Session:

Sediment management
What are the mitigation options?

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Mitigation Strategies of Reservoir Sedimentation in China

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2. Soil erosion control and vegetation-erosion dynamics
3. Methods of sediment removal
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1. Reservoir sedimentation

- The worldwide average annual rate of reservoir storage loss due to sedimentation is on the order of 0.5 to 1% of total storage capacity.
- United States had an average storage loss rate of 0.71%.
- China had an average storage loss rate of about 2%. 
<table>
<thead>
<tr>
<th>Reservoir</th>
<th>River</th>
<th>Drainage area (km²)</th>
<th>Dam Height (m)</th>
<th>Total capacity (10⁶ m³)</th>
<th>Years surveyed</th>
<th>Sedimentation (10⁶ m³)</th>
<th>Capacity loss (%)</th>
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<td>14 years</td>
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Miaogong reservoir in Chengde in North China lost a lot of capacity due to sedimentation.
About 750 million tons of Sediment has deposited in the Guanting Reservoir (Beijing water resources)
Mitigation Strategies

1. Control gully incision and re-vegetate slopes to reduce soil erosion and reduce sediment load entering into reservoirs;

2. Prevent sediment from deposition in the reservoirs by: storing clear and releasing turbid, and releasing turbidity current (density current)

3. Remove sediment from the reservoirs by: flushing and dredging
2. Soil erosion control and Vegetation-erosion dynamics

• Soil erosion in a reservoir watershed can be predict by using vegetation erosion chart


• Soil erosion and vegetation development can be modeled by using vegetation-erosion dynamics model
Wang et al. proposed the following differential equations as the core of the vegetation-erosion dynamics:

\[
\begin{align*}
\frac{dV}{dt} - aV + cE &= V_\tau \\
\frac{dE}{dt} - bE + fV &= E_\tau
\end{align*}
\]

In which \( V \) is vegetation cover, \( E \) is the rate of erosion; \( V_\tau \) is the sum of various stresses on the vegetation; and \( E_\tau \) is the sum of various human disturbances on erosion.
Four parameters for the Anjiagou (in loess plateau) and Xiaojiang Watersheds (in Yunnan Plateau) (obtained by trial and error with 40 years data)

- **Anjiagou**
  - $a = 0.001 (1/\text{yr})$
  - $c = 0.0000018 (\text{km}^2/\text{yr})$
  - $b = 0.01 (1/\text{yr})$
  - $f = 400 (\text{t}/(\text{km}^2 \cdot \text{yr}^2))$

- **Xiaojiang**
  - $a = 0.03 (1/\text{y})$
  - $c = 0.000005 (\text{km}^2/\text{ton})$
  - $b = 0.054 (1/\text{yr})$
  - $f = 200 (\text{ton}/\text{km}^2 \cdot \text{yr}^2)$

The values of $a$, $c$, $b$, $f$ are eigenvalues of watershed and are independent of the stresses and present vegetation and erosion.
Computed and measured development process of vegetation cover ($V$) and the variation of the computed and measured rate of erosion ($E$) for the Anjiagou Watershed in the loess plateau.
Theoretical solution for vegetation (V) and erosion rate (E) for the Xiaojiang Watershed in comparison with measured data.
Vegetation-Erosion Chart

Assume no disturbances on the vegetation development and erosion. The differential equations become homogeneous and can be written as:

\[
\begin{align*}
\frac{dV}{dt} &= aV - cE \\
\frac{dE}{dt} &= bE - fV
\end{align*}
\]

The solution for \( \frac{dV}{dt}=0 \) and \( \frac{dE}{dt}=0 \), are two lines

\[
E = \frac{a}{c}V; \quad E = \frac{f}{b}V
\]
Vegetation-erosion chart for the Xiaojiang (Baihetan reservoir) Watershed and its sub-watersheds (● - Xiaojiang Watershed in the 1990s; ▲ - Heishuihe Watershed in the 1998; ■ - Shengou Watershed in the 1996)
There are two stable status of vegetation and erosion under no human disturbances: Zone C and A. **Zone A**, $dV/dt < 0$, $dE/dt >0$. vegetation reducing and erosion increasing. The larger is $a/c$, the bigger is the Zone. **Zone C**, $dV/dt>0$, $dE/dt<0$. vegetation developing and the erosion decreasing. The larger is the value of $f/d$, the bigger is the Zone C. The forest may be logged to a certain extent and the vegetation may restore by itself. **Zone B**, $dV/dt>0$, $dE/dt >0$. Transitional zone. or **Zone D**, $dV/dt<0$, $dE/dt <0$. Transitional zone.

