative losses
  - altering river flows and natural flooding cycles
  - sedimentation in reservoir and erosion downstream
Reservoirs built in the upper and middle parts of a river basin can be used for multiple purposes.

However, along with the impoundment of water in the reservoir, the cross-sectional flow velocity will dramatically decrease and the sediment-carrying capacity of the flow becomes very weak.

Therefore large quantity of sediment deposits in the reservoir. The continuous sedimentation in the reservoir will greatly reduce the storage capacity, function, and life span of the reservoir.
Delta Sedimentation

- Formation Reasons: usually occurs in the reservoir with relatively stable and high operational water level, as well as a long backwater area.
- Characteristics: consists of two parts: delta body and delta front.

Reservoir Sedimentation & Its Control
Sedimentation Profiles

- Conical Sedimentation
  - Formation Reasons: small-sized reservoir, low operational water level, short back water area, hyper-concentrated flow, and very fine suspended sediment.
  - Characteristics: gradually increase of the sedimentation thickness along the longitudinal channel bed.
Reservoir Sedimentation & Its Control

**Sedimentation Profiles**

- **Banded Sedimentation**
  - Formation Reasons: big variation of operational water level, long variable back water zone, the dual characteristics of river and reservoir in the variable backwater zone.
  - Characteristics: nearly uniform thickness of sedimentation along the longitudinal channel bed.
In China, according to the statistics of 43 reservoirs in Shanxi Province in 1974, 31.5% of the initial volume has been lost, the annual capacity lost is 50 million m$^3$. Data from 192 reservoirs with the volume over 1 million m$^3$ in Shaanxi Province in 1973 also show that 31.6% of the total volume 1.5 billion m$^3$ has been lost.

In Japan, up to 1979, from statistics on 425 reservoirs with a combined capacity exceeding 1 million m$^3$, 6.3% of the reservoir capacity had been lost due to deposition.
In India, according to statistics presented in 1969, the annual rate of loss of reservoir capacity was 0.5-1.0 % for 21 reservoirs with a combined capacity greater than 1.1 billion m$^3$.

In Russia, in the Middle Asian Region, the life span of reservoirs with dam height lower than 6m is 1~3 years; the life span of reservoir with dam height 7~30m is 3~13 years.

In the United States, the total annual amount of deposition in reservoirs had reached 1.2 billion m$^3$. 
Negative Effects by Reservoir Sedimentation

- Decrease both the flood-control storage and the live storage of a reservoir. Affect the efficiency of flood control, electricity generation, navigation, irrigation and fishery.

- The decrease of the longitudinal slope results in the rising of water level in the upper reach and deposition extension headwater. As a result, nearby cities, factories, mines, and farm land have to face the threatening of flooding.

- The deposition extension headwater may also result in the rising of ground water, salinization of top-layer soil, and deterioration of eco-environment.
Reservoir Sedimentation & Its Control

◆ Negative Effects by Reservoir Sedimentation

- Negative effects on the navigation channel in the movable backwater reach.
- Sedimentation in the front area of the dam may affect the safe operation of the hydraulic project, including ship locks, navigation channel, the entrance of turbines, the entrance of water diversion intakes, the erosion of turbine blades, etc.
- Pollutants attached in the surface of sediments may affect the water quality of the reservoir.
- Clear water released from the reservoir may cause severe erosion downstream and affect the channel stability and the applicability of existing hydraulic projects such as water diversion intakes.
Reservoir Sedimentation & Its Control

◆ Negative Effects by Reservoir Sedimentation

➢ Statistic data (Mahmood 1987) show that the mean life span of reservoirs in the world is about 22 years due to the sedimentation.
➢ Reservoir sedimentation is very important to reservoirs. To some extent, the reservoir life span is not determined by the dam construction quality, but by the reservoir sedimentation.
Control of Reservoir Sedimentation

- Using water and soil conservation and check dams to decrease sediment yield, to reduce sediment entering the channel, and finally to alleviate reservoir sedimentation.
Control of Reservoir Sedimentation

- Using the operation of storing clean water and discharging muddy flow to mitigate reservoir sedimentation. Low water levels are used during flood seasons to discharge more sediment, and high water levels can be operated during dry seasons.
Control of Reservoir Sedimentation

- **Using density flow to discharge sediment.** When the density flow happens, the sediment flushing gate should be lifted to let the density flow with high sediment concentration go through the dam.
Ungated operation (empty reservoir). When the sedimentation in a reservoir is very serious, an ungated operation can be used to flush a large quantity of sediment to the downstream. This operation has an obvious effect to restore storage capacity.

