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Reservoir Sedimentation Management in Hydropower Plant Regarding Flood Risk and Loss of Power Generation

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ABSTRACT:
Reservoir sedimentation is one of the most important problems for securing long term hydropower plant operation in the future. Reservoir sedimentation causes various problems. There are two severe problems, one is increasing flood risk of infrastructures around reservoirs, and the other is decrease of the active water capacity of reservoir leading to loss of power generation.
The first problem is well known. In this paper considering the properties of reservoir sedimentation, facility condition and infrastructures around reservoir, several measures have been proposed and verified regarding their feasibilities. The second problem is not known and needs more study, therefore this paper has evaluated influence of reservoir sedimentation on loss of power generation, and has discussed measures against the problem.

Keywords: Reservoir sedimentation, Hydropower plant, Increasing flood risk, Loss of power generation

1. INTRODUCTION

Sustainability of hydropower stations is endangered by reservoir sedimentation. Practically many reservoirs of hydropower stations are under sedimentation control or under planning. In 2005, Japan electric power civil engineering association researched 354 reservoirs of hydropower plants, which had over 15m height dam or over 1 million m^3 water capacity in order to analyse the impacts of increasing sedimentation. Table 1 shows the result of this analysis where 95 reservoirs are influenced by increasing sedimentation and the major influence is increasing flood risk. Loss of power generation is not the major problem at this analysis.

In order to solve the problem of increasing flood risk, this paper discusses the current sedimentation problems by considering the differences of two major types of hydropower plants, which are storage type and regulating type. Using the result of the analysis, effective and economical reservoir sedimentation management measures which are mainly conducted by reservoir draw-down operation are proposed.

Table 1. Influence by sedimentation on hydropower reservoirs

Items	Numbers
Total number of investigated reservoirs	354
Reservoirs influenced by sedimentation	95
Specific influences	
Increasing flood risk	91
Environmental problem	5
Loss of power generation	6

Analysis on reservoirs that have over 15m height dam or over 1 million m^3 storage capacity

Also this paper has focused on loss of power generation by sedimentation in hydropower plant, which is not the big problem now. By the analysis of relationship between water use efficiency and sedimentation in active water capacity, the influence of reservoir sedimentation on hydropower plant operation has been indicated in some reservoirs. And we have found that some reservoirs need sedimentation control against loss of hydropower plant operation.

2. SEDIMENT MANAGEMENT MEASURES FOR INCREASING FLOOD RISK

2.1. Storage Reservoir and Regulating Reservoir

Cascade hydropower plants are usually placed in a river basin as shown in Fig. 1 where the large generator with the large storage reservoir for power peak is placed on the upstream and smaller generators with smaller reservoirs for level power demand are placed on the downstream of the river. Storage reservoir is working as

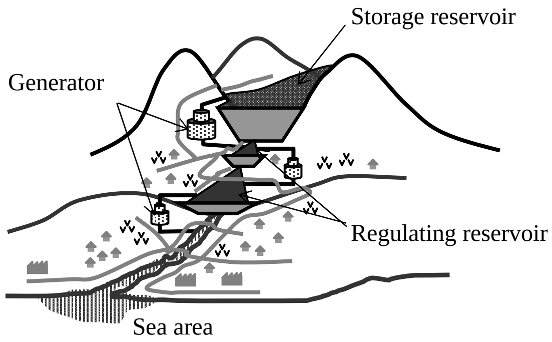


Figure 1. Location and position of hydropower stations

a catchment of flood flow caused by typhoon, seasonal rain and melting snow. Regulating reservoir is set for adjustment between water supply and power demand in the short term per a day or a week.

Storage and regulating reservoirs are very different in two points of views. Fig. 2 shows the relation of storage and regulating reservoir capacity. By comparing two types in terms of total capacity, the storage types are about 3 to 100 times larger than the regulating ones. Regarding the active water capacity that can be used for power generation, the storage types are about 10 to 200 times larger than the regulating ones. These differences are caused by the difference of available draw-down depth in active water capacity. Average draw-down depth in storage type reservoirs is more than 25 meters, and that in regulating ones is less than 5 meters.

