EFFECTIVE COUNTERMEASURES TO LONG-TERM TURBID WATER EFFLUENCE FROM HITOTSUSE RESERVOIR

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1. Introduction

The Hitotsuse Dam which constructed in 1963 is located in the center of the Hitotsuse River watershed. In 1963, a hydroelectric power station started commercial operation downstream from the dam. Since around 1965 a phenomena of long-term turbid water effluence have been occured in the river downstream of the reservoir after every flood. To solve this problem, we installed selective water withdrawal equipment in 1974, and since 1989, when the problem of turbid water effluence reemerged, we have taken an additional five countermeasures: 1) improvement of selective water withdrawal equipment; 2) improvement in operation of selective water withdrawal equipment; 3) maintenance of reservoir slope; 4) dilution with tributary stream flow water 5) elimination of the turbid water from Sugiyasu Regulating Reservoir and the downstream region[1),2)].

However, due to the extraordinary scale of flooding that occurred in 2004 and 2005, landslides occurred in the upstream region of the watershed causing huge amounts of turbid water occurrence. In particular, a long-term turbid water effluence in 2005 took place for approximately eight months caused to discuss further countermeasures against turbid water effluence from the reservoir.

Concerning countermeasures related to the reservoir, Kyushu Electric Power CO.,INC (KEPCO) examined and developed the measures in an in-house technological study committee with the help of experts, based on an analysis of the present state of the reservoir. The proposal was submitted to the Advisory Committee for Countermeasures against Turbid Water Effluence in the Hitotsuse River System (established in July 2006, hereafter called the Advisory Committee) with representation by Miyazaki Prefecture, municipalities in the basin, experts, and KEPCO. The Advisory Committee examined and discussed measures for the upstream region, which is the source of the turbid water, for the reservoir that stores the turbid water, and for the downstream region that is affected by the turbid water. The plan for countermeasures for the entire basin was then drawn up in June 2008.

This paper focuses on the renewed countermeasures to reduce the prolongation of turbid water effluence in future.

2. Outline of Hitotsuse River basin

Hitotsuse River is a class B river, which has its riverhead in Mt. Ichifusa and Mt. Ishinita in the Kyushu mountain range, and runs through the center of Miyazaki Prefecture to the southeast, before flowing into the Sea of Hyuga.

It joins together with the Oyabu River, Itaya River, Ogawa River, Shiromi River, and other rivers along its course, and with the Sanzai River in the vicinity its estuary. It has a river basin of $846km^2$ and a total length of approximately 310km. Shiiba Village, Nishimera Village, Saito City, Miyazaki City (formerly Sadowara Town), and Shintomi Town are located in the basin. The water of Hitotsuse River is utilized for power generation, water supply, and irrigation (See Figure 1).

3. Characteristics of Hitotsuse Reservoir

3.1 Flow form of reservoir (turnover rate)

Hitotsuse Dam is an archdam 130m in height and with a total storage capacity of 260 million m^3, making it the largest reservoir in the Kyushu area (see Table 1). Value of the exchange ratio of reservoir water α(total annual inflow/total storage capacity) of Hitotsuse Reservoir is 4.32, it is classified as a stratified reservoir ($\alpha<10$: stratified type, $\alpha>10$: mixed type).

3.2 Distribution of water temperature and turbidity of reservoir

Hitotsuse Reservoir shows water temperature

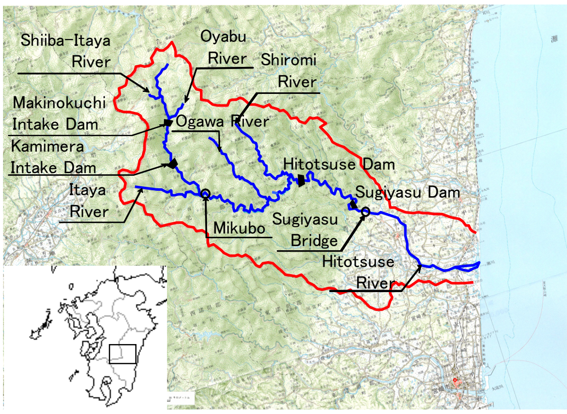


Figure 1 Map of Hitotsuse River basin

Table 1 Dimensions of Hitotsuse Hydroelectric Power Station (Dam) and Sugiyasu Hydroelectric Power Station (Dam)

