# 1-D MATHEMATICAL MODEL FOR HEAVILY SEDIMENT–LADEN RIVERS AND ITS APPLICATIONS

Yanjing Zhang[1], Chunhong Hu[2], and Yangui Wang[3]

## ABSTRACT

Reservoirs on heavily sediment–laden rivers face serious sedimentation and big capacity loss. In this paper a 1-D non-equilibrium mathematical model is used to calculate two typical reservoir sedimentation cases. For Sanzuodian Reservoir, in order to maintain its long-term available capacity, main factors concerning reservoir design, such as reservoir operation mode, dam scale and discharge facilities, are studied. Also the way to reduce sedimentation, such as lowering pool level during floods, using density flow, etc. are discussed. For Daxia Reservoir the core issue is how to recover and maintain a long-term capacity through appropriate operation, a concept of critical flow and sediment load is introduced in calculation. Taking into account of pool level, discharge of scouring sediment, several operation alternatives are calculated. Optimal plans are recommended for the two reservoirs.

## 1. INTRODUCTION

Sedimentation is a main factor for reservoir design and operation. There exits a sharp contradiction between water supply and reservoir deposition of heavily sediment–laden rivers. To deal with sediment properly is one of the key technologies to fulfill the comprehensive benefits of a reservoir. On the basis of fully understanding the processes of scour and deposition in a reservoir, it is an economic and effective way to determine an optimum operation mode by a mathematical model in the light of the scale and the purpose of the reservoir, as well as the condition of inflowing water and sediment load. The 1-D sediment mathematical model established in this paper is based on non-equilibrium sediment transport theory, meanwhile the scour and deposition, various features of reservoir deposition, high sediment content and density flow of a heavily sediment–laden river are fully considered. Applying the model to Sanzuodian Reservoir and Daxia Reservoir respectively, many alternatives are calculated and analyzed to gain the optimal plan, offering a scientific base for project design and operation.

[1] Senior Engineer, Department of Research and Training, International Research and Training Center on Erosion and Sedimentation , 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R.. Phone: 86-10-68786409 Fax: 86-10-68411174 Email: zhangyj@iwhr.com
[2] Professor & Secretary-General, International Research and Training Center on Erosion and Sedimentation, 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R.. Phone: 86-10-68413372 Fax: 86-10-68411174 Email: chhu@iwhr.com
[3] Professor and Section Chief, Department of Research and Training, International Research and Training Center on Erosion and Sedimentation , 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R.. Phone: 86-10-68786683 Fax: 86-10-68411174 Email: wangyg@iwhr.com

The annual sediment concentration of the Yinhe River, on which the Sanzuodian reservoir is located, amounts to 43.26kg/$m^3$, and the maximum sediment concentration 750kg/$m^3$. Sanzuodian Reservoir is faced up with serious sedimentation. Considering the main factors concerning reservoir design, such as reservoir operation mode and dam scale, the calculation of reservoir deposition is carried out. Also the feasibility of lowering operation pool level and using the density current to discharge sediment are discussed.

Daxia Reservoir is located on the upper Yellow River, and its capacity loss reached 50 percent of the original capacity for the first three years of operation. This greatly impacts the efficiency of the Daxia hydro-plant. It is an urgent task that fully utilizing the condition of inflowing water and sediment and fluvial processes of reservoir to effectively control sediment deposition and maintain the reservoir capacity in some extents under the condition of maximum power generation benefit. In which, the core issue to be studied is economical operation pool level of the reservoir. For the purpose of reducing reservoir deposition, a concept of critical flow and sediment is introduced in calculation. Taking into account of pool level and discharge of scouring sediment, several operation alternatives are calculated, and the economical operation pool level is discussed. The results show that lowering operation pool level when the water discharge or sediment concentration exceed a critical value in a flood season, and further lowering operation pool level at the end of a flood season to scour the deposit in the reservoir is the optimum operation mode, which can give attention to both controlling reservoir sedimentation and maintaining power generation benefit.