2.2. Characteristics of Reservoir Sedimentation and Dam Facility Conditions

In order to select an appropriate sediment management strategy according to reservoir conditions, characteristics of sedimentation (position, sediment inflow rate) and dam facility conditions were measured by J-Power Electric Company. In total, 14 storage and 21 regulating type reservoirs are operated by J-Power. The average

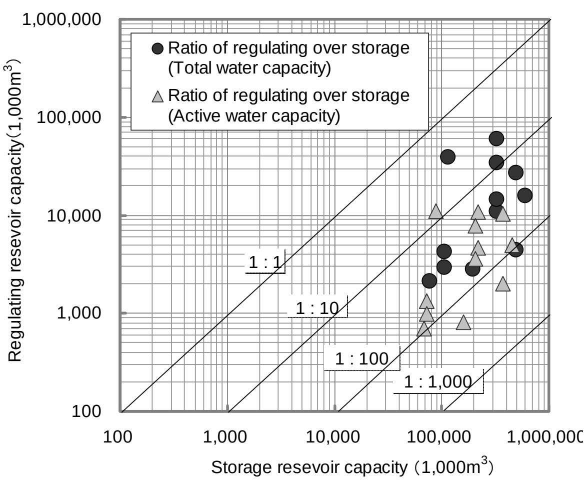


Figure 2. Comparison of storage and regulating reservoir capacity

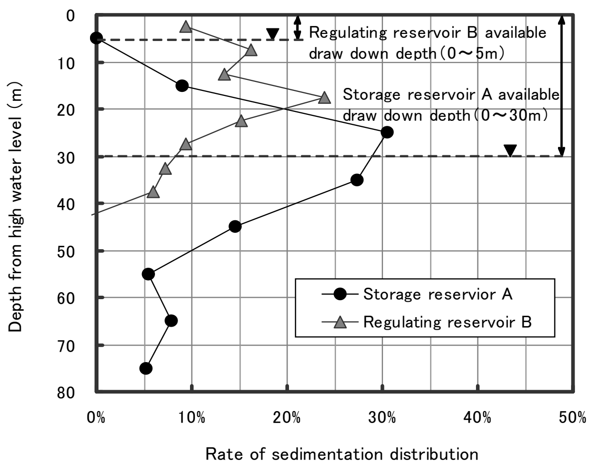


Figure 3. Rate of sedimentation distribution

ages after dam completion are 47 years old in storage reservoir and 43 years in regulating type.

Fig. 3 shows rate of vertical sedimentation profiles in reservoirs. Storage reservoir A and regulating reservoir B are located in the same river. It is found that there is high rate of sedimentation at high water level in regulating reservoirs which causes high flood water level. Available draw-down depth and vertical sedimentation profiles are correlated which indicates that water level control can be effective for sedimentation control.

Fig.4 shows relation of sedimentation inflow rate and life span of reservoirs. Life span can be defined as the ratio of the reservoir capacity over annual inflow sediment volume. Plot areas of storage reservoirs and regulating reservoirs are separated. Highlighted reservoirs by dotted circle are under sedimentation control. Many regulating reservoirs are highlighted because of their huge sedimentation near high water level. Moreover, it is noticed that the necessity of sedimentation control does not depend on sediment inflow rate, but on the reduction of the reservoir life span.

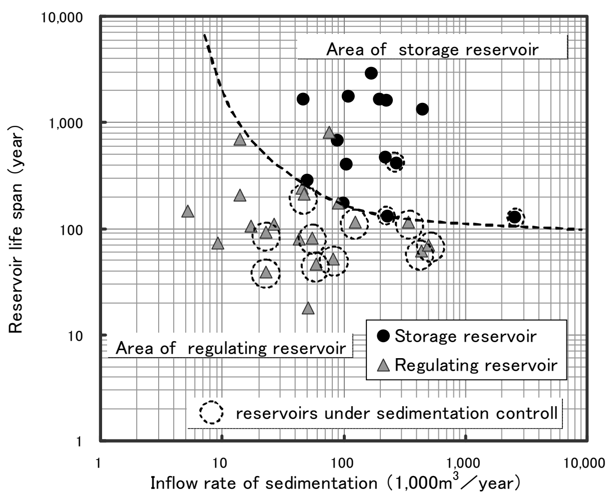


Figure 4. Relation of sedimentation discharge and life span of reservoirs

Table 2. Impacts of reservoir sedimentation on infrastructures

Items	Storage reservoir（14）	Regulating reservoir（21）
Total water capacity (average)	195,500,000m^3	11,900,000m^3
Active water capacity (average)	149,800,000m^3	3,700,000m^3
Rate of sedimentation to total water capacity	11.0%	22.3%
Rate of sedimentation to active water capacity	6.5%	4.31%
Rate of reservoir that has inundation area	57.1%	71.4%
Area of inundation	4,100m^2／reservoir	22,700 m^2／reservoir
Road length of inundation	0m／reservoir	403m／reservoir
Bridge affected by flood water level	0.1 bridge／reservoir	1.5 bridge／reservoir