Item		Hitotsuse	Sugiyasu
Dam	Type	Arch-type concrete	Arch-type concrete
	Dam length x height	415.62m×130.00m	156.00m×39.50m
	Design flood discharge	4,400m3/s	4,800m3/s
Reservoir	Catchment area	415.00km2	485.70km2
	Total storage capacity	261 million m3	9 million m3
	Available water depth	30.00m	3.50m
Power generation	Maximum output	180,000kW	11,500kW
	Maximum water use flow	137.00m3/s	60.00m3/s
	Effective head	151.99m	22.60m

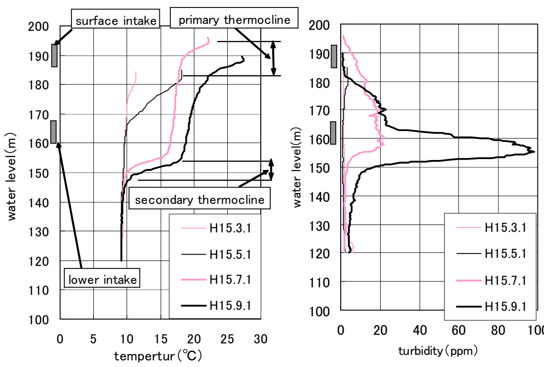


Figure 2 Distribution of water temperature and turbidity in Hitotsuse Reservoir (front of intake)

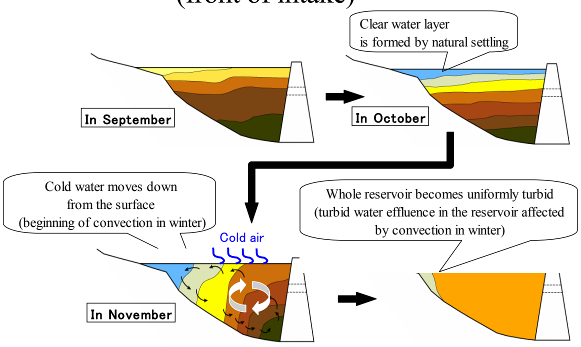


Figure 3 Convection in reservoir in winter

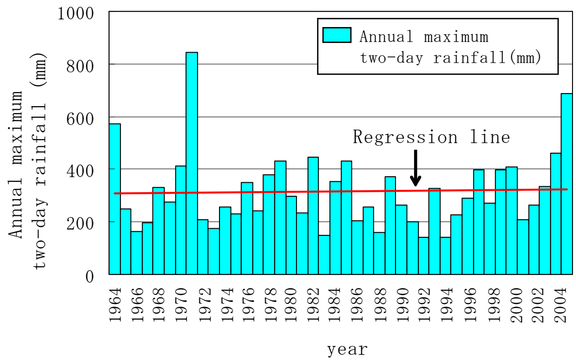


Figure 4 Annual maximum two-day rainfall upstream (at Murasho)