## 2. 1-D NON-UNIFORM SEDIMENT TRANSPOT MODEL

### 2.1 Flow Equations

The 1-D differential equations describing gradually varied flow in open channels can be written as follows (Chaudhry, 1993):

Continuity equation $$Q = AU \tag{1}$$

Momentum equation $$\frac{\partial H}{\partial x} + \frac{1}{2g}\frac{\partial U^2}{\partial x} + \frac{U^2}{C^2 R} = 0 \tag{2}$$

Where x is the direction of flow, Q is the flow discharge, A is the flow area of the cross section, U is the average velocity of the cross section, H is the pool level, R is the hydraulic radius, C is the Chezy coefficient ($C$= $R^{1/6}$/n, where n is the Manning roughness), and g is the gravitational acceleration.

### 2.2 Sediment Transport Equations

One-dimensional sediment transport equation can be expressed as:

$$\frac{dS}{dx} = -\frac{\alpha\omega}{q}(S - S^*) \tag{3}$$

Where $S$ is the suspended sediment concentration, $\omega$ is the sediment settling velocity, $\alpha$ is a coefficient, and $S^*$ is the sediment-carrying capacity which can be expressed as:

$$S^* = k_s k_c \left(\frac{U^3}{h\omega}\right)^m \tag{4}$$

Where $k_s$ and $m$ are coefficients, and $k_c$ is the modified coefficient for hyper-concentrated flow. The applications of Eq. (4) to many rivers and reservoirs show that the exponent $m$ has a very stable value, about 0.92. The coefficient $k_s$ could vary in a quite big range, from 0.01 to 0.05, and should be determined by calibration. It should be noted that Eq. (4) is not a dimension-harmony expression. The units for S*, U/w, and h are kg/m$^3$, m/s, and m, respectively.

## 2.3 Sediment Continuity Equation / Bed Variation

According to the continuity of sediment transport, the bed variation within a small spatial interval $D_x$ and temporal interval $D_t$ should be equal to the difference of two cross-section sediment transports for a steady flow. Thus, referring to Eq. (3), the bed variation equation can be written as:

$$\rho' \frac{\partial Z_b}{\partial t} = \alpha\omega(S - S^*) \tag{5}$$

Where $\rho'$ is the dry bulk density of the bed materials and $Z_b$ is the channel bed elevation. Eqs. (1), (2), (3), and (5) represent the fundamental equations that describe the transport of flow and suspended sediment in rivers. The unknown variables are the flow velocity ($U$), water level ($H$), suspended sediment concentration ($S$), and the bed elevation ($Z_b$).

For hydraulic factors, combining Eqs. (1) and (2) results in a finite difference equation to calculate water level at the cross section i when the water level at cross section i+1 is given.

For sediment concentration, integrating Eq. (3) along the flow direction and using the assumption that the sediment-carrying capacity changes linearly with distance (Han, 1980), and considering the non-uniform suspended sediment mixtures, and dividing the suspended particles into L groups, the sediment concentration for the jth group size at the outlet section i+1 could be calculated.

## 2.4 Density Flow

If the relationship between the amount of sediment carried by density flow and turbulent diffusion is directly considered, there is no essential difference between law of sediment carrying capacity of a density flow and that of an open-channel flow (Han). Non-equilibrium sediment transport equation that reflects antinomy between turbulent diffusion and the effect of gravity could also be applied to describe the law of density flow.

### 2.4.1 Criterion of Plunge Point of Density Flow

(1) Calculation of water depth at the plunge point, $h'_{0,i,j}$

$$h'_{0,i,j} = [1.667 \frac{Q^2{}_{i,j}}{\eta_{gij} g B_{i,j}^2}]^{1/3} \tag{6}$$

where $$\eta_{g,i,j} = \frac{S_{i,j-1}}{S_{i,j-1} + \dfrac{\gamma_0 \gamma_s}{\gamma_s - \gamma_0}}$$

where, $\eta_{g,i,j}$ is the gravity modified coefficient; $\gamma_s$ is the sediment bulk density ($\gamma_s$=2650kg/m$^3$); $\gamma_0$ is the water bulk density ($\gamma_0$=1000kg/m$^3$)。

(2) Calculation of water depth $h'_{n,i,j}$ of uniform flow of density flow

$$h'_{n,i,j} = (\frac{\lambda}{8J_{i,j}} \frac{Q_{i,j}^2}{\eta_{g,i,j} g B_{i,j}^2})^{1/3} \tag{7}$$

Where， $\lambda$ is the resistance coefficient of density flow, $\lambda$=0.025～0.03, $J_{i,j}$ is the energy slope.