The vegetation may be restored and has capacity of self-restoration because the C-zone is big.
Two status in the Xiaojiang Watershed
Poor vegetation and severe erosion
– A-zone

Good vegetation
no erosion
In C-zone
Two status in the same watershed

(a) Vegetation in Zone A (Wudu in Bailong Watershed in Gansu)

(b) Vegetation in Zone C
    (Bailong Watershed - about 200 km from Wudu)
Vegetation-erosion chart for the Xiaojiang (Baihetan reservoir) Watershed and its sub-watersheds (●- Xiaojiang Watershed in the 1990s; ▲- Heishuihe Watershed in the 1998; ■- Shengou Watershed in the 1996)
Reservoir watershed erosion can be controlled by moving vegetation-erosion status into C-Zone.

Building check dams to move the status point down and reforestation to move the status point right in the chart.
Vegetation-erosion chart for the Anjiagou watershed and the west hilly-gully area of the loess plateau
Summary of vegetation-erosion dynamics

- Two stable status- vegetation developing and erosion reducing and vegetation deteriorating and erosion increasing
- For a reservoir watershed the best erosion control strategy is to move the status into C-zone
- The most effective erosion reduction and vegetation restoration method is: One by one in small watershed rather than step by step in large watershed
3. Sediment Removal

- Strategies for reservoir sedimentation control:
  - 1) Drawdown flushing or pressure flushing;
  - 2) Empty flushing or free flow flushing;
  - 3) Releasing density currents;
  - 4) Storing the clear and releasing the turbid;
  - 5) Sediment mining and dredging;
(1) Empty flushing

• Some irrigation reservoirs with small capacity are emptied before flood season and flushed during the first part of the flood season.

• A wider channel can be deepened by using either smaller or larger flows, but widening is achieved by large flows only “Deepen by small flow, widen by flood flow.”

• Flushing effect is maximized if the reservoir is emptied immediately prior to the arrival of floods so that the flood flow can exert its erosive force on deposits which have not yet had the time to fully dewater and consolidate after emptying the reservoir.
(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
Sefid-Rud Reservoir in Iran is emptied for empty flushing; (after Sharifi Forood & Mohammad Ghafouiri, 2007)
Sediment discharge and sediment concentration of the inflow and outflow of the Sefid-Rud Reservoir in Iran during the empty flushing.
Hengshan Reservoir on the Tangyu River (a tributary of the Yongding River) in Shanxi, China

The reservoir was emptied to flush sediment in 1974 and 1.19 million t of sediment were flushed out of the reservoir. It was emptied and flushed again in 1979 and 1.55 million t of sediment were flushed out.
Sediment concentration and discharge of mud flow during the empty flushing from the Hengshan Reservoir in 1979 (Data from Guo et al., 1985).
Zhuwo Reservoir

- The Zhuwo Dam is on the Yongding River near Beijing, which is 33 m high with a reservoir capacity of 14.75 million m³.
- The reservoir began to store water in 1961 and lost 5.3 million m³ of reservoir capacity due to sedimentation after 25 years of operation.
- Most of the sediment deposit was cohesive sediment with a median diameter of 0.004 mm.
The Zhuwo Reservoir on the Yongding River near Beijing

A physical model experiment to study the efficiency of empty flushing of cohesive sediment from the reservoir.
Sediment concentration and discharge during mud flow stage of empty flushing of the Zhuwo Reservoir
Sediment concentration process during retrogressive erosion stage of empty flushing of the Zhuwo Reservoir
(2) Drawdown Flushing

- Drawdown 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.