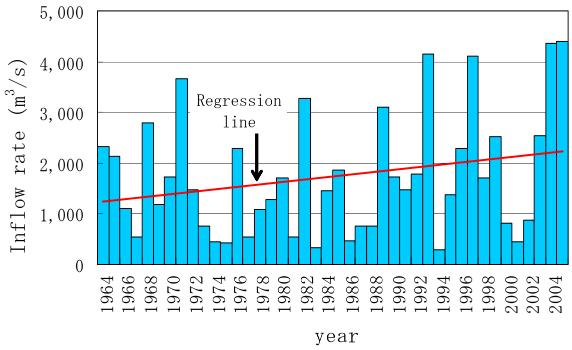


Figure 5 Annual maximum inflow into Hitotsuse Dam

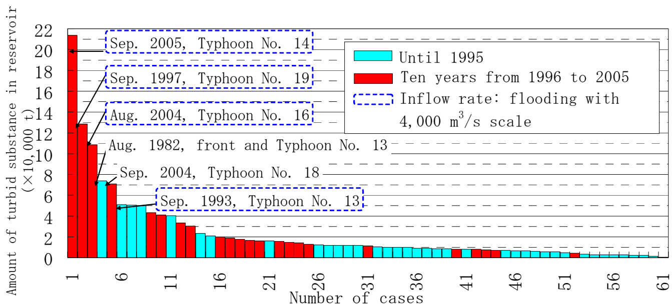


Figure 6 Amount of turbid substance flow into reservoir

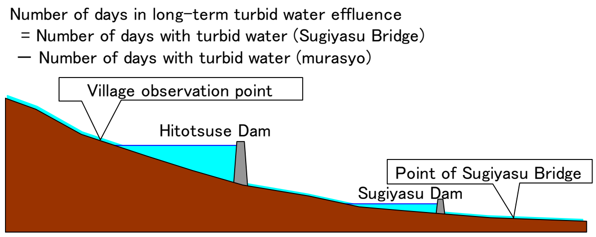


Figure 7 Concept for estimating number of days in long-term turbid water effluence

profile in a vertical direction over the period of a year, as shown in Figure 2,. between April and October the primary thermocline forms at the level of the surface of the reservoir. The secondary thermocline forms at the level of the lower intake. Through November to March of the following year, convection occurs in the reservoir, and there is a feature that the water temperature and turbidity resulted in no differences in each profile.

3.3 Mechanism of long-term turbid water effluence in Hitotsuse River basin

The mechanism of long-term turbid water effluence in the Hitotsuse River basin can be described as follows: Turbid water that flows in from the upstream due to flooding (the effluence containing weak sedimentary rock's particle, which is fine and does not precipitate easily) is stored in the Hitotsuse Reservoir, having the largest scale (storage capacity) in the Kyushu area, and precipitates temporarily. As shown in Figure 3, the turbid substance that precipitates rises to the surface due to convection in winter, turbid water effluence breaks out again, caused by the power generation discharge to the downstream.

4. Analysis of existing countermeasures against turbid water effluence

4.1 Hydrology, weather, and conditions of turbid water occurrence

a. Changes in amount of rainfall and inflow

Figure 4 shows the change in the annual maximum two-day rainfall at the observation point located in Murasho and Figure 5 shows the change in the annual maximum inflow into Hitotsuse Dam. Although there is no clear increasing tendency in the annual maximum two-day rainfall, the annual maximum inflow shows a tendency towards increase every year.

b. Change in amount of turbid substance* flowing into reservoir

(*Weight of soil contained in the turbid water. 〔Amount of turbid substance(t)〕 = 〔Vertical distribution of turbidity degree on the day (mg/L)〕 × 〔Reservoir water volume of each observation section (m^3)〕 × 10^{-6},and total of vertical amount of turbid substance)

Figure 6 shows the turbidity that has occurred at flooding, which has impacted Hitotsuse Reservoir in the past thirty years, set out in descending order. The graph indicates that six out of the top ten cases occurred in the last ten years.

For Hitotsuse River, water exceeding a turbidity of 10 ppm is defined as turbid water, and the number of days when long-term turbid water effluence is occurred is estimated as “the number of days with turbid water at Sugiyasu Bridge downstream of the reservoir minus the number of days with turbid water at Murasho, upstream of the reservoir” (see Figure 7). Figure 8 shows the number of days that long-term turbid water effluence is occurred every year. Since 1993 especially, the number of days with turbid water at Murasho, upstream of the reservoir, has been increasing, as is the tendency for the number of days for which long-term turbid water effluence is occurred.

4.2 Changes in condition of denuded land and logged-off land in upstream area

As already stated, in recent years, although the amount of peak inflow due to flooding has not changed much, increased amounts of turbid substance have come to flow in.

Desolation within the basin is thought to be one of the factors causing increased amounts of turbid substance to flow in. Figure 9 indicates the location and area of denuded land and logged-off land, based on aerial photographs of the basin shot in 1984 and 1995, and satellite photographs shot in 2004 and 2006. Although it is not possible to compare between aerial photographs and satellite photographs directly because the resolution of the photographs is different, there is a tendency for areas of denuded land and logged-off land, assumed to be the main sources of turbid substance, to increase with time.