(3) Criterion of Water Depth $h'_{i,j}$

When a density flow plunges and moves in a uniform state, the water depth at the plunge point should satisfy the following expression

$$h'_{i,j} > \text{Max.}[\, h'_{0,i,j}\, , h'_{n,i,j}\,] \tag{8}$$

Also

$$\frac{A_{i,k-1}}{B_{i,k-1}} \le \text{Max.}[\, h'_{0,i,j}\, , h'_{n,i,j}\,] < \frac{A_{i,k}}{B_{i,k}} \tag{9}$$

Then, the fact that the density flow plunges at the cross-section *j*=*k*, moves in a uniform state and does not ascend to water surface could be confirmed.

2.4.2 Flow Equations of Density Flow

Strictly speaking, a density flow is different from a steady uniform flow, but it could be treated as a quasi- steady flow, that is, within a time period it could be calculated as a non-uniform slack water, its steady non-uniform flow is as follows.

$$\frac{dh'}{dx} = \frac{J - \frac{\lambda}{8} F_r'^2}{1 - F_r'^2} \tag{10}$$

where $$F'_{r,i,j} = \frac{Q'_{i,j}}{A'_{i,j}\sqrt{\eta_{g,i,j} g h'_{i,j}}}$$

where the superscript means hydraulic elements of density flow, $F'_{r.i,j}$ is Froude number.

## 3. SANZUODIAN RESERVOIR

### 3.1 General Situations and Problems of the Reservoir

Sanzuodian Reservoir is located on the Yinhe River, the second largest tributary of Laohahe River, which is the main tributary of Xiliao River. It is mainly built for flood control, water supply, agriculture irrigation and power generation, etc. Its total storage is 0.327×10$^9$ m$^3$. It is a valley reservoir. The reservoir is with a length of 17.4km, the average width about 748m, 600m at dam site, the bed slope 3.9‰. The Yinhe River is a river with excessive sediment, low flow and high sediment concentration. The record sediment concentration was 750kg/m$^3$. The annual mean sediment concentration is 43.26kg/m$^3$, even greater than that of the Yellow River, the world famous sediment-laden river. Sedimentation in the Reservoir is very serious. To simulate the scour and silting of high sediment concentration correctly is important for the prediction of reservoir sedimentation. Furthermore, because the benefit of water supply influences the operation mode, there exits a contradiction between water supply and reservoir sedimentation, thus a reasonable operation mode is important for exerting the integrated benefit of the Reservoir.

### 3.2 Calibration of the Model

The recovery saturation coefficient of the model is taken as 1.0 when scouring, and 0.25 when silting. The sediment carrying capacity coefficient *K* is taken as 0.03. The calibration reach is the reservoir area, from cross section Y15 to Y0 with a length of 13.68 km. Because there are only measured topography data of 1975 and 2002, so the calibration periods is from 1975 to 2002.

The comparison between the measured and calculated accumulated sedimentation (including deposition and erosion) is shown in Fig.1, which shows that the calculated results agree well with the measured ones. Therefore, the model is reasonable and applicable for the Sanzuodian Reservoir.

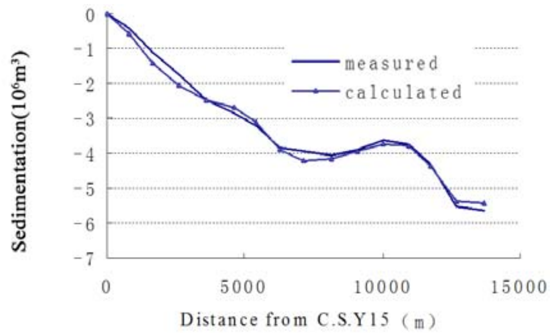


Fig.1 Comparison between the Measured and Simulated Sedimentation

### 3.3 Calculation and Discussions of Design Plans

3.3.1 Calculation of Typical Design Plans

The reservoir operation mode, dam site, discharge facilities as well as reservoir scale should be considered in reservoir design. Whereas, the reservoir operation mode is dependent on the task of a reservoir, its type and capacity. Three reservoir operation modes are considered, that is, the flood storage operation mode, the discharging sediment operation mode, which is to lower the pool level

