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Influence of reservoir sedimentation on power generation

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ABSTRACT: Reservoir sedimentation is one of the most important problems for securing sustainable hydropower plant operation in the future. We have already classified the sedimentation problem regarding the reservoir types and proposed some effective sediment control measures for regulating reservoirs. On the other hand, sedimentation problems in storage reservoirs need to be more studied. In this paper, we have evaluated the influence of sedimentation progress in storage reservoir on power generation by analyzing long-term operation record, and predicted the future influence of storage reservoir sedimentation assuming active storage capacity decreasing.

1 INTRODUCTION

Reservoir sedimentation is one of the most important problems for securing sustainable hydropower plant operation. Figure 1 shows location and position of hydropower plants in a river. Usually couples of hydropower plants are installed consequently in a river to use river water efficiently. In upstream of a river, a storage reservoir with large capacity is located to store inflow water by seasonal rain with typhoon and melting snow. And regulating reservoirs with small capacity are located in downstream of the river to regulate inflow water in scale of a day or a week for power generation.

We have already classified the sedimentation problems regarding the reservoir types and concluded that there is present severe flood risk in regulating reservoirs. Then we have proposed effective sediment control measures for regulating reservoirs, which are mainly conducted by drawdown operation, regarding their properties. On the other hand, sedimentation problems in storage reservoirs are not clear and need to be more studied shown in Figure 2.

Japan electric power civil engineering association (2005) and JCOLD (2010) researched the sedimentation problems in Japanese hydropower reservoirs and concluded that sedimentation influence on power generation was not severe in present. Although sedimentation ratio in active water capacity of storage reservoirs is averaged 6.5%.

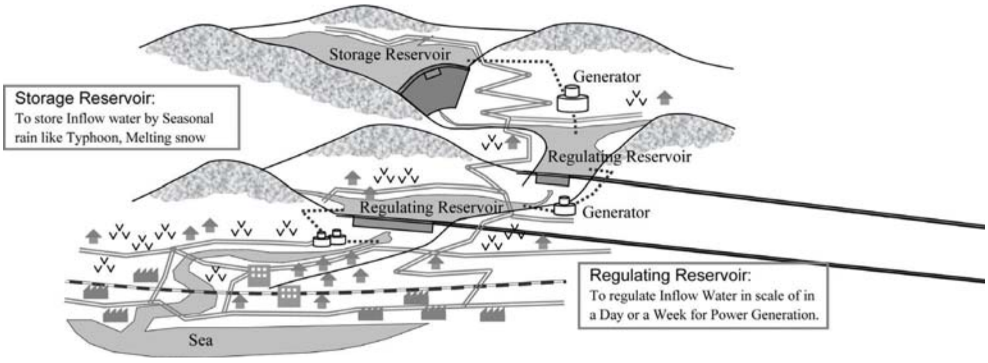

Figure 1. Location and position of hydropower plants.

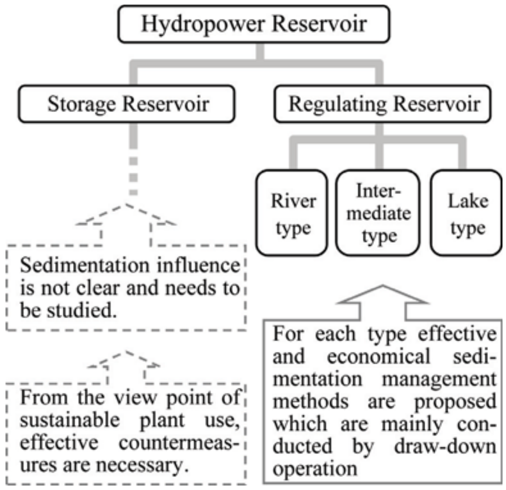

Figure 2. Sedimentation management in hydropower reservoir.

In this paper, we studied influence of sedimentation in storage reservoir on power generation, predicted the influence in the future, and discussed countermeasures.