Using big flood to flush sediment. Usually big floods carry large quantity of sediment. Therefore, according to hydrological forecast, lowering the operation water level in advance can discharge the heavy sediment load out and efficiently alleviate sedimentation in the reservoir.
Control of Reservoir Sedimentation

Using by-pass channel to flush sediment. For some middle/small size reservoirs, by-pass channels are used to discharge floods with heavy sediment load.
Control of Reservoir Sedimentation

Using high floodplain channel to wash floodplain surface. A low dam is constructed in the upper reach to divert flow to channels on the high floodplain. Then hydraulic erosion and gravity erosion formed by the steep between high floodplain and main channel are used to break up and transport sediment on the surface of the slope. Thereby the purpose of cleaning out sediment can be achieved.

(a) Plan view

(b) I-I Cross section

1—Diversion dam, 2—diversion channel on the high floodplain
3—steep channel from floodplain to main channel, 4—main channel
Control of Reservoir Sedimentation

- **Mechanical cleaning and dredging.** For large scale reservoirs, mechanical cleaning devices such as dredge boats are used to locally dredge sedimentation. For middle/small scale reservoirs, small-size power machines are used to clean deposition, such as air-driven pumps and hydraulic dredgers.
Sedimentation and Dam Design

The relation between reservoir sedimentation and dam design exhibits in the following aspects.

- **Silt pressure.** With development of sedimentation on the upstream face of the dam, the silt pressure will become an important external force acting on the dam.
- **Turbine abrasion.** When the sedimentation body reaches the dam site, sediment particles going through the power intakes may cause severe abrasion of turbine blades.
Sedimentation and Dam Design

The relation between reservoir sedimentation and dam design exhibits in the following aspects.

- **Erosion of hydraulic structures.** Hydraulic structures such as spillways, flow or sediment flushing outlets may be badly eroded by sediment particles.

- **Sedimentation processes and distribution.** The flow discharging capacity of hydraulic structures will affect not only the progress of reservoir sedimentation, but the sedimentation distribution in the dam area as well.
Sedimentation and Dam Design

◆ Silt Pressure

- The principal external force to be resisted by the dam is water pressure. However, with development of sedimentation on the upstream face of the dam, the silt pressure will become an important external force acting on the dam, even greater than the hydrostatic pressure. In this case, for the sake of dam safety, the silt pressure and vertical weight should be estimated.

- To estimate sediment load on the dam, the equilibrium (final) sedimentation level in front of the dam and the distribution of silt pressure in the upstream face of the dam should be known.
Sedimentation and Dam Design

◆ Silt Pressure

- To know the final sedimentation level, a **numerical model** to simulate the development of reservoir sedimentation and a **physical model** to simulate the sedimentation distribution in the front area of the dam **should be needed**.

- Generally, the silt load develops slowly upon the dam face. As a result, the silt settlement tends to consolidate and partially support itself in the reservoir. For most small gravity and arch dams, the silt load is not usually important. However, for buttress dams with slopping face, this accumulated silt may increase pressures significantly.
Sedimentation and Dam Design

◆ Sediment flushing sluices

Sediment entering turbines results in a serious abrasion of blades. The degree of abrasion is related to both sediment concentration and particle size.

- The higher the concentration, the more severe the turbine abrasion.
- Turbine abrasion is not obvious, if sediment size < 0.05mm.
- Turbine abrasion becomes more serious with the increase of sediment size if the size is between 0.05mm to 0.5mm.
- The degree of blade abrasion will not increase much with increase of sediment size when the size exceeds 0.5mm.
- The degree of turbine erosion is also affected by the mineral composition of sediment.
Sediment flushing sluices

To control the abrasion of turbines, sediment flushing sluices should be constructed to lower sediment concentration as well as sediment size going through the turbines.