- Sediment from the upper portion of the Liujiaxia reservoir was transported towards the dam during draw down, but only material in the scour hole in front of the outlets can be flushed out.
Original total capacity: $14.3 \times 10^9 \text{m}^3$
Capacity below min. pool: $2.4 \times 10^9 \text{m}^3$
Sediment volume 1991: $2.6 \times 10^9 \text{m}^3$
Sediment vol. projected end 1994: $3.0 \times 10^9 \text{m}^3$

Typical sediment composition:
- Sand $D_{s50} = 0.20 \text{mm}: 59\%$
- Silt $D_{s50} = 0.04 \text{mm}: 34\%$
- Clay $D_{s50} = 0.002 \text{mm}: 7\%$

Draw-down flushing or pressure flushing was used to flush:
- sandy bed material in the Tarbela Reservoir in Pakistan
- Advancement of delta deposits toward Tarbela Dam,
  Indus River, Pakistan)
(3) Storing the Clear and Releasing the Turbid

- Sanmenxia, Xiaolangdi and Three Gorges reservoir are operated for storing the clear and releasing the turbid.
- Sediment transportation in many Chinese rivers occurs mainly in 2-4 months of the flood season, that is, 80-90% of the annual sediment load is transported with 50-60% of the annual runoff.
- The strategy is to draw down the pool level for releasing high concentration flow in the flood season from June to September when the sediment concentration is high and allow the turbid water to wash downstream through the reservoir. The reservoir starts to store water in October when the inflowing water becomes clear.
Storing the clear and releasing the turbid - During the flood season, when the river carries 90% of the annual sediment load and 61% of the annual runoff, the pool level is drawn down to 145 m to create a condition in favor of sediment flushing.

Water and load into and out of the Three Gorges Reservoir
Three cross sections of the TGP Reservoir and sedimentation in the first 10 years

Cross section No.34 (5.6km upstream of the dam)

Cross section No.113 (160.1 km upstream of the dam)

Cross section No.205 (356km upstream of the dam)
Total Sedimentation in the first 10 years

- Incoming sediment load 1.9 billion tons (designed 5.1 billion tons)
- Sedimentation in the reservoir 1.43 billion tons (predicted 3.2 billion tons)
- Sediment releasing efficiency = 24.4% (predicted 35%)

\[ E = \frac{\text{volume} \sim \text{of} \sim \text{released} \sim \text{sediment}}{\text{volume} \sim \text{of} \sim \text{income} \sim \text{sediment}} \]
(4) Mining and Dredging

- Mining has become an important factor affecting reservoir sedimentation since the 1990s
- Dredging has for a long time been used for small reservoir sedimentation management.
- Various dredgers have been used: dredge boat; dipper dredger; hauling scraper; excavator, bulldozer; trailer dredger and agitating with jets and transporting with current to the downstream of the reservoir.
It is estimated that about 15 million tons of coarse sand and gravel (bed load and bed material) are mined for building materials per year, which has reduced the sedimentation in the TGP reservoir.
Sediment amount scoured from the wake area of Sanmenxia Reservoir by jet dredgers
(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.

• Since the density difference is small, the reservoir water creates a large buoyancy effect within the inflow liquid. Usually $g'$ is defined as effective gravity given by:

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

• And the Froude number becomes

$$Fr' = \frac{U_c}{\sqrt{g' h'}}$$
Velocity and sediment concentration profiles varying along the reservoir during the transition from an open-channel flow to a density current.
Sanmenxia Reservoir on the Yellow River
Xiaolangdi Dam is about 130 km downstream of the Sanmenxia Dam
Density currents were created using the Sanmenxia reservoir and released from the Xiaolangdi Dam (about 60 km from the immersion point to the dam, Discharge 200-2800 m$^3$/s, Concentration 13 kg/m$^3$ to 530 kg/m$^3$, and Velocity 0.2 m/s to 1.2 m/s. Fr= 0.5-0.61)
The layer of density current became thicker and thicker along the Xiaolangdi reservoir because of water entrainment. Thus the concentration was reducing. As the concentration reduced to the minimum value for sustaining density current it would stop and disappear.
Sediment concentration, $S$, and discharge, $Q$, of density currents reaching and not reaching the dam occurred in 2001-2004.
Sediment releasing efficiency

\[
E = \frac{\text{volume of released sediment}}{\text{volume of income sediment}}
\]

\[
E = \frac{\text{time needed for sedimentation}}{\text{time to flush the sediment}}
\]

The sediment releasing efficiency is: 30-100% for storing the clear water and releasing the turbid water, 6-36% for turbidity current, 1-100% for pressure flushing. 2400-5500% for empty flushing.
4. Lessons learned from Sanmenxia

• Sanmenxia is the first large dam on the Yellow River and water impoundment commenced in September 1960.

• The main purposes of the dam are flood control, ice jam flood control, trapping sediment to reduce the downstream channel sedimentation, power generation, and irrigation.