2 SECULAR CHANGE OF POWER GENERATION

Figure 1 shows roles of storage reservoir, which is to store inflow water by seasonal water inflow, with typhoon and melting snow. It means that it is important for storage reservoir to have a large active water capacity. Planning storage type hydropower plant, it is designed that active water capacity has more than 20% of yearly total water inflow, this means storage reservoir should have less than 5 reservoir turnover ratio in active water volume. Table 1 shows secular change of reservoir turnover ratio in active water capacity which J-POWER owns. Figure 3 shows the area where 7 reservoirs are located. They show all of 7 reservoirs have higher turnover ratio than original ratio because of capacity loss by sedimentation. However, problems of generation loss caused by capacity loss have not been issued in all of seven hydropower plants.

To evaluate the influence of sedimentation in storage reservoir on power generation, water use efficiency of each plant is calculated by Equation (1) per annum.

$$\textit{Water use efficiency} = \frac{\textit{Yearly total turbine discharge volume}}{\textit{Yearly total inflow volume}} \quad (1)$$

Table 1. Reservoir turnover ratio (active water capacity) original and as of 2011.

Reservoir (plant)	Original active cap. (1,000 m^3)	Start of operation	Reservoir turnover ratio (active cap.) Original	2011
A	458,000	1960	3.14	3.19
B	330,000	1961	4.14	4.21
C	68,000	1962	4.42	4.47
D	72,500	1970	5.33	5.65
E	50,000	1964	7.56	7.66
F	89,000	1960	12.55	13.63
G	205,444	1956	24.98	31.97

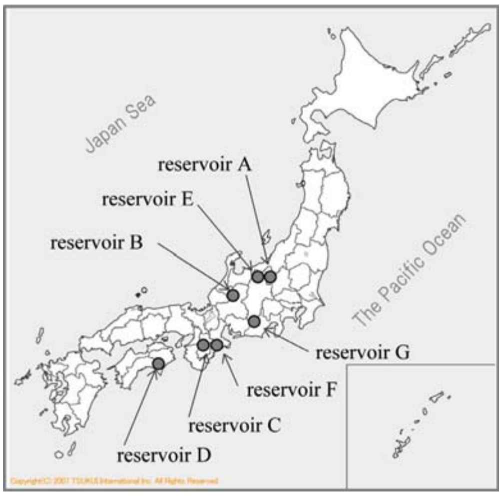

Figure 3. Location of reservoirs (A~G).

Water use efficiency is ratio of yearly turbine discharge volume to yearly inflow volume. When it rains much in reservoir catchment area and a reservoir discharges much water from spillway gate, then water use efficiency of the year is calculated low.

Table 2 shows summary of water use efficiency calculation result with from 1988 to 2011 record of 7 hydropower plants. Six reservoirs have sedimentation progressed and five plants have decreasing water use efficiency through the period of the record. The summary indicates that reservoir sedimentation in storage reservoir is gradually increasing and water use efficiency is gradually decreasing.

Figures 4 and 5 show secular changes of water use efficiency in hydropower plant E and D. On figures, regression line, inclination, yearly total

Table 2. Secular change of water use efficiency.

	Sedimentation ratio		Water use efficiency	
Res. (plant)	1988~2011 average	1988~2011 change*	1988~2011 average	1988~2011 change*
A	1.68%	0.058%/yr.	99.67%	–0.059%/yr.
B	1.59%	0.045%/yr.	99.11%	+0.035%/yr.
C	1.10%	0.066%/yr.	78.73%	+0.485%/yr.
D	5.61%	0.105%/yr.	91.22%	–0.158%/yr.
E	1.36%	0.133%/yr.	97.89%	–0.183%/yr.
F	7.94%	0.058%/yr.	78.84%	–0.104%/yr.
G	21.86%	–0.027%/yr.	89.82%	–0.125%/yr.

*Change means inclination of regression line.