Table 2 shows impacts of sedimentation in regulating and storage reservoirs on surrounding infrastructures (bridge and road). Flood water level is the maximum one under the design flood discharge. It can be noticed that regulating type has a severe sedimentation problem more than storage type reservoirs. For example, the regulating reservoir has about 5 times inundation area, 15 times number of affected bridge compared with the storage reservoir. Moreover, no affected road is found in storage reservoirs. There are 2 reasons that make these differences; the first is location of reservoirs and the second is sedimentation condition determined by reservoir operation. Compared to storage reservoir sites, regulating reservoirs are located relatively in downstream river near large cities that have more infrastructures like roads, bridges, farms, factories and houses around reservoirs. Since a regulating reservoir usually has very little available draw-down depth, the inflow sediment will be deposited in almost higher water level.

It can be concluded that it is more important to implement sedimentation control in regulating reservoirs than in storage ones.

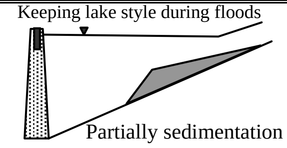
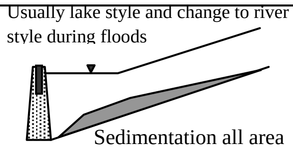
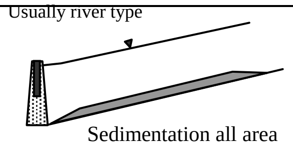
2.3. Effective Management Measures for Regulating Type Reservoir Sedimentation

We already know that sedimentation management of regulating reservoir is very important, and we have to plan effective management measures considering properties of sedimentation and reservoir operation. Regulating reservoirs can be classified to 3 types by shape of flood water level and condition of sedimentation. Table 3 summarizes characteristics of these types, which are river, lake and intermediate types.

Also table 3 shows effective sediment management measures for each type of reservoirs. According to the condition of each type, shear velocity, deposition and erosion location during flood event, appropriate sediment management measures are proposed as shown in the Table 3. It is verified by numerical analysis that these management measures were all physically effective.

Lake type reservoir is relatively large which is similar to lake even at the time of flood and has sedimentation partially in the upstream of reservoir. Lake type reservoir has generally large dam whose average height is 58m. In this case, design flood discharge is small about 2,700m^3/sec and average ratio of spillway gate height to dam height is about 13%.

Table 3. Effective sediment management measures for 3 regulating reservoir types

Type	Shape of flood water level Condition of sedimentation	Height of dam*	Design flood discharge*	Ratio of spillway gate height to dam height (%)*	Number of dams	Effective sedimentation management measures
Lake		58m	2,700m^3/s	13%	5 (26%)	Draw-down operation during flood and guide sedimentation to lower dead space. Addition of facility like sediment bypass or sediment trapping dam
Intermediate		42m	4,000 m^3/s	29%	9 (48%)	Draw-down operation during flood and guide sedimentation to lower dead space or pass through the gate. Excavate some sedimentation for total management.
River		27m	8,000 m^3/s	54%	5 (26%)	Draw-down operation during flood, and pass sedimentation through the gate.