**Table 1** Sediment Deposition of Typical Plans

| No. | Dam site | Dam scale | Operation mode | Discharge facilities | Deposition ($10^9$t) | | Discharging sediment rate (%) | Storage capacity ($10^9$m$^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 30 year | 50 year | 50 year | 30 year | 50 year |
| Plan1 | Lower dam site | Low dam | Flood storage | Large undersluice | .1485 | .2383 | 3.42 | .0884 | .0610 |
| Plan 2 | Lower dam site | Low dam | Flood storage | Small undersluice | .1481 | .2388 | 3.22 | .0884 | .0608 |
| Plan 3 | Lower dam site | Low dam | Discharging sediment encountering flood once per 5 year | Large undersluice | .1413 | .2276 | 7.74 | .0952 | .0622 |
| Plan 4 | Lower dam site | Low dam | Flood storage by stages | Tunnel | .1473 | .2371 | 3.91 | .0911 | .0638 |
| Plan 5 | Lower dam site | High dam | Flood storage | Tunnel | .1489 | .2405 | 2.55 | .1354 | .0964 |
| Plan 6 | Upper dam site | High dam | Flood storage | Tunnel | .1489 | .2410 | 2.32 | .1162 | .0811 |

when encountering a 20% frequency flood or larger, and the stage flood storage operation mode, which operates at low pool level at initial stages and enhances the pool level by stages. For dam sites, the upper dam site located in upper cross section Y2 and the lower dam site located in lower cross Y0 are included. For dam scale, a low dam and a high dam are included. For discharge facilities, a large undersluice, a small undersluice and a tunnel are taken into account, respectively. The typical plans are listed in Table 1.

The measured data for the period of 1956~2000 are adopted for the reservoir design life of 50 years, in which the average annual sediment load was $4.93\times10^6$ ton, the total sediment load was $246.8\times10^6$ ton and the total runoff was $122.7\times10^6$ $m^3$.

The sedimentation and sediment discharge rate of six plans are listed in Table 2. For all the plans, the amount of deposition is over $0.2\times10^9$ ton, and sediment discharge rate is less than 10%, reservoir sedimentation is quite serious. Deposition does not show the tendency of decrease in 50 years, and no evidence of deposition balance exists.

The longitudinal profile of the reservoir is shown in Fig.2, from which it can be seen that the reservoir deposition is a typical delta and the deposition body are moving toward the dam gradually.

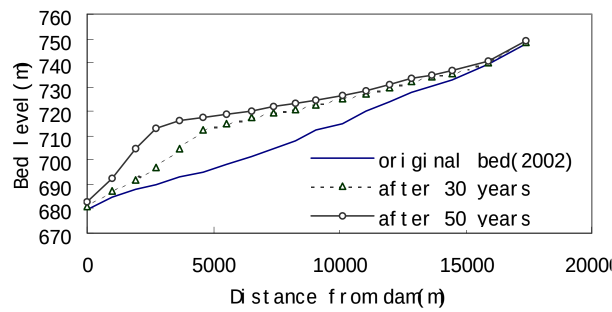


Fig. 2 Longitudinal Profile of the Reservoir Sedimentation

As for reservoir operation mode, by reviewing plan1, plan 3 and plan 4, plan 3 results in the least deposition amount. Plan 3 is the plan that lowers the pool level to the dead pool level when encountering a 20% flood, which will lead to a big loss of water amount. Among these plans, plan 4 seems to be the most reasonable for the normal year, which gradually raise the pool level in different operation periods and can meet the demands of reservoir goal.

As for the discharge facilities, the large undersluice has the biggest discharge capacity, the small undersluice has the smallest discharge capacity in the three facilities, the tunnel has almost the same discharge capacity as the large undersluice. By reviewing plan 1 and plan 2 (Table 1), there is no obvious difference in sediment discharge rate for 30 and 50 years, respectively. The reason for this is that the water flow is low and no big flood occurs during the 50 years, and the discharge capacity has a little effect on reservoir sedimentation.

In order to distinguish influences of each plan on reservoir sedimentation, a 1% flood and 2% flood are calculated, respectively. Table 2 lists the amount of reservoir sedimentation for the three discharge facilities. The results show the amount of reservoir sedimentation decreases as the discharge flow capacity of the discharge facility increases.