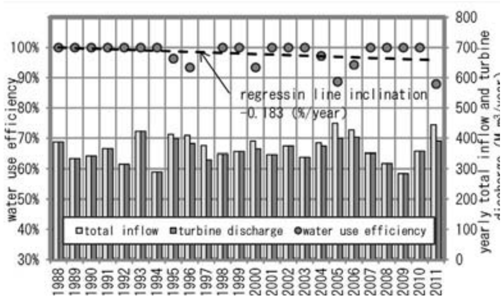

Figure 4. Secular change of water use efficiency in hydropower plant E (1988–2011).

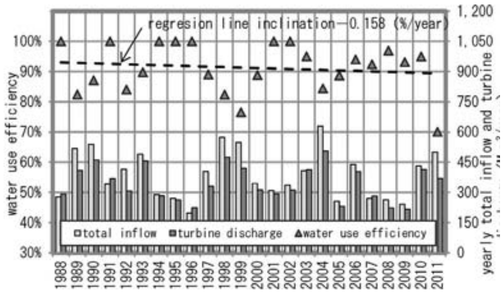

Figure 5. Secular change of water use efficiency in hydropower plant D (1988–2011).

inflow volume and turbine discharge are placed. Regression lines in both figures are downward to right. Two hydropower plants have different ways of water use. Hydropower plant E is on Japan Sea side, water discharge is tranquil through seasons compared to on the Pacific Ocean side. Reservoir E is expected to be averaged inflow including snow melting discharge and has less dam discharge than Reservoir D, and water use efficiency is high every year almost 100%. Hydropower reservoir D has heavy seasonal discharge induced by typhoon and weather front and has many occasions of dam spillway gate discharge every year. Then water use efficiency of hydropower D plant is lower around 90%.

3 FACTORS OF INFLUENCE ON POWER GENERATION

3.1 *Active water capacity*

Water use efficiency does not depend only on inflow regime, but on active water capacity. Figure 6 shows the typical inflow regime of reservoirs on Japan sea side and ones on the Pacific Ocean side. Inflow regime is presented by total water inflow volume more than ninety-five-day discharge. Ninety-five-day discharge is almost equal to discharge for firm power. When inflow is more than ninety-five-day discharge, it tends to discharge water through dam spillway gate not through the turbines.

Figure 7 shows relation among water use efficiency, inflow regime and active water capacity, of hydropower plant E and D. Figure 7 indicates that

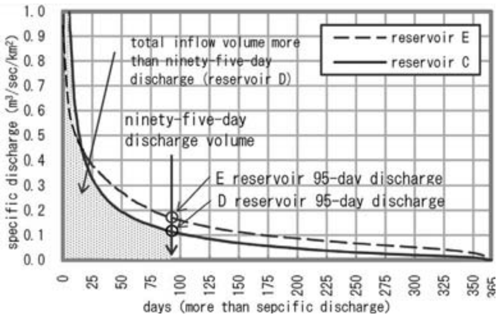

Figure 6. Inflow regime of reservoir E and C.

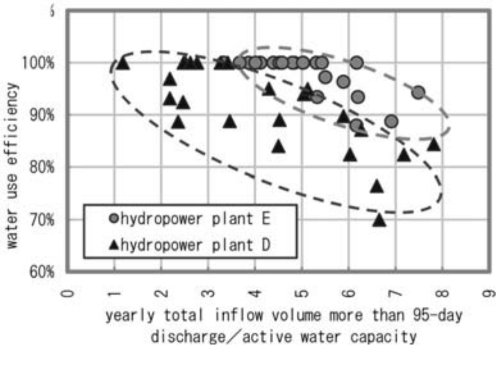

Figure 7. Relation between water use efficiency and total inflow volume more than 95-day discharge.