*average figures of dams J-Power owns

Table 4. Cost comparison between draw-down operation and excavation for 3 regulating reservoir types

Type	Case No.	Contents of measure	Cost/30 years	Model reservoir
Lake	CASE-L01	Draw-down operation Sediment bypass	¥9,780million	Reservoir capacity : 43,000,000m^3 Catchment area : 801km^2 Annual sedimentation : 250,000m^3/a year Remark : large sediment discharge from a branch into reservoir
	CASE-L02	Sediment bypass Excavation (60,000m^3)	¥20,310million	
	CASE-L03	Draw-down operation Excavation (100,000m^3)	¥20,334million	
	CASE-L04	Excavation (160,000m^3)	¥31,524million	
Intermediate	CASE-I01	Draw-down operation Excavation (15,000m^3)	¥ 4,361million	Reservoir capacity : 4,420,000m^3 Catchment area : 217km^2 Annual sedimentation : 30,000m^3/a year
	CASE-I02	Excavation (30,000m^3)	¥ 5,236million	
River	CASE-R01	Draw-down operation	¥ 1,066million	Reservoir capacity : 9,930,000m^3 Catchment area : 1,692km^2 Annual sedimentation : 30,000m^3/a year
	CASE-R02	Excavation (30,000m^3)	¥4,434million	

River type reservoir is relatively small that looks like river and has sedimentation all over area. It has relatively small dam whose average height is 27m. In this case, design flood discharge is large about 8,000m^3/s and the ratio of spillway gate height to dam height is about 54%.

Intermediate type reservoir looks like between lake and river types during the flood and has sedimentation all over area. It has dam whose average height is 42m. In this case, design flood discharge is around 4,000m^3/s and the ratio of spillway gate height to dam height is about 29%.

Effectiveness of draw-down operation depends on the type of reservoirs. In the river type reservoir, bed load material is easily passed through the spillway, while it is almost sedimented in the lake type. In lake and intermediate types of reservoir there will be remained sedimentation located at upstream area of reservoir even after draw-down operation, and combination with excavation will be needed for total sediment management.

2.4. Economic Superiority of Sediment Management Measures Mainly Conducted by Draw-Down Operation

There are several measures of sediment management in reservoir. One of the most usual ways is excavation. Table 4 shows the cost comparison between proposed measures and the usual one which is mainly conducted by excavation. By numerical analysis, these different measures are the almost same on the viewpoint of flood risk mitigation. Cost includes constructing and maintenance of bypass system, excavation, fixture of disposal area and transportation. In case of the lake type environmental protection measure and loss of power production are added.

Lake type needs sediment management if it has large sediment discharge from a branch into the reservoir. Sediment bypass is very effective if it is very expensive to construct sediment bypass. From a viewpoint of long term use of power plant, e.g. 30 years, 50 years, it would be reasonable to pay the initial cost. On the other hand, excavation is not economical at the situation where large volume of reservoir has much sedimentation volume.

Intermediate type needs excavation whether draw-down operation is conducted or not. But it is more economical to implement draw-down operation than no draw-down operation.

Sediment management in river type is completed by draw-down operation, and it is much more economical than excavation.

2.5. Sediment Management by Draw-Down Operation

We verified the effectiveness of draw-down operation for sedimentation control in regulating reservoirs. Regulating reservoir is usually under operation of smaller active water depth, and it causes much deposition in the same area of reservoir. On the other hand, it is very effective to make regulating reservoir under such operation as to lower the dam reservoir water level below usual active water depth. Draw-down operation reduces the head of power generation and loses some power generation, but it is still more economical than excavation.

3. EVALUATION OF THE SEDIMENT INFLUENCE ON POWER GENERATION

3.1. Introduction

Fig. 5 shows schematic drawing of sedimentation and active water capacity in reservoirs. Fig. 6 shows that sedimentation is increasing in the reservoir and thus active water capacity is decreasing in some hydropower plants. But Table 1 shows only 6 of 354 reservoirs are influenced by sedimentation on their hydropower plant operation. There are 2 major reasons of it. One is that small loss of active water capacity could be almost covered by plant operation abilities, and the other is that we hardly realize the loss of power generation because of its smallness and difficulty to find the actual loss in the annual big fluctuation of river flow discharge.

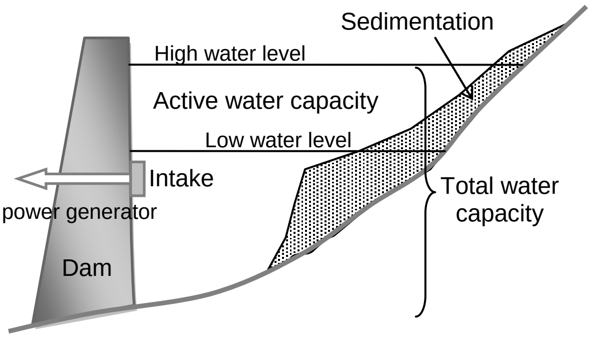


Figure 5. Schematic drawing of sedimentation and active water capacity in a reservoir

In this chapter, we picked up some hydropower plants to analyse the relation between sedimentation progress and loss of power generation. And countermeasures have been discussed based on the result of the analysis.