Table 2 Reservoir Sedimentation during Big Floods

| Flood frequency | Total sediment load ($10^6$ton) | Sedimentation ($10^6$ ton) | | | Discharging sediment rate（%） | | |
|---|---|---|---|---|---|---|---|
| | | Undersluice | | Tunnel | Undersluice | | Tunnel |
| | | Big | Small | | Big | Small | |
| 1% | 18.43 | 8.99 | 10.04 | 9.63 | 51.23 | 45.52 | 47.73 |
| 2% | 14.12 | 5.79 | 6.65 | 6.28 | 58.97 | 52.89 | 55.53 |

For the dam scale, comparing plan 5 of high dam with plan 1 of low dam, the amount of deposition of plan 1 is $2.154\times10^6$ton less than that of plan 5, but due to the normal pool level of plan 5 is 728m, 4 m higher than that of plan 1, the available storage of 30 year and 50 year are $0.047\times10^9$ $m^3$ and $0.035\times10^9$ $m^3$, larger than that of plan 1, respectively. From the view of less deposition and high sediment discharge, the low dam (plan 1) is better. However, if no investment limit exists, a high dam of plan 5 can be considered.

From above studies, plan 4, that is a low dam located at cross-section Y0 (the lower site) with a tunnel and operated by the mode of stage flood storage, is recommended.

3.3.2 Possibility of Density Flow

For the design water and sediment series of 50 years, density flows are calculated. The results show that, when a density flow occurs, the discharging sediment rate increases a little for the 50 years. However, for a 1% flood, when a density flow occurs, the discharging sediment rate increases by 10%, from 25.54 % of non-density flow to 36.72% of density flow. Table 3 shows the comparison between non-density flow and density flow during 1% flood.

Thus, in order to use density flow to decrease reservoir sedimentation, it is necessary to enhance the forecast of floods, when a density flow occurs, open the bottom outlet to let the density flow out of the reservoir.

Table 3 Discharging Sediment Rate during 1% Flood (%)

| Cases | Plan 2 | Plan 3 | 1% flood |
|---|---|---|---|
| Non-density flow | 3.22 | 7.74 | 25.54 |
| Density flow | 3.28 | 8.59 | 36.72 |

## 4. DAXIA RESERVOIR

### 4.1 The General Situations and Problems of Daxia Reservoir

Daxia Reservoir is located on the upper Yellow River, and it is mainly built for power generation, and also giving attention to irrigation and some other beneficial uses. Daxia Reservoir is of a type of montane channel, and it can be divided into two segments, one is from the gorge entrance to dam site which is 21km long and the bed slope is 1.38‰(cross-section 00~13), and the other is the upper reach of the Reservoir, Shenchuan reach, which is 8km long (cross-section 13~20) and the bed slope is 0.78‰. The measured longitudinal profile of the reservoir is shown in Fig.3.

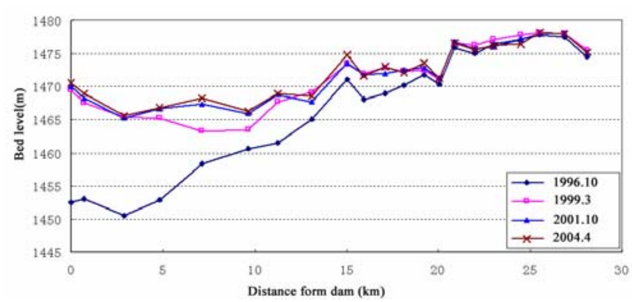


Fig.3 Longitudinal profile of Daxia Reservoir

Only 3 years after its impounding, the reservoir capacity loss reached 50 percent of the original capacity. This greatly impacts the efficiency of the Daxia hydro-plant. The contradiction between the benefit and sedimentation of the Reservoir becomes more distinct. The serious sedimentation near the dam makes the reservoir operation to be kept in very high pool level in order to satisfy the need of power generation, and this makes reservoir sedimentation more serious, and the long-term efficiency of the hydro-plant would also be threatened. It is an urgent task that fully utilizing the condition of inflowing water and sediment and characteristics of reservoir sediment scour and deposition to effectively control sediment deposition and maintain the reservoir capacity in some extents under the condition of maximum power generation benefit.

## 4.2 Calibration and Verification of the Model

The recovery saturation coefficient of the model is 1.0 when scouring, and 0.25 when silting. The carrying capacity coefficient $K$ is 0.03 in gorge reach, and 0.04 in the Shenchuan reach.