4.3 Effect of countermeasures

a. Effect of reduction of amount of turbid substance flowing into reservoir

Figure 10 shows the annual changes in the amount of turbid substance in the reservoir resulting from countermeasures taken after flooding from 1991 to 2005. It indicates that the amount of turbid substance in the reservoir decreased greatly as a result of taking countermeasures (maximum intake from the lower intake). When the amount of turbid substance that flowed in was less than 50,000 tons, long-term turbid water effluence caused by convection in winter could be controlled, while in the years when the amount of turbid substance that flowed in exceeded 50,000 tons after September, the occurrence of turbid water

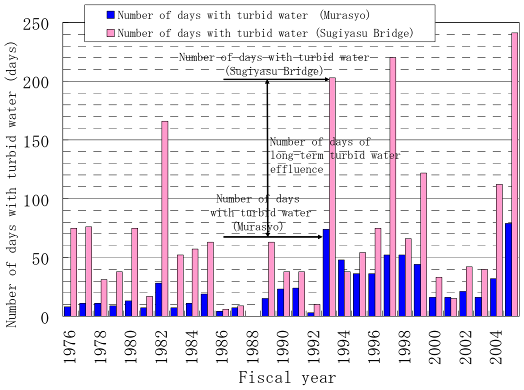


Figure 8 Number of days of long-term turbid water effluence by year

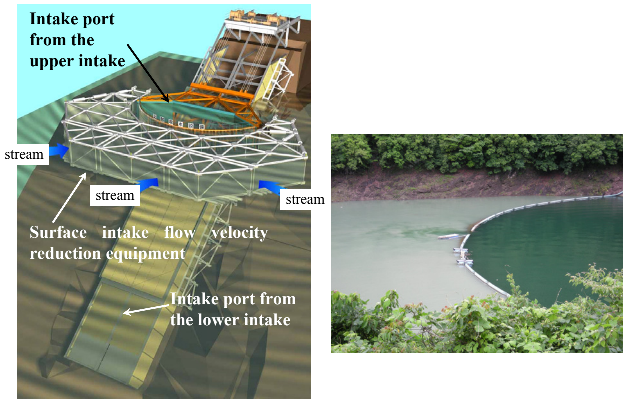


Figure 11 "Selective intake equipment" and "Turbid water control sheathing"

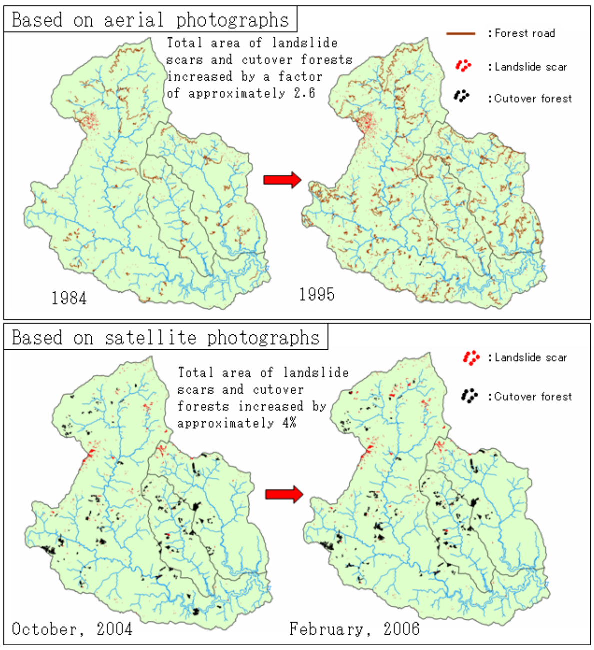


Figure 9 Changes in denuded land and logged-off land in Hitotsuse Reservoir basin

