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Turbidity control and sediment management using sluicing tunnel at hydropower dam

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ABSTRACT: Hydropower emits no green-house effect gas and is renewable and domestic energy. It is necessary to solve the problems around dams and reservoirs which will be described in this paper to secure the stability of hydropower supply by effective and sustainable countermeasures. A dam stores not only clear water but also turbid water and sediment in a reservoir during flood. Turbid water stored causes long-term persistence of turbid water in the downstream area of the dam, because this turbid water is discharged repeatedly during generation. Sedimentation causes the loss of the reservoir capacity, obstacle against intake and outlet function, rising water level in the upper area of the reservoir and bad influence on river environment in the downstream area. In this paper, a countermeasure against problems at Futatsuno dam located in Kii peninsula, Japan is studied. It is planned that a sluicing tunnel which connects up- and downstream areas of the dam will make volume of turbid water stored after flood smaller and make sediment bypassing the dam. The numerical simulation has been implemented for the validation on capability of the plan. Then it is concluded that the sluicing tunnel is an effective countermeasure for turbidity control and sediment management.

RÉSUMÉ: Les aménagements hydroélectriques n'émettent pas de gaz à effet de serre et ils génèrent une énergie renouvelable d'origine locale. Il est nécessaire de résoudre les problèmes liés aux barrages et aux réservoirs qui seront décrits plus bas afin d'assurer la stabilité de l'approvisionnement en énergie hydroélectrique grâce à des contre-mesures efficaces et durables. Un barrage emmagasine non seulement de l'eau claire, mais aussi de l'eau trouble et des sédiments dans le réservoir pendant une crue. Les eaux turbides stockées entraînent une persistance à long terme de la turbidité de l'eau dans la zone en aval du barrage, car cette eau trouble s'écoule de manière répétée pendant la production d'énergie. La sédimentation entraîne une perte de capacité du réservoir, nuit aux fonctions d'adduction et de restitution, augmente le niveau d'eau dans la partie supérieure du réservoir et exerce une mauvaise influence sur l'environnement fluvial dans la zone aval. Dans cet article, une contre-mesure face aux problèmes du site du barrage F est envisagée. Il est prévu qu'une galerie sous le barrage reliant les zones amont et aval sera construite afin de réduire le volume d'eau turbide stockée après les inondations et de faire en sorte que les sédiments contournent le barrage. Une simulation numérique a été effectuée pour valider la capacité de cette approche. Il a ensuite été conclu que la galerie de vidange est une contre-mesure efficace pour le contrôle de la turbidité et la gestion des sédiments.

1 BACKGROUNDS

1.1 *Expectation for hydropower*

Fossil fuels are in danger of running out, global warming is now one of the largest world problems, and renewable energy sources are very useful but need to be supported by ancillary service because generation by renewable energy sources, such as solar power, wind power depends on condition of weather and fluctuates in comparison with fire power, nuclear power and so on.

Hydropower is not concerned with such kind of problems, but produces ancillary service to stabilize supply and demand of electric power network, because it is easy to start and stop generation. In Japan it is difficult from the view of economic efficiency to install a new hydropower plant in certain scale, because there is no more suitable site and people's interest for environment is very high in these days. (Okumura, Kantoush & Sumi 2011)

Then it is essential to maintain hydropower plants in good condition and use existing hydropower plants sustainably.

1.2 *Problems with dams*

Basic of energy policy in Japan is 3E plus S. 3E mean "Energy security", "Economic efficiency" and "Environment" and S means "Safety", shown in Figure 1. Safety means safety management for power plant, in regard to hydropower, safety of dam is the most indispensable in the plant. In these days monitoring techniques are developing, for example global positioning system, earth quake response analysis, these have made dams safer than ever. Dams for J-POWER are operated and maintained under RBM, which is Risk Based Maintenance. In RBM, risk of equipment is to be estimated by the scale and the probability of risk. Based on the result of the estimation, method and period of the maintenance is determined. RBM supports Energy security and Economic efficiency.