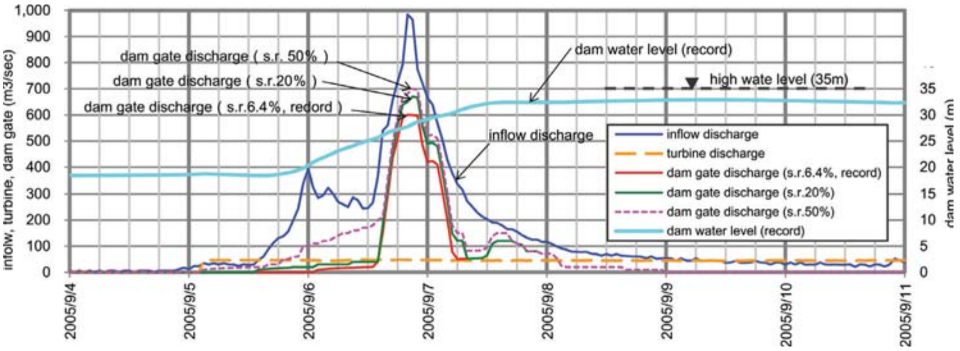

Figure 8. Comparison of dam gate discharge condition between record and simulation result at reservoir D.

Table 3. Summary of comparison between record and simulation result at reservoir D.

Sedimentation ratio in active water capacity	Maximum of dam gate discharge	Date of dam spillway gate open	Total volume of dam gate discharge
6.4% (2005)	601 m^3/sec	2:00, 6th Sep.	29,458,000 m^3
20%	670 m^3/sec	14:00, 5th Sep.	34,575,000 m^3
50%	700 m^3/sec	3:00, 5th Sep.	45,800,000 m^3

Average yearly total inflow volume: 384,572,000 m^3.

three index are correlated clearly. If total water inflow volume which is more than ninety-five-day discharge is high, water use efficiency is low. And if active water capacity is small, water use efficiency is low, too. These things mean that progress of reservoir sedimentation makes active water capacity small, clear influence on power generation results. On the other hand, keeping active water capacity large preventing from sedimentation is very important for sustainable use of hydropower plant.

Figure 8 shows time-discharge curves of reservoir D during the flood time. When flood occurred sedimentation ratio in active water capacity was 6.4% in fact. Simulation results in case of sedimentation ratio 20% and 50% are shown on Figure 8. Table 3 shows comparison of dam gate discharge condition between the record and simulation results. Sedimentation progress in active water capacity makes dam gate discharge volume larger, and start of dam gate open earlier.

3.2 *Maximum turbine discharge*

Water use efficiency also depends on the maximum turbine discharge. Figure 9 shows relation between water use efficiency and the maximum turbine discharge. It is clear that hydropower plant has the larger maximum turbine discharge, the plant has the higher water use efficiency. This is opposite way from way of planning the hydropower plant.

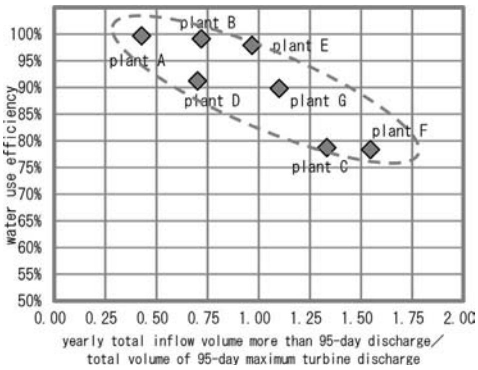

Figure 9. Relation between water use efficiency and maximum turbine discharge.

4 WATER USE EFFICIENCY EVALUATION MODEL

4.1 *Conceptual diagram*

Figure 10 is the conceptual diagram of water use efficiency and factors influencing on the efficiency. The conceptual model is based on the result of chapter 3. Power generation (Water use efficiency) is influenced by relation between active water capacity and inflow regime and relation between the maximum turbine discharge and inflow regime. When hydropower plant is under planning, these relation, power demand, and economic efficiency are considered to fix the design of the plant. Now, 50 years after installation, sedimentation in active

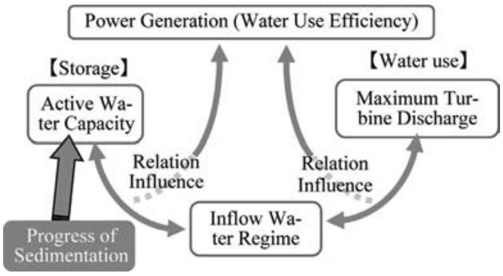

Figure 10. Conceptual diagram of water use efficiency and factors.