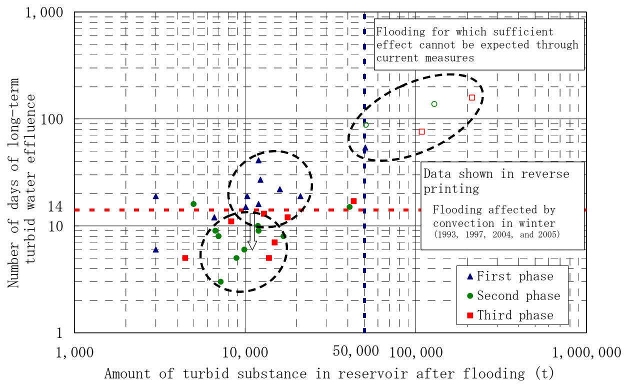
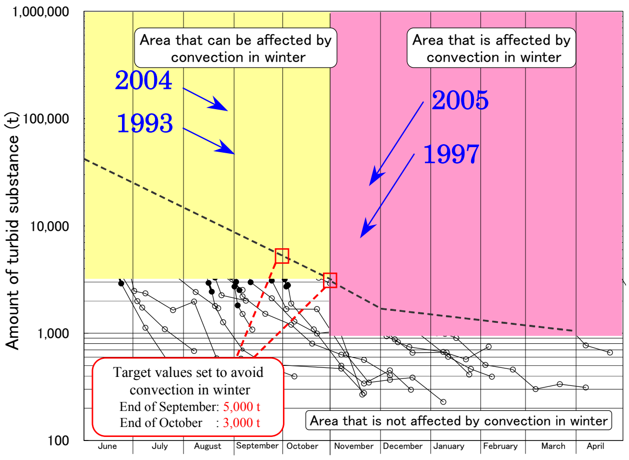


Figure 12 Effect of past countermeasures on reducing number of days of long-term turbid water effluence



Bold line: Period for eliminating turbid substance by maximum,

● : Turbidity at Sugiyasu Bridge exceeds 10 ppm

○ : Turbidity at Sugiyasu Bridge 10 ppm or less

Figure 10 Effect of reduction of amount of turbid substance flowing into reservoir

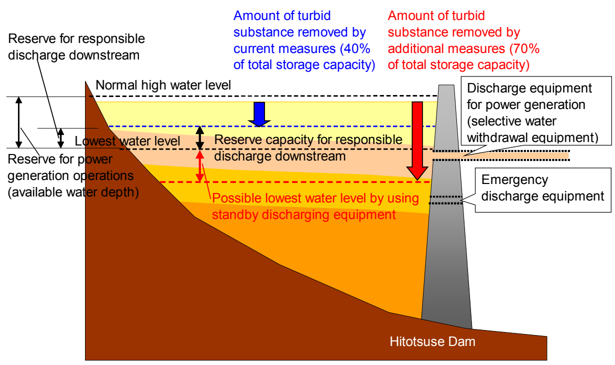


Figure 13 Schematic diagram of additional countermeasures

effluence was prolonged. It is important to reduce turbid substance before convection in winter is arisen.From historical result, if it is possible to decrease the amount of turbid substance remaining in the reservoir to 5,000 tons or less by the end of September, long-term turbid water effluence due to convection in winter can be constrained. Moreover, considering a natural precipitation of turbid substance, decreasing the amount of turbid substance remaining in the reservoir to 3,000 tons or less by the end of October is the target values of the countermeasures.

b. Effect of reducing number of days of long-term turbid water effluence

Turbid countermeasures were separately evaluated at the following three time. The evaluation is excluded before 1976 because of no detailed observational data. (see Figure 11)

<First phase> 1976 to 1989: "Installation of selective intake equipment "

<Second phase> 1990 to 1998: "Execution of five countermeasures to reduce turbid water"

<Third phase> 1999 to 2005: "Installation of turbid water control sheathing " and " Installation of surface intake flow velocity reduction equipment"

Figure 12 shows the relationship between past countermeasures (first phase to third phase) and their effect on reducing the number of days of long-term turbid water effluence. Concerning flooding that occurred less than 50,000 tons, the number of days of long-term turbid water effluence was reduced to approximately two weeks .

Concerning flooding that generated more than 50,000 tons, the number of days of long-term turbid water effluence was one month or more.

Consequently, it has comprehended that flooding that occurs in excess of 50,000 tons of turbid substance flow requires additional countermeasures.