3.2. Relation between Sedimentation and Power Generation

Fig. 7 shows relation between sedimentation in active water capacity and water use efficiency at C reservoir. In vertical axis, water use efficiency means yearly ratio of total turbine discharge volume to total inflow volume. Plots in the figure are distinguished by every ten years. This figure indicates that sedimentation actually influences on hydropower plant operations since water use efficiency is lowering according to the decrease of active water capacity. It is not only by sedimentation but also by some other events such as change of operation rules, maintenance and climate change.

7 reservoirs shown in Table 5 were picked up to analyse the history of the relation between sedimentation in active water capacity and water use efficiency which is described in Fig. 8. Annual turnover rate of reservoir water in Table 5 is defined as the ratio of the reservoir total capacity over annual inflow water volume. In Fig. 8 active water capacity and water use efficiency are averaged every ten years (60'~70', 71'~80', 81'~90', 91~00', 01'~10') and the relations are different on dams. Reservoir C, shown in Fig. 7, is in tendency that sedimentation is increasing and water use efficiency is

Table 5. Characteristics of reservoirs for analysis of the relation between sedimentation in active water capacity and water use efficiency

Reservoir	Operation	Active water capacity	Annual turnover rate of reservoir water
A	Storage	89,000,000m^3	9.5
B	Storage	72,500,000m^3	3.7
C	Storage	22,800,000m^3	8.9
D	Storage	205,444,000m^3	15.0
E	Storage	458,000,000m^3	2.6
F	Regulating	11,000,000m^3	44.8
G	Regulating	980,000m^3	192.2