Though reservoir sediment management is supported by RBM, it is difficult to find and implement the best management to keep reservoir available. Excavation is usually selected shown in Figure 2, but it does not work because amount of yearly reservoir sedimentation is much more than capability of excavation, there is rare site around reservoir for disposal area and there is small demand for gravel around reservoir. And in river and coast area it is not at good condition in quality and quantity of sand and it is an environmental problem concerned with dam because dam stores sediment in its reservoir. Regarding reservoir, reservoir sedimentation causes reservoir capacity decreasing which makes power plant ability lower and riverbed rising which increases flood damage risk. (Okumura & Sumi 2013)

Dam stores turbid water which flows into reservoir during the flood and this causes long-term persistence of turbid water in the downstream area of the dam, because turbid water is discharged repeatedly during generation shown in Figure 3. Due to frequent heavy rain, degree of turbid water from devastated mountains is getting worse and long-term persistence

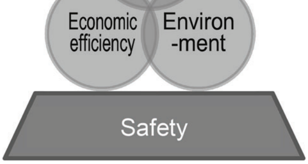


Figure 1. Basic of energy policy in Japan (3E plus S)

Figure 2. Excavation in reservoir

Figure 3. Turbid water from outlet of hydropower plant

of turbid water is also getting worse in these days. The problem of turbid water damages ecology in river and sea area.

In order to use hydropower for long period it is important to make the effective turbid water control plan and the sedimentation management and implement them.

2 COUNTERMEASURES AND CHALLENGES

As a sample, countermeasures against turbid water and sedimentation in Futatsuno dam which is located in Kii peninsula in Japan are studied and challenges against difficulties of countermeasures are extracted.

The outline of Futatsuno dam is shown in Table 1. Sediment production in dam catchment area is relatively high, and turbidity of inflow water is also relatively high. Then dam influence on environment is large. Lifetime of reservoir is that capacity divided by yearly sedimentation.

2.1 *Countermeasures against long-term persistence of turbid water*

As a countermeasure against long-term persistence of turbid water in Futatsuno dam, early replacement of reservoir water from turbid water to clear water is applied. Procedure of early water replacement is that after flood necessity of early water replacement is determined based on reservoir turbidity distribution observed and if it is necessary then turbid water discharge through the spillway in 5 days according to dam gate operation rules and clear water storage in 9 days are implemented, shown in Figure 4.

Table 1. Outline of Futatsuno dam

item	exposition
Date of operation start	Jan.1962
Purpose	Power
Dam type	Arch
Dam height	76m
Catchment area	801km^2
Sediment catchment area*	248km^2
Design discharge	9,600m^3/s
Reservoir capacity	43,000,000m^3
Sediment discharge**	13,686,000m^3
Sediment discharge***	16,280,000m^3
Sediment rate*	1,194m^3/yr.km^2
Reservoir turnover rate	45
Lifetime of reservoir	145years

* excluding the catchment area of the large dam in upstream
** as of 2017
*** including excavation

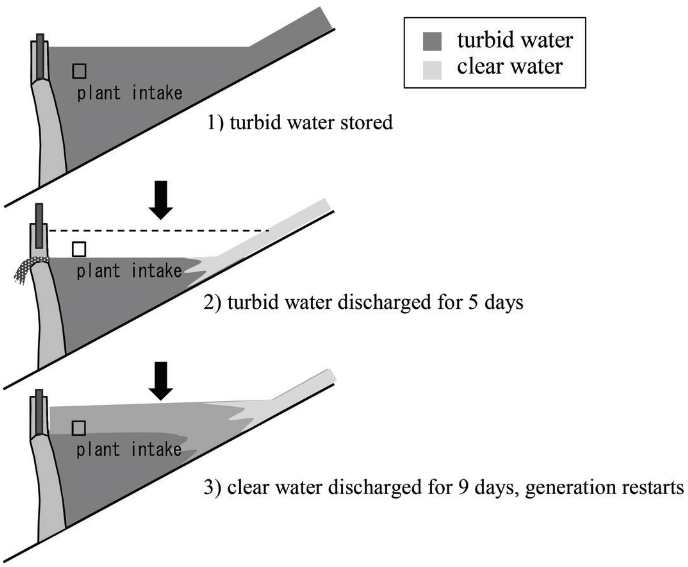


Figure 4. Countermeasure of early water replacement for long-term persistence of turbid water in Futatsuno dam

This countermeasure brings two weeks downtime of the power plant. And there is a limit of turbid water discharge because of high spillway position in hydropower dam. Hydropower dam has no function of flood control and has spillway gate just for discharge of influent.