- If the power station locates in a bend reach, the headrace of turbines should be put in the outer bank to mitigate the bed load entering the turbine tunnel by using the principle of circulation flow in the bend channel.
- The top layer water is diverted by power intakes for electricity generation, and the bottom flow is used to flush sediment and density flow. By doing this, sediment flushing sluices or deep outlets should be built under the power inlets.
Sedimentation and Dam Design

◆ Sediment flushing sluices

- When the reservoir sedimentation nearly reaches the equilibrium state, the sediment flushing outlets can discharge bed load and coarse sediment to avoid the turbine abrasion. For this case, the discharging capacity of the sluices is not important, but the sluices should be located in the main band of bed load movement.

- For low hydraulic head projects, it may be difficult to build flushing sluices under the power intakes. In this case, sediment-guiding wall or settling basin should be considered to divert bed load and coarse sediment to other flow discharge structures.
Sediment flushing sluices

The use of sediment flushing sluices can form an erosion funnel in front of power intakes. When floods come, they can discharge hyper-concentrated flow and coarse sediment. When the sluices are closed during low flow periods, the erosion funnel can be used to store coarse sediment to decrease sediment concentration and size going through the turbines.
Sedimentation and Dam Design

- Sediment flushing sluices

- For small rivers, the discharging capacity of sluices should be greater than the average discharge in flood seasons.
- For big rivers, the main function of flushing sluices is to reduce sediment through turbines and to maintain a stable erosion funnel.
- If flushing sluices are mainly used to reduce bed load and coarse sediment through turbines, they should be located in the main band of bed load.
Sedimentation and Dam Design

 Sufficient discharge capacity

➢ For any dams, to alleviate severe reservoir sedimentation during flood seasons, sufficient discharge capacity of hydraulic structures at a certain water level should be considered in order to avoid the detention of floods.

➢ Sufficient discharge capacity of hydraulic structures is one of pre-conditions to use the operation mode ‘storing clear water and discharging muddy flow’, which is an efficient way to alleviate reservoir sedimentation.
Sedimentation and Dam Design

- **Sufficient discharge capacity**

  - In flood seasons, the water level is generally lower than the normal storage water level. To avoid severe sedimentation due to detention of flood, the discharge capacity of hydraulic structures should be as big as 2% to 5% of frequency floods.

  - For the period of dead water level operation, the discharge capacity of hydraulic structures should be bigger than the bank-full discharge (1.2 to 1.5 times) of the natural river (before dam construction) to form a new equilibrium river in the reservoir area.
Sedimentation and Dam Design

- Sufficient discharge capacity

- For the highest water level, the discharge capacity should be meet two basic requirements: (1) to be equal to or bigger than the design flood discharge, (2) to empty the reservoir within a required time in emergency.

- For the dam with ship locks, to avoid sedimentation in ship locks, the so-called transferring ships in still water and flushing sediment with moving flow should be used.
Sufficient discharge capacity

Four pre-conditions to use the operation mode ‘storing clear water and discharge muddy flow’.
(1) Flood and sediment concentrate in flood seasons;
(2) Sufficient incoming runoff after flood season;
(3) River-shape reservoir, not lake-shape reservoir;
(4) Hydraulic structures have sufficient discharge capacity at the low level during flood seasons.
Typical cases—arrangement of structures

Three Gorges Dam Reservoir

The Three Gorges Dam is a large hydraulic project on the Yangtze River for multi-purposes of flood control, power generation and navigation.