• The crest elevation of the dam is 353 m and the designed reservoir capacity was 35.4 billion m³ with a normal pool level of 350 m.

• The reservoir controls a drainage area of 688,000 km² and 89% of the total runoff of the Yellow River basin.
The reservoir area consists of three parts: 1) the Yellow River from the dam to Tongguan; 2) the Yellow River from Tongguan to Longmen; and 3) the Weihe River from Tongguan to Xianyang.
Severe sedimentation

From 1960.09 to 1962.03, the reservoir began to function as a storage basin. Severe sedimentation became evident, 93% sediment was trapped in the reservoir. The reservoir lost 17% of its capacity due to sedimentation in 18 months.

The operation scheme of the Sanmenxia Reservoir had to be substantially changed because the sedimentation in the Weihe River caused flood threat to the City of Xian and the power generation had to be stopped.
Variations of accumulated deposition and reservoir capacity in Sanmenxia Reservoir: (a) accumulated deposition; (b) reservoir storage capacity.
Tong-guan elevation is defined as the stage of flood discharge 1000 m$^3$/s at Tong-guan station, which is in fact the datum of the bed profile of the Weihe River.
Tong-guan elevation has been increasing since operation of Sanmenxia, which resulted in the fast sedimentation in the Weihe River and flooding risk to Xian (ancient capital city of China).
Sedimentation in the lower Weihe River: WY2 .. are measurement cross sections on the Weihe River
The bridge on a river flowing into the Weihe had to be elevated two times because of sedimentation.
Due to the unacceptable negative impact of rapid sedimentation in the lower Weihe River the Sanmenxia dam had to be reconstructed to provide high sediment releasing-capacity of outlet structures.
(b) Front view of original design; (c) Front view after reconstruction
Three operation modes in three stages: 1) Storage-1960.9-1962.3; 2) Detaining flood water and sluicing sediment from 1962.03 to 1973.10; and 3) Storing clear water and releasing turbid water from 1973.11 to the present.
• A flood in the Weihe River caused a lot of economic loss and thence rekindled the debate of decommission of the Sanmenxia Dam

• Because the problems of siltation and induced flooding risk to the lower Weihe river has not been solved, decommission of Sanmenxia dam is under discussion as an alternative strategy to eventually solve the problem.

• Assume the Tongguan’s elevation will be reduced by 2 m, can the sedimentation and flooding in the lower weihe river be solved or mitigated?
Numerical simulation indicated that 15 years late after the reduction in Tongguan elevation the flood stage may reduce for small floods but not reduce for large
In the past 20 years the soil erosion and load into Sanmenxia have been greatly reduced due to 110000 check dams, reforestation, terracing the farm land and trapping sediment of upstream large dams.
Sediment yield reduction at 9 stations on the Yellow River from 1950 to 2005
From sedimentation to erosion

• The sediment load from the middle Yellow river and Weihe River has been reducing in the past decade quickly.

• Sedimentation in the reservoir has been changed from siltation to erosion from 2004:

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<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<th>2011</th>
<th>2012</th>
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<td>-33</td>
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<td>+3</td>
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<td>-102</td>
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In which – means erosion, + sedimentation
Sanmenxia has become a swan lake in North China
Future of Sanmenxia

Sanmenxia has become the swan lake of China. More than 20,000 white and black swans spent 6 months in the reservoir. Great sediment reduction make it possible to operated the reservoir at higher level. It is possible for the reservoir capacity to be restored and the operation mode may be adjusted to achieve its planned benefit.
Conclusions 1

• Soil erosion reduction is the essential strategy for reservoir sedimentation control.
• For a reservoir watershed there are two possibilities: C-status - vegetation developing and erosion reducing and A-status - vegetation deteriorating and erosion increasing.
• Human may change the reservoir watershed from A-status into C-status.
Conclusions 2

• Reservoir sedimentation may be controlled by applying the strategies of storing the clear and releasing the turbid; releasing density currents; flushing and dredging.

• The sediment releasing efficiency is:
  30-100% for storing the clear and releasing the turbid; 6-20 % for density current; 2400-5500% for empty flushing.

• Storing the clear and releasing the turbid is the best strategy to control reservoir sedimentation while achieving hydro-power benefit and maintain ecological stability.
Thank you

Questions are welcome

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