2.2 *Countermeasures against reservoir sedimentation*

As a countermeasure against reservoir sedimentation excavation and movement to disposal area is mainly implemented in Futatsuno dam. About 200,000m^3 of sediment is treated this way every year. In April 2011, a large tropical storm named Talas hit Kii peninsula and

Table 2. Problems of countermeasures against turbid water and reservoir sedimentation in Futatsuno dam

category	problem	explanation
Turbid Water	Small amount of turbid water for early water replacement	Position of the spillway is high which is 10m lower than high water level, then amount of water replacement is limited small.
	High turbidity water from the power plant when generation restarts after early replacement	Because amount of turbid water remained after discharge is not small, reservoir water mixed with clear water stored has relatively high turbidity.
Reservoir Sedimentation	High cost for excavation and movement to disposal area	Excavation needs temporary roads and bridges, long way transport to disposal area, then cost on them is very high and continuous, and influences on financial balance of the plant.
	Large amount of sediment deposited every year	Amount of sediment yearly deposited is more than amount which can be excavated every year.
	Limited excavation area	Excavation area is dominated by access, therefore sometimes area which can be accessed is not area which should be excavated.
	Continuous heavy machinery traffic on the route from the reservoir to the disposal area	Over 100 large dump tracks pass the same route every day. Noise, vibration and fear distress people who are near the route.
	Rare site for disposal area	It is difficult to find a disposal area or gravel use near the reservoir in the mountains.
	Against policy of integrated sediment management in river basin	The government of Japan puts integrated sediment management into practice and intends sediment flown into the reservoir to pass through the reservoir and flow down river to sea area. Countermeasure of excavation and dispose is opposite to the management.

1,000,000m^3 sediment deposited in the reservoir. It changed yearly amount of excavation from 100,000m^3 to 300,000m^3, and three years later it settled 200,000m^3 as now.

The effect of excavation is no more than maintain of the riverbed level which has some flood damage risks. And it is not effective against large sedimentation in big flood like the 2011 strorm, therefore sedimentation of Futatsuno dam reservoir is increasing gradually.

2.3 *Challenges*

Countermeasures against turbid water and reservoir sedimentation have efficiency, but to be a sustainable hydropower plant, which is well matched with environment, challenges are needed to solve the problems in Table 2.

3 SLUICING TUNNEL

3.1 *Concept*

Considering the problems summarized and surroundings of Futatsuno dam and reservoir, the sluicing tunnel, shown in Figure 5 and Figure 6, is selected as new countermeasure which makes hydropower plant sustainable. Sluicing tunnel could solve all of problems and is applicable for Futatsuno dam condition shown in Figure 7. (Okumura & Sumi 2012)

The effect on turbidity control and sedimentation management is studied below.

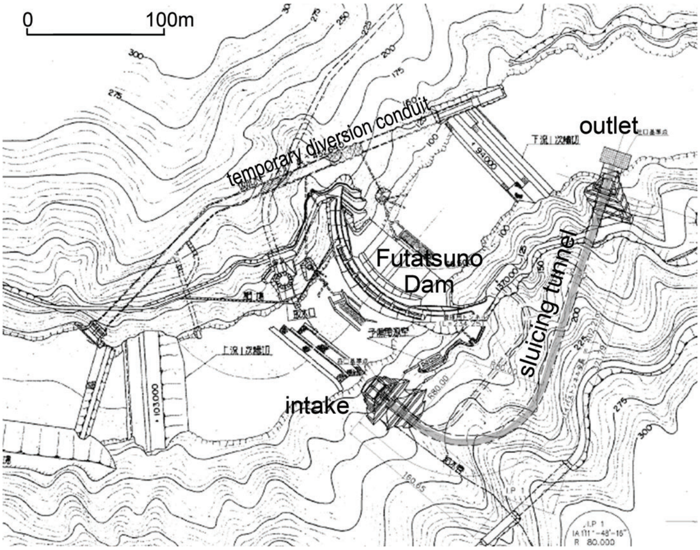


Figure 5. Layout of sluicing tunnel at Futatsuno (in ground plan)