- Crest elevation: 185m
- Maximum height: 181m
- Length: 2309m
- Total storage capacity: 39.3bm³
- Storage for flood control: 22.2bm³
- Power units: 26
- Total installed capacity: 18200MW
- Annual electricity: 84.68TWh.
- Start operation: Jun. 2003
- Construction completion: 2009
The Three Gorges Dam comprises three parts: the dam, the power station and the navigation facility.
**Typical cases—arrangement of structures**

**Three Gorges Dam Reservoir**

**Hydraulic structures**

<table>
<thead>
<tr>
<th>Hydraulic structure</th>
<th>Number</th>
<th>Elevation (m)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crest outlets</td>
<td>22</td>
<td>158</td>
<td>Discharge flow</td>
</tr>
<tr>
<td>Floating outlets</td>
<td>2</td>
<td>138</td>
<td>Discharge floating trash</td>
</tr>
<tr>
<td>Deep sluices</td>
<td>23</td>
<td>90</td>
<td>Discharge flow &amp; sediment</td>
</tr>
<tr>
<td>Power penstocks</td>
<td>26</td>
<td>108</td>
<td>Power generation</td>
</tr>
<tr>
<td>Flushing sluices</td>
<td>7</td>
<td>90/75</td>
<td>Flushing sediment</td>
</tr>
</tbody>
</table>

Operation water level: 145m in flood seasons
175m in non-flood seasons
Typical cases—arrangement of structures

Three Gorges Dam Reservoir

Arrangement of hydraulic structures

Right power station (R)  Hydraulic structure section  Left power station (L)
Sanmenxia reservoir is the first large-scale hydraulic project on the Yellow River. It controls 91.5% area of the Yellow River basin, 89% runoff and 98% sediment yield.
Crest elevation: 353m
Maximum height: 106m
Length: 713.2m
Storage capacity: 9.84 billion m$^3$ (335m)
Sanmenxia reservoir started to operate in Sept. 1960. The operation mode ‘Storing water and detaining sediment’ was used at that time. The highest water level reached 332.58m. The reservoir received very serious sedimentation. The TG elevation rose about 5m. The total sedimentation amount reached 1.53bt and 93% sediment deposited in the reservoir in the period of 1960.09 to 1962.03.
To alleviate the severe sedimentation, the operation mode was changed to ‘Detaining flood and discharge sediment’. However, due to insufficient flow discharge capacity of the hydraulic structures, 63% of sediment still deposited in the reservoir. Till Oct. 1964, the total sedimentation reached 4.7bt.
Typical cases—arrangement of structures

Sanmenxia Dam Reservoir

Longitudinal profile for different time
The main reasons to cause severe sedimentation are (1) insufficient discharge capacity of hydraulic structures, and (2) the high water level in flood seasons.

To control the continuous sedimentation, the discharge capacity of hydraulic structures has to be enlarged and correspondingly the water level in flood seasons had to be lowered.

As result, the project experienced two times of re-built to enlarge discharge capacity and three operation modes.
Typical cases—arrangement of structures

Sanmenxia Dam Reservoir

Arrangement of hydraulic structures

- Right-side dam section
- Power station dam section
- Flushing section
- Left-side section

- Two flood tunnels
- 8 penstocks, 7 for power generation, 1 for sediment flushing
- 12 bottom outlets
- 12 deep outlets
Total number of outlets for discharge flow and sediment is 27. In addition, there are 7 penstocks for power generation.
**Typical cases—arrangement of structures**

- **Sanmenxia Dam Reservoir**

**Two times of re-construction to outlets**

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Duration</th>
<th>Discharge at WL 315m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Build two additional flood tunnels and change 4 power penstocks into flood outlets</td>
<td>1965 to 1968</td>
<td>3084 to 6102 (m³/s)</td>
</tr>
<tr>
<td>2. Reopen bottom outlets 1#-12# and change a few more penstocks to flood outlets</td>
<td>1969 to 2000</td>
<td>6102 to 9701 (m³/s)</td>
</tr>
</tbody>
</table>
Typical cases—arrangement of structures

Sanmenxia Dam Reservoir

The discharge capacity of the dam has tremendously increased after two times of re-constructions.