5 Discussion and development of counter -measures for reservoir

5.1 Basic principles for additional counter -measures against turbid water effluence

The countermeasures against turbid water effluence consist of the control of the source of turbid water and the reduction of trapped turbid water in the reservoir. Of these, KEPCO, as the company who built the dam, will take the initiative in countermeasures aimed at reducing trapped turbid water in the reservoir. KEPCO has worked to discharge as much turbid water due to flooding as possible from the reservoir before the start of convection in winter. However, the amount of turbid water occurrence at the upstream has increased to the point that the current measures do not suffice. Earlier and more removal of turbid water and dilution of turbid water by storing clean inflow water after discharge are thought to be the most effective steps that can be taken as additional countermeasures. Specifically, although Hitotsuse Dam is a dam that provides water for power generation, only in the case when massive amounts of turbid water flow into the dam due to large-scale flooding, the water level of the dam is lowered below the required water storage level for power generation operations and responsible discharge for downstream water uses, in order to discharge turbid substance (see Figure 13).

5.2 Analysis of regeneration of turbid water

Figure 14 shows categorized patterns of regeneration through a year of turbid water due to convection in winter under current measures, and amount of turbid substance.

1) When turbid water occurs in or before August

Because there is enough time before convection in winter is occurred, the current countermeasures can reduce turbid substance in the dam, even if the amount of turbid substance is large, it can avoid reoccurrence of turbid water.

2) When turbid water occurs in or after September and amount of turbid substance in the dam is less than 50,000 t

Because the current countermeasures can reduce the amount of turbid substance in the dam before convection in winter begins, it can avoid regeneration of turbid water.

3) When turbid water occurs in or after September and amount of turbid substance in the dam is 50,000 t or more

Because the amount of turbid substance in the dam exceeds the limit that can be managed under current countermeasures , and because it is not possible to reduce the amount of turbid substance to the target value before winter convection begins, regeneration of turbid water occurs.