Table 4. Multi regression analysis result.

Plant reservoir	Coefficient	Water use efficiency	
		Record	Calculation
A	$a1 = +0.03509$	99.67%	101.79%
B	$a2 = -0.06467$	99.11%	97.50%
C	$a3 = -0.1183$	97.89%	92.84%
D	$b = +1.065$	89.82%	91.30%
E		78.73%	84.35%
F		91.22%	90.91%
G		78.34%	76.08%

Correlation coefficient 0.926.

water capacity has been progressed over estimation, and water use efficiency has been gradually decreasing.

4.2 *Evaluation model*

For prediction of the future influence on power generation by progressed sedimentation in storage reservoir, evaluation model of water use efficiency is needed. Model structure is shown in Equation (2), coefficients *a1*, *a2*, *a3* are determined by multi regression analysis.

$$\begin{aligned}&\textit{Water use efficiency}\\&= +\frac{a1 \times \textit{total inflow volume} + a2 \times \textit{total volume more than 95-day discharge}}{\textit{Active water capacity}}\\&\quad + \frac{a3 \times \textit{total water inflow volume more than 95-day discharge}}{\textit{Maximum turbine discharge for 95 days}} + b\end{aligned} \tag{2}$$

Result of multi regression analysis is summarized on Table 4. Correlation coefficient is 0.926. Record and results of water use efficiency are similar, and evaluation model has sufficient reliability for future prediction calculation.

5 SEDIMENTATION MANAGEMENT FOR STORAGE RESERVOIR

5.1 *Sedimentation influence in the future*

Water use efficiency in the future of 7 hydropower plants A~G are evaluated by Equation (2). Figure 11 shows evaluation results. This indicates that progress of sedimentation in storage reservoir makes water use efficiency of plants low, and influence of sedimentation are varied. Efficiency of plant C, D, F which have heavy rainy season are influenced much by sedimentation. On the other hand, efficiency of plant A, B, E, G are not so much. This is the reason why reservoir which has heavy rainy season needs active water capacity for storage of flood inflow water more than the other reservoirs.

Average of sedimentation ratio of hydropower reservoir is about 10%. According to estimation result, water use efficiency is not much influenced in case of 10% sedimentation. Research result of Japan electric power civil engineering association (2005) and JCOLD (2010) are appropriate.

5.2 *Sedimentation management*

Hydropower plant is expected to generate sustainably. Influence on generation by sedimentation in the future, especially in plant which has heavy rainy season, is elucidated in chapter 5.1. Sedimentation management is needed from the two points of view bellow. The first point is that rack of storage function of reservoir which is installed upstream of the river damaged largely to hydropower system in the river, including regulating type hydropower plant downstream of the river. The second point is that storage reservoir is too large to excavate sedimentation in reservoir. It is better to take away before sediment flows into the reservoir.

Table 5 shows simulation cases of sedimentation management in storage reservoir F. Reservoir F is needed to treat averaged 180,000 m^3 sediment every year, and has a regulating reservoir hydropower plant downstream. Case A is simulation of no sedimentation management and loss of power generation is recorded as an expense. In Case B~D, loss of power generation is also recorded as an

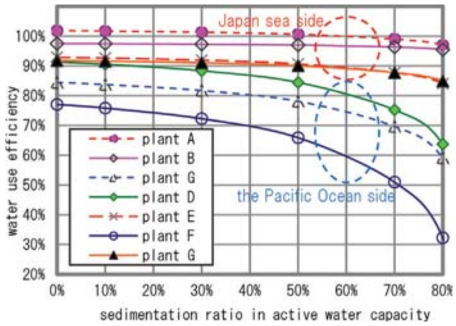

Figure 11. Prediction of water use efficiency.