The measured data for the period of 1996~2001 and the measured data for the period of 2001~2004 are used for calibration and verification, respectively. The comparisons between the measured and calculated results are shown in Fig.4. All calculated results agree well with the measured ones. Therefore the model is reasonable and applicable for Daxia Reservoir.

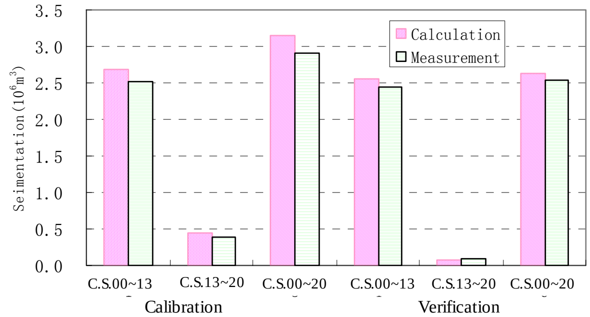


Fig.4. Calibration and Verification of the model

## 4.3 Proposed Plans and Its Discussions

### 4.3.1 Proposed Plans

The condition of inflowing water and sediment of the reservoir has the characteristics of concentrating in flood seasons, which can be used to reduce reservoir sedimentation. When the water discharge or sediment concentration exceeds a critical value in a flood season, the operation pool level is lowered timely, to increase flow velocity and reduce reservoir sedimentation of high sediment concentration or to let the sediment carried by big discharges to flow out of the reservoir.

The critical value of water discharge or sediment concentration is multi-value, according to the condition of inflowing water and sediment and the operation pool level, but it should have a quite high kinetic energy or high concentration, and appear in a certain frequency during a year. 1200 m$^3$/s、1610 m$^3$/s and 2500 m$^3$/s are chosen as critical values of water discharge, 4 kg/m$^3$ and 10 kg/m$^3$ as critical values of sediment concentration by statistical calculation.

The pool level is adjusted according to the amount of water discharge and sediment concentration. The proposed plans (plan1~plan8) are listed in Table 4.

Table 4 Proposed Plans of Daxia Reservoir

| Time | Flow Discharge and Sediment Concentration | Pool level (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Plan1 | Plan 2 | Plan 3 | Plan 4 | Plan 5 | Plan 6 | Plan 7 | Plan 8 | Plan 9 |
| Flood season May.~Oct. | $Q$ <800m$^3$/s & $S$ <4kg/m$^3$ | 1478 | 1478 | 1478 | 1478 | 1478 | 1476 | 1474 | 1472 | 1479.5 |
| | 800≤ $Q$ <1200m$^3$/s or $S$ <4kg/m$^3$ | 1478 | 1478 | 1478 | 1478 | 1478 | 1476 | 1474 | 1472 | 1479 |
| | 1200≤ $Q$ < 1610m$^3$/s or 4≤ $S$ < 10kg/m$^3$ | 1478 | 1476 | 1474 | 1476 | 1472 | 1474 | 1472 | 1472 | 1477 |
| | 1610≤ $Q$ < 2500m$^3$/s & $S$ < 10kg/m$^3$ | 1478 | 1476 | 1474 | 1474 | 1472 | 1472 | 1472 | 1472 | 1475 |
| | $Q$ ≥2500m$^3$/s or $S$ ≥10kg/m$^3$ | 1478 | 1476 | 1474 | 1472 | 1472 | 1472 | 1472 | 1472 | 1474 |
| Non-Flood season Nov~Apr | | 1479.5 | | | | | | | | |

4.3.2 Fluvial Processes in the Reservoir

Table 5 Accumulated Sedimentation of Plan 1~ Plan 9 and Plan 13(Unit： $10^6 m^3$)

| Serial Number of 15 Years | Hydrological Year | Plan1 | Plan 2 | Plan 3 | Plan 4 | Plan 5 | Plan 6 | Plan 7 | Plan 8 | Plan 9 | Plan 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 1992 | 9.62 | 7.07 | 4.41 | 3.89 | 2.11 | 1.20 | -1.99 | -4.09 | 7.23 | 4.84 |
| 8 | 1994 | 7.62 | 3.96 | 2.33 | 1.30 | -2.14 | -1.45 | -4.13 | -5.03 | 4.51 | 2.80 |
| 11 | 1997 | 17.29 | 14.24 | 10.73 | 10.16 | 7.65 | 6.90 | 3.45 | 0.21 | 15.02 | 11.16 |
| 15 | 2001 | 4.95 | 3.30.7 | 1.66 | 2.42 | -0.34 | -0.89 | -3.76 | -4.94 | 5.79 | 2.98 |

The accumulated reservoir sedimentation during a typical hydrological series of 15 years is shown in Fig.5, and the amount of sedimentation of eight plans are listed in Table 5. By analyzing the calculated results, some knowledge of reservoir sedimentation can be summarized as follows:

(1) The reservoir deposition is of pyramidal feature.