Discharge at 310m: $1728 \rightarrow 4376 \rightarrow 7829 \text{m}^3/\text{s}$

<table>
<thead>
<tr>
<th>Items</th>
<th>Time</th>
<th>1960-09</th>
<th>1968-08</th>
<th>2000-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow discharging structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep sluices</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bottom sluices</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Flood tunnels</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penstocks</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow discharge under a certain level (m$^3$/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>290m</td>
<td>0</td>
<td>0</td>
<td>1188</td>
<td></td>
</tr>
<tr>
<td>300m</td>
<td>0</td>
<td>712</td>
<td>3633</td>
<td></td>
</tr>
<tr>
<td>310m</td>
<td>1728</td>
<td>4376</td>
<td>7829</td>
<td></td>
</tr>
<tr>
<td>320m</td>
<td>4044</td>
<td>7312</td>
<td>11153</td>
<td></td>
</tr>
<tr>
<td>330m</td>
<td>5460</td>
<td>9226</td>
<td>13483</td>
<td></td>
</tr>
</tbody>
</table>

Numbers of hydraulic structures and discharge capacity in different periods.
Three operation modes

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>Duration</th>
<th>Lowest WL</th>
<th>Highest WL</th>
<th>Mean WL in flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Storing water and detaining sediment</td>
<td>Sept. 1960 to Mar. 1962</td>
<td>324.0m</td>
<td>332.6m</td>
<td>320.0m</td>
</tr>
<tr>
<td>2. Detaining flood and discharging sediment</td>
<td>Mar. 1962 to Oct. 1973</td>
<td>298.0m</td>
<td>325.9m</td>
<td>310.0m</td>
</tr>
<tr>
<td>3. Storing clear water and discharging muddy flow</td>
<td>after Oct. 1973</td>
<td>300.0m</td>
<td>318.0m</td>
<td>304.0m</td>
</tr>
</tbody>
</table>

**Sanmenxia Dam Reservoir**

The increase of discharge capacity of the dam provided a possibility to lower operation water level during flood seasons. The water level in flood seasons was lowered: $320 \rightarrow 310 \rightarrow 304\text{m}$

**Typical cases—arrangement of structures**
The operation water level in flood and non-flood seasons

Sanmenxia Dam Reservoir

Typical cases—arrangement of structures

The operation water level in flood and non-flood seasons

very high (330m) → very low (298m) → stable (304m/316m)

320→310→304m
The reservoir sedimentation has experienced three stages:

- Rapid deposition
- Erosion
- Nearly stable
The adjustment of reservoir operation modes and the reconstruction of the project were successful in controlling further sedimentation.

The practice of storing clear water and discharging muddy flow in the Sanmenxia Reservoir has set a model and provided valuable experiences for solving sediment problems in large size reservoirs built on high sediment laden rivers.
(1) Reservoirs provide many benefits to mankind, but at the same time we have to face many negative affects from reservoirs. To some extent, the reservoir life span is not determined by the dam construction quality, but by the reservoir sedimentation.

(2) There are many ways can be used to alleviate reservoir sedimentation and prolong the life span of the reservoir. If a proper operation mode is used, the reservoir can maintain a stable live capacity for long term use.
(3) Sedimentation in the dam area may change the load acting on the dam. So when one designs a dam, the final sedimentation elevation on the upside face of the dam should be considered.

(4) For any dam design, to alleviate the severe sedimentation during flood seasons, sufficient flow discharge capacity under a certain water level should be considered in order to avoid the detention of floods.
Summary

(5) For any dam with power generation, to alleviate the turbine blade erosion by sediments, deep sediment flushing sluices lower than power outlets should be considered. In this way, a stable erosion funnel in front area of the power intakes could be maintained.

(6) The practice of storing clear water and discharging muddy flow in the Sanmenxia Reservoir has set a model and provides a valuable experience for solving sediment problems in reservoirs built on high sediment laden rivers.
(7) The operation mode ‘Storing clear water and discharging muddy flow’ is very useful to alleviate reservoir sedimentation. To use this mode, four pre-conditions should be met: (a) Both flood and sediment concentrate in flood seasons; (b) Sufficient incoming runoff after flood season; (c) River-shape reservoir, not lake-shape reservoir; (d) Hydraulic structures have sufficient discharge capacity at the low level during flood seasons.
Thank you!