Table 5. Simulation cases of sedimentation management in storage reservoir F.

No.	Measure	Unit cost	Start period
A	Nothing	–	–
B	Dredging	¥100,000,000/port ¥5,000/m^3	1st year 25th year 50th year 100th year 150th year
C	Check dam & excavation	¥100,000,000/dam ¥2,500/m^3	
D	Sediment bypass	¥13,200,000,000/pass ¥121,000,000/year	

Subject Amount of Sediment (yearly): 180,000 m^3.

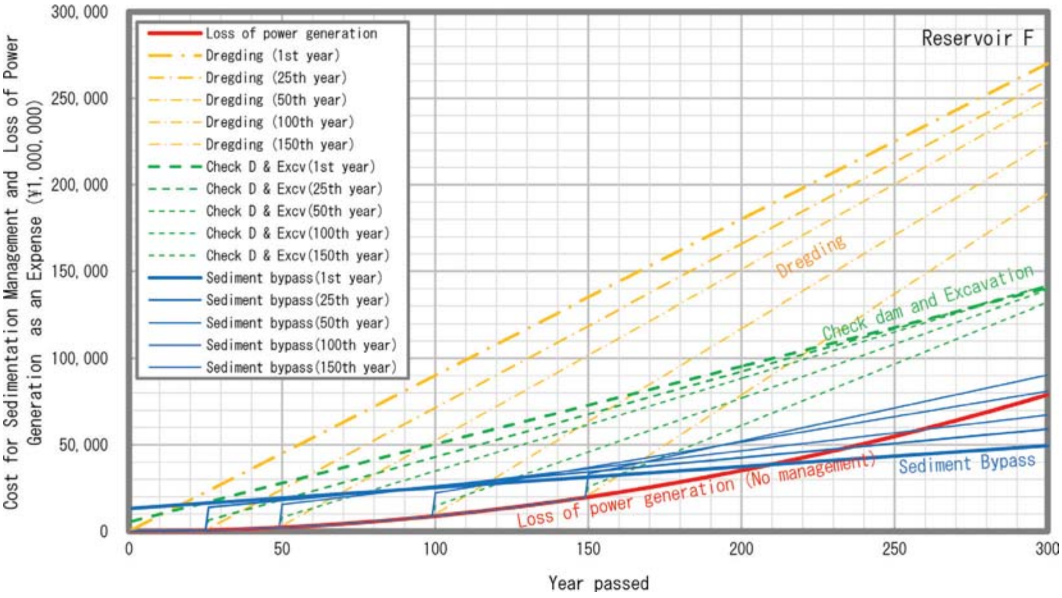

Figure 12. Sedimentation management cost simulation result in storage reservoir F.

expense. Unit price used in calculation of generation loss is ¥8.4/kWh, which was average of JEPX (Japan Electric Power Exchange) from 2005 to 2010.

Figure 12 shows simulation result of 300 years. From the view point of sustainable use of hydropower plant, it is economically feasible to install a sediment bypass, which is appropriate way to restore sediment to river for environment including the coastal area. The result indicates the period of starting management. In situation sediment bypass could be installed, it would be better to be done earlier for cost and environment.

6 CONCLUSION

This paper presents the reservoir sedimentation influence on power generation, analyzing long-term operation record. Also this paper predicts the future sedimentation influence using the model which is based on the analysis. Then this paper discussed the countermeasures for sedimentation in storage reservoir considering properties and purpose of storage reservoir. Result includes some useful findings as follows.

1. Reservoir sedimentation in storage reservoir is gradually increasing and water use efficiency is gradually decreasing.

2. In storage reservoir type hydropower plant, water use efficiency is influenced by sedimentation.
3. Evaluation model of water use efficiency is formulated.
4. Water use efficiency in hydropower plant which has heavy rainy season will be much influenced by sedimentation in the future.
5. Cost simulation of sedimentation management in storage reservoir results that it is the best way to install sediment bypass because of cost and environment.

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