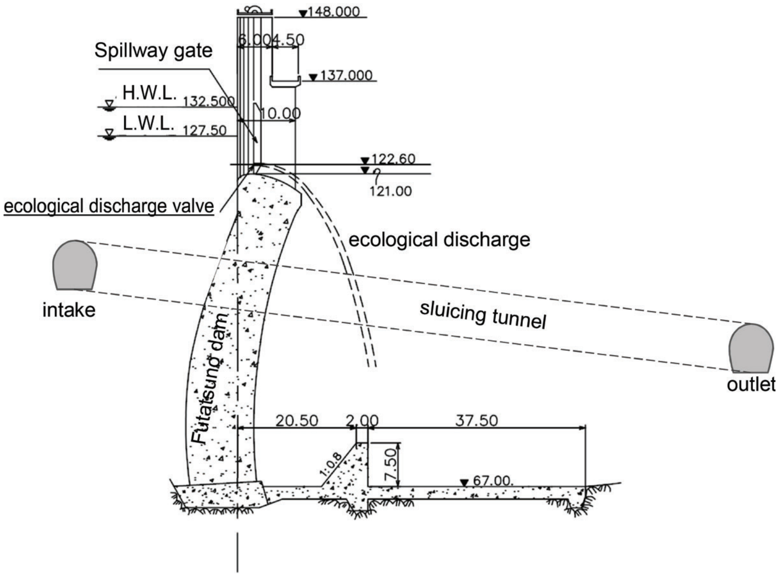


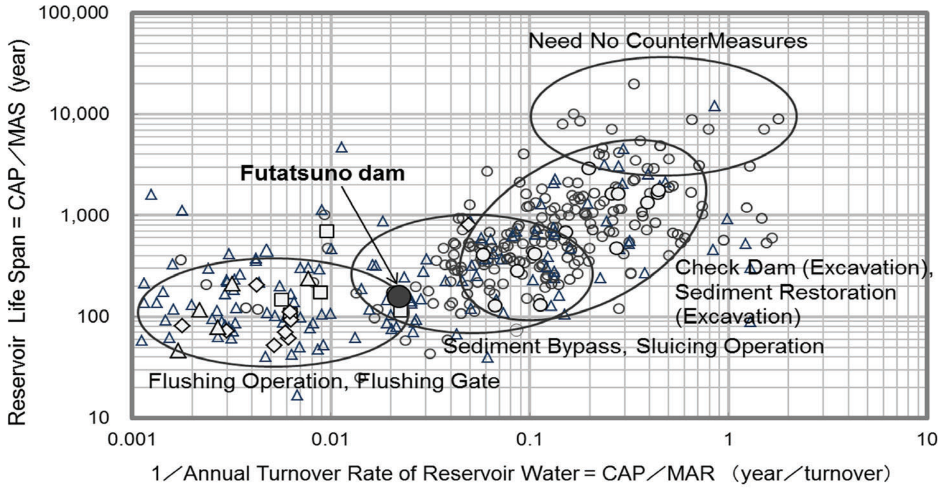
Figure 6. Layout of sluicing tunnel at Futatsuno (in cross section)

3.2 *Effect on turbidity control*

The calculation of predicting the turbidity when power generation restarts after water replacement with the sluicing tunnel is implemented, based on the turbidity record around Futatsuno dam.

The intake position of the sluicing tunnel is designed lower than the spillway and makes the amount of water replacement larger. Outline of the tunnel is shown in Table 3.

Process and result of the calculation are shown in Figure 8 and Table 4. The sluicing tunnel makes turbidity of water from the outlet of Futatsuno dam hydropower plant lower, which is from 25 to 11, shown in Table 4.



*CAP = Capacity of the reservoir
MAR = Mean Annual Runoff
MAS = Mean Annual Sediment inflow

Figure 7. Applicability of sediment management based on CAP, MAS and MAR

Table 3. Outline of Sluicing Tunnel

items	contents
Intake position (bottom crest)	20m or 30m lower than the spillway
Diameter	9.0m
Length	400m
Gradient	2%

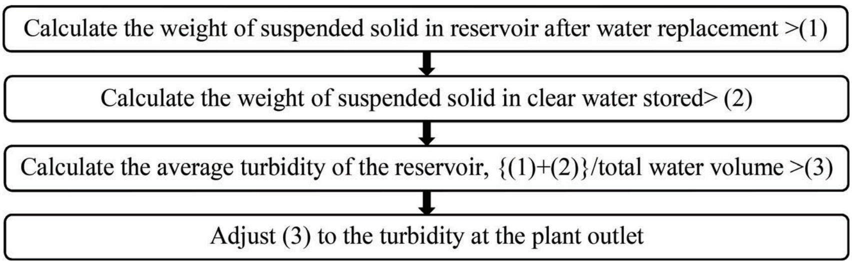


Figure 8. Process of the predictive calculation of turbidity from Futatsuno dam hydropower plant