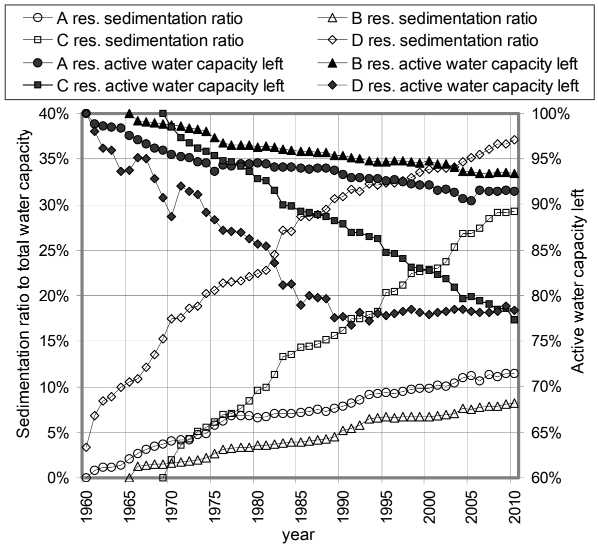


Figure 6. Relation between sedimentation and active water

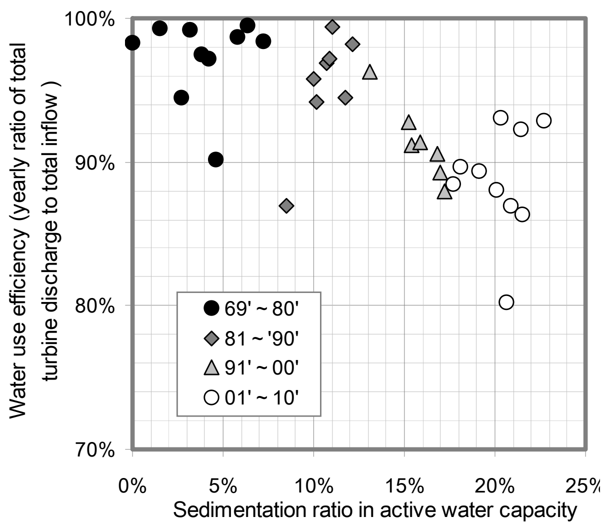


Figure 7. Relation between sedimentation in active water

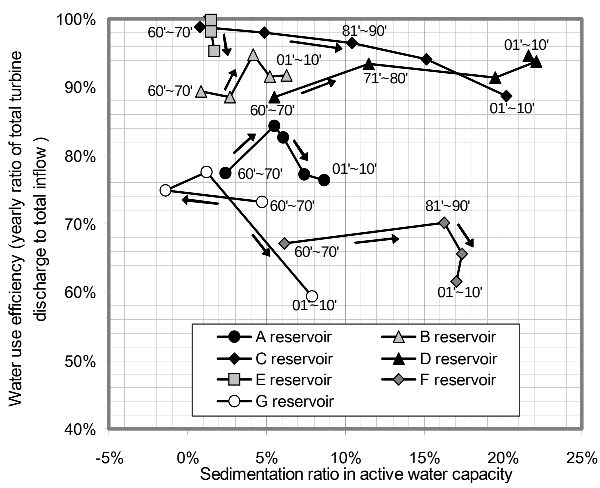


Figure 8. Time history of the relation between sedimentation in active water capacity and water use efficiency

lowering as time goes. Reservoir C has relatively high water use efficiency and it is important to store water during floods and to keep reservoir capacity as much as possible without sedimentation. Moreover, daily operation for power generation is based on the standard dam water level for each period. If dam water level is higher than the standard water level, it is needed to make daily turbine discharge more. Therefore it would be the more strict operation for power generation if reservoir has the more sedimentation in active water capacity.

Reservoir A and B are in tendency that water use efficiency is almost the same level though sedimentation is increasing. In resent 20-30 years, two reservoirs have been losing their water use efficiency gradually. Reservoir B has relatively high water use efficiency, and it could lose its water use efficiency like reservoir C hereafter. Reservoir A does not have high water use efficiency, but has low annual turnover rate of reservoir water shown in Table 5. For reservoir A, it is also important to storage water like reservoir C.

In reservoir F and G, sedimentation in active water capacity and water use efficiency are not related each other. Since annual turnover rates of reservoir water are high and much water always flows into them, they do not need to storage water relatively.

In reservoir D, although sedimentation has been increasing, water use efficiency is maintaining the same level. Reservoir D is large enough to be able to continue the same operation even if reservoir sedimentation is increasing.

In reservoir E, sedimentation has been almost maintaining same, and water use efficiency has been lowering about 5% in 50 years. There is no relation between them. This indicate that there are some reasons except sedimentation to lower water use efficiency.

Relations between sedimentation in active water capacity and water use efficiency are various. Power generation in some reservoirs have been influenced by sedimentation but others have not. Also mechanisms of influence are various. We found that some reservoirs need sedimentation management measure conducted now or in the future.

3.3. Sediment Influences on Power Production

It is found that there is a relation between sedimentation in active water capacity and water use efficiency in some reservoirs. If annual turnover rate of reservoir water is low, water use efficiency could be influenced by sedimentation. Lowering water use efficiency has been occurred not only by sedimentation but also by change of operation rules, maintenance and also climate change.

In purpose of planning countermeasures against loss of generation in hydropower plants, we have to continue to analyse relation between sedimentation in active water capacity and water use efficiency, and to expand analysing scope to dam operation and cascade hydropower system in the river.

4. CONCLUSION

The paper presents the reservoir sedimentation in hydropower stations, considering operation rules of storage type regulating reservoirs. Based on specific characteristics and dam facility condition of sedimentation, we can propose suitable countermeasures against reservoir sedimentation by classifying the regulating reservoir to 3 types. Also influence by sedimentation on power generation is discussed on this paper. Result includes some useful findings as follows.

1) It is more important to manage sedimentation control in regulating reservoirs than storage ones. Because that sedimentation in regulating ones is dominant to surrounding infrastructures more than the storage ones.
2) There is clear relationship between reservoir operation and sedimentation progress.
3) It is effective to classify regulating reservoirs into 3 types; lake, river, and intermediate types, and propose suitable countermeasures depending on each conditions. The measures for river type and intermediate type are mainly conducted by draw-down operation which is physically effective and economically feasible comparing to other alternative measures.
4) There is a clear relation between sedimentation in active water capacity and water use efficiency. If annual turnover rate of reservoir water is low, water use efficiency could be influenced by sedimentation.
5) Some reservoirs need sediment management to minimize loss of power generation.

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