(2) Scour and silting alternate during years. During 15 years, the reservoir keeps scouring before 1991(the 5th year), after that except a big scour occurs in 1993, the reservoir keeps depositing and reaches the maximum of deposition ranging from $0.21\times10^6 m^3$~$17.29\times10^6 m^3$ in 1997(the 11th year), until 2000(the 14th year) the scour and silting of reservoir tends to be mild. The condition of inflowing water and sediment is the main factor to influence the fluvial processes of reservoir. During a high flow year such as the year of 1989, scour occurs in the reservoir, while during middle and low flow years such as the year of 1992, sediment deposits a lot in the reservoir.

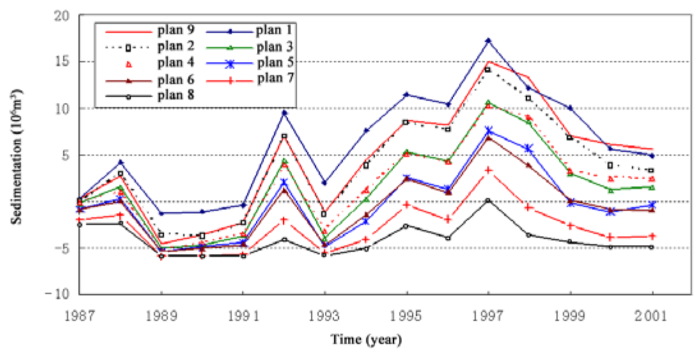


Fig.5 Accumulated sedimentation of Daxia of paln1~plan9

(3) The fluvial processes in the reservoir are closely related to the pool level. From plan 1 to plan 8, the pool level falls one by one, and the amount of sedimentation decreases correspondingly.

(4) Sediment mainly deposits in the gorge area, which accounts for about 90% of the total. Sedimentation in Shenchuan area depends on the pool level, which increases as the pool level rises.

4.3.3 Comparisons Among Eight Proposed Plans

Among plan 1 ~ plan 8, sedimentation of plan 4 amounts to $10.16\times10^6 m^3$, which is smaller than that of plan1 ~ plan 3, and larger than that of plan 5 ~plan 8, and the reservoir capacity is larger than that of plan 1~ plan 3, and smaller than that of plan 5 to plan 8. The average pool level of plan 4 is equivalent to plan 3, and the pool level of plan 4 is much higher than that of plan 5 ~ plan 8. So plan 4 could be considered to be the most reasonable plan among plan 1 ~ plan 8, that can give attention to both keeping quite high pool level and controlling reservoir sedimentation.

4.3.4 Discussion of Practical Plans

Considering present operation state of the reservoir and the efficiency of power generation, the pool level of plan 1 ~ plan 8 is a little low, which could not meet the demands of power generation. So based on plan 1 ~ plan 8, a flow discharge of 800 $m^3/s$ is further chosen as one of the critical discharges, and the pool level rises suitably, plan 9 is proposed (Table 4).

The accumulated deposition of plan 9 amounts to $15.02 \times 10^6 m^3$ in 1997(the 11th calculated year). It is obvious that the reservoir sedimentation of plan 9 is more serious than plan1~plan6. A measure to scour the deposit should be taken into account, that is, to drop operation pool level within a short time at the end of a flood season to scour the deposit in the reservoir. Then, plan 10 ~ plan 17 are proposed. Details of plan 10 ~ plan17 are listed in Table 6.