3.3 *Effect on sediment management*

To estimate the effect of sluicing tunnel on sediment management, numerical simulation of riverbed fluctuation is implemented. Numerical model is single dimensioned and tuned by the record from 1988 to 2010. Parameters are tunnel intake position, flow rate of the tunnel and velocity of draw-down. Cases of numerical simulation are shown in Table 5 and Figure 9.

Intake position of the tunnel is dominated by tunnel outlet position which is designed by water level. Outlet of sluicing tunnel should be upper than water level while it is operating.

Table 4. Effect on turbidity control of sluicing tunnel

	Turbidity when power generation restarts	
	Reservoir Average	Water from Outlet*
Record (averaged 9 cases**)	47	25
Under sluicing tunnel operation	22	11

* Record observed
** 9 cases when water replacement was implemented between 2002 and 2011

Table 5. Cases of the numerical analysis (prediction period is 50 years)

No.	Countermeasure	Intake Position of the Tunnel	Flow rate of the Tunnel	Velocity of the Draw-down
1	Without countermeasure			
2		Low	$500m^3/s$	0.5m/hr. (start after 3days)
3		(-30m from the spillway)		0.5m/hr.
4		High		0.5m/hr. (start after 3days)
5		(-20m from the spillway)		0.5m/hr.
6		Low	$1,000m^3/s$	0.5m/hr.
7	Sluicing tunnel	(-30m from the spillway)		1.0m/hr.
8				2.0m/hr.
9		High		0.5m/hr.
10		(-20m from the spillway)		1.0m/hr.
11				2.0m/hr.

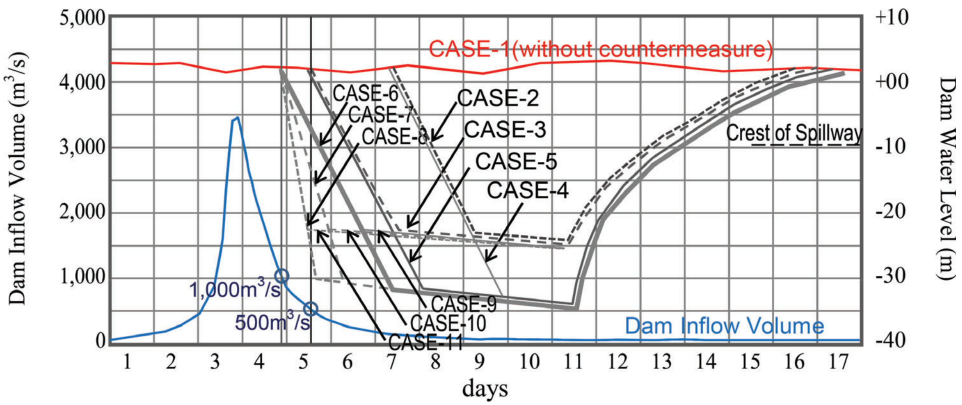


Figure 9. Draw-down operation

Two positions in cases are set for parameter study, one outlet position is 10m upper than water level (High) and the other is equal to water level (Low).

Flow rate of the tunnel and velocity of draw-down are set as parameter to study influence of time length while dam water level is low. Flow rate of tunnel is the larger, start time of draw-down is the earlier.

Velocity of the draw-down are dominated by the reservoir bank condition which is unknown now and set 0.5m/hr. to 2.0m/hr. Velocity of the draw-down is the faster, dam water level reaches draw-downed level the earlier.

Because draw-down operation should be implemented more than once a year in leading sites, inflow $1,000m^3/s$ is set as decision standard.

Table 6. Results of the numerical analysis

No.	Intake Position	Tunnel Flow-rate	Draw-down Velocity	Amount of sediment(m^3) Inflow*	Outflow	Sedimentation	Effect of Tunnel	Time while water level is low (hr.)
1				407,258	209,975	197,283	-	
2	Low	500m^3/s	0.5m/hr.**	425,939	307,835	118,104	79,179	11
3			0.5m/hr.	469,262	406,249	63,013	134,270	193
4	High		0.5m/hr.**	425,103	272,961	152,142	45,141	48
5			0.5m/hr.	457,648	329,799	127,849	69,434	254
6	Low	1,000m^3/s	0.5m/hr.	481,571	436,241	45,330	151,953	217
7			1.0m/hr.	495,434	466,016	29,418	167,865	303
8			2.0m/hr.	503,086	482,691	20,395	176,888	326
9	High		0.5m/hr.	465,726	352,504	113,222	84,061	259
10			1.0m/hr.	474,450	367,904	106,546	90,737	316
11			2.0m/hr.	479,156	376,256	102,900	94,383	339

* adjusted based on the record
** draw-down starts 3day after the peak of flood

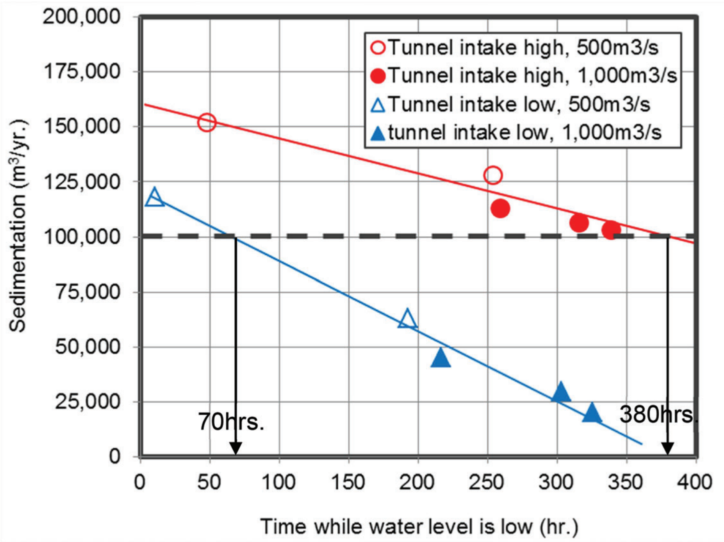


Figure 10. Relation between yearly Sedimentation and Time while water level is low (average of 50 years)

The results of the numerical analysis predicting 50 years are shown in Table 6 and Figure 10. They indicate that the effect of the sluicing tunnel is dominated mainly by position of tunnel intake and time length while water level is low. When the tunnel is under design, it is very important to determine the amount of discharge sediment, to fix the tunnel intake position considering the field condition and to make an operation rule which regulates the time length while dam water level is low.

In Futatsuno dam reservoir, there will be a dredging facility in next three years which could enable to excavate 100,000m^3 per year. Sluicing tunnel system is asisted by excavation with this facility. Under 100,000m^3 sediment excavation is allowed and Figure 10 indicates that if intake position is low, it needs to take about +70 hours to keep dam water level low, if intake position is high, it needs to take about +380 hours.

4 CONCLUSIONS

It is very important for sustainability of hydropower plant to plan and implement the appropriate countermeasure against sedimentation and long-term persistence of turbid water. The countermeasures as now are excavation and water replacement with spillway gate, they are not enough in tough situation of Futatsuno dam.

It is studied in efficiency of the sluicing tunnel against the problems. The result of the study is concluded the bellows:

1. Against long-term persistence of turbid water, increasing of the amount of early replacement water from turbid water to clear water utilizing the sluicing tunnel is effective. The effect is dominated by the amount of replacing water.
2. Against reservoir sedimentation, sluicing tunnel is effective. The effect is dominated by the position of the sluicing tunnel intake and time length while dam water level is low.
3. A sluicing tunnel in Futatsuno dam is effective on two ways which are turbidity control and sediment management.

It is prospected that sediment management in Futatsuno dam with the sluicing tunnel is more economic than excavation which is applied at the present. Life cycle cost of the sluicing tunnel will be estimated considering construction cost, maintenance cost, monitoring cost and downtime of the power plant. And the gate of the tunnel intake will be operated in 30m water depth, the gate structure and the operation rule are very important and should be both considered.

Sustainability of hydropower will be more important in the future than at the present. Against turbidity water and sedimentation in dam reservoir, countermeasures based on the facilities at the present are not enough to keep the sustainability, and the equipment modifications are needed.

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