Table 6　Details of plan 10~plan 17

| Plans / Items | Plan 10 | Plan 11 | Plan 12 | Plan 13 | Plan 14 | Plan 15 | Plan 16 | Plan 17 |
|---|---|---|---|---|---|---|---|---|
| Discharge($m^3/s$) | 1000 | 1000 | 1500 | 1500 | 1000 | 1000 | 1500 | 1500 |
| Pool level(m) | 1472 | 1474 | 1472 | 1474 | 1472 | 1474 | 1472 | 1474 |
| Time(Day) | 3 | | | | 5 | | | |

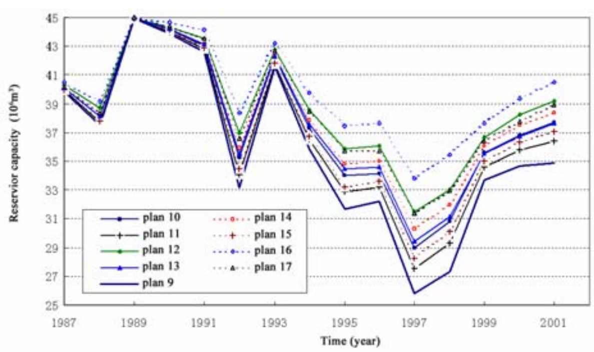


Fig.6 Reservoir Capacity Changes of Plan10~Plan17

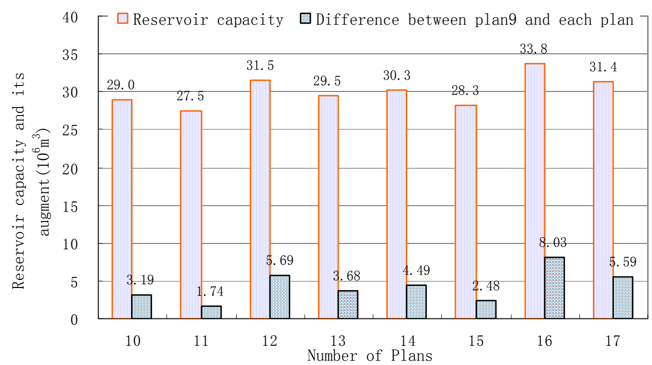


Fig. 7 Comparison of Reservoir Capacity of Plan 10 ~ Plan17 with Plan9

Compared with plan 9, the amount of sedimentation of Plan 10 ~ plan 17 in the year of 1997 reduces to $1.88 \times 10^6 m^3$ ~$8.22 \times 10^6 m^3$. This shows that lowering water at the end of a flood season is effective in reducing deposition. Fig.6 and Fig.7 show the changing processes of the reservoir capacity and the comparison with plan 9.

Considering the effectiveness of scour sediment, the operation feasibility of pool level and the discharge, plan 13 is the best plan among plan 10~plan17. Plan 13 is a plan that lower pool level for three days, its pool level is 1474m, and its discharge is 1500 $m^3/s$ at the end of a flood season, which can give attention to both controlling reservoir sedimentation and maintaining power generation benefit.

## 5. CONCLUSIONS

(1) The 1-D sediment mathematical model established in this paper is based on non-equilibrium sediment transport theory, meanwhile scour and deposition, various features of reservoir deposition, high sediment content and density flow of a heavily sediment–laden river are fully considered. Through calibration and verification, the model is reasonable and applicable for Sanzuodian Reservoir and Daxia Reservoir.

(2) Sanzuodian Reservoir built on the heavily sediment–laden Yinhe river is confronted with serious sedimentation and a great loss of reservoir capacity, losing 72% of its original reservoir capacity after 30 year operation. So a way to maintain a long-term available capacity should be studied. The research shows that the reservoir deposition is a typical delta, and discharging sediment rate is less than 10% during 50 year's operation. Density flows can increase discharging sediment rate quite a bit when big floods occur. By studying several typical design plans, the stage flood storage operation is recommended, which operates at a low pool level at initial stages and raises the pool level by stages.

(3) Daxia Reservoir built on the upper Yellow River lost 50% of its original reservoir capacity after 3 year operation, and the main concern for it is how to recover and maintain a long-term capacity. Through studies on economical pool level, by using the characteristics of the inflowing flow and sediment load highly concentrating in flood seasons, a critical value of discharge and sediment concentration is introduced. The reservoir adjusts the pool level according to the inflowing flow and sediment load, when the flow discharge or sediment concentration exceeds a critical value in a flood season, lowering the operation pool level, and further lowering the operation pool level at the end of a flood season to scour the deposit in the reservoir, which is the optimum operation mode and can give attention to both controlling reservoir sedimentation and maintaining power generation benefit.

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