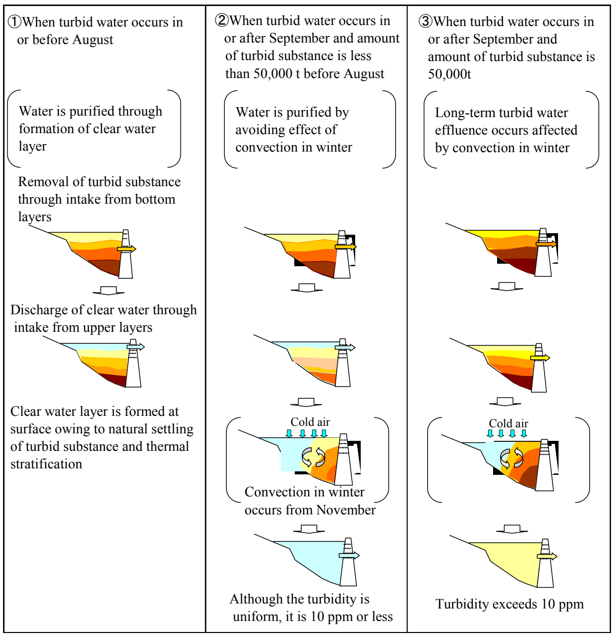


Figure 14 Analysis of regeneration of turbid Water

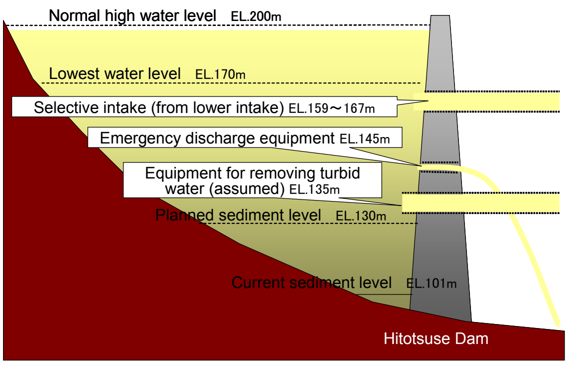


Figure 15 Schematic of discharge equipment in proposed comparative study

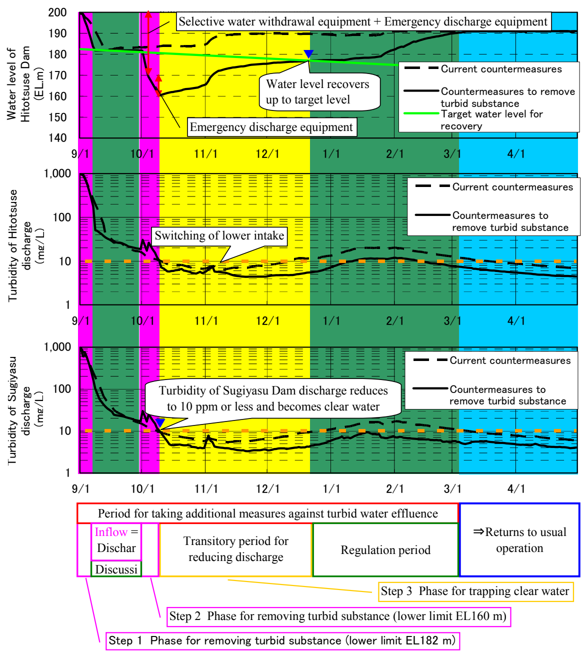


Figure 16 Effect of reducing turbidity (analytical results)

Table 2 Results of study on effects of removing turbid substance

Year	Maximum inflow rate (m^3/s)	Amount of turbid substance (t)	Amount of turbid substance in reservoir at the end of October (t)							
			Actual result	①Selective intake CASE-1		②Selective intake + standby discharge equipment CASE-2				③ CASE-3
				lowest water level						
				EL. 182	EL. 170	EL. 182	EL. 170	EL. 160	EL. 150	EL. 150
2000	1, 393	8, 300	2, 000	800	400	900	400	200	-	-
2003	2, 531	17, 800	1, 200	700	400	900	400	200	-	-
1999	2, 528	43, 300	3, 600	3, 700	1, 300	3, 200	1, 600	700	-	-
1993	4, 146	51, 000	6, 400	5, 300	3, 700	4, 700	2, 300	1, 700	-	-
1997	4, 103	128, 600	16, 600	8, 600	4, 500	10, 500	5, 100	2, 600	-	-
2005	4, 439	213, 600	34, 500	17, 600	15, 700	14, 600	10, 400	7, 200	6, 700	3, 600

Table 3 Volume of responsible discharge downstream

Purpose	Irrigation period: March 5 to October 20	Non-irrigation period: October 21 to March 4
Agricultural water	8. 4m^3/s	1. 0m^3/s
Water supply	0. 3m^3/s	0. 3m^3/s
Saltwater intrusion prevention	4. 3m^3/s	7. 7m^3/s
Total	13. 0m^3/s	9. 0m^3/s

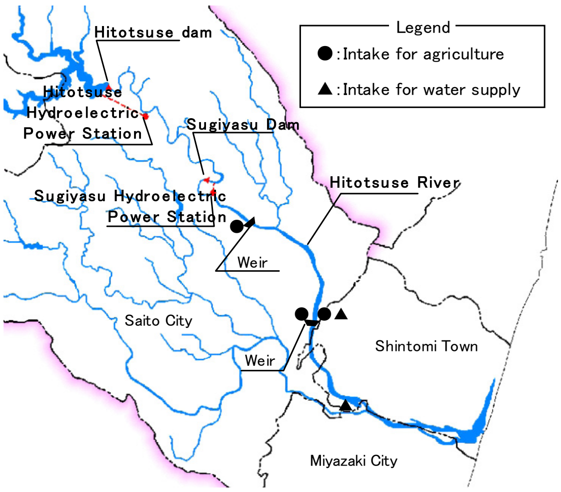


Figure 17 Water utilization map in downstream region

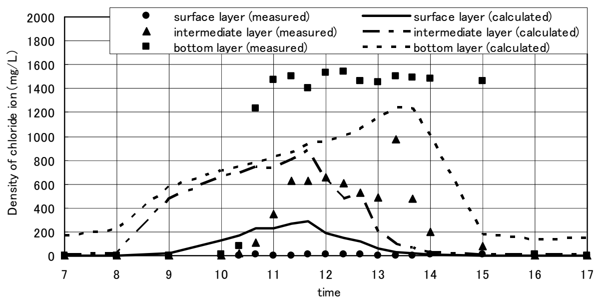


Figure 18 Comparison of chloride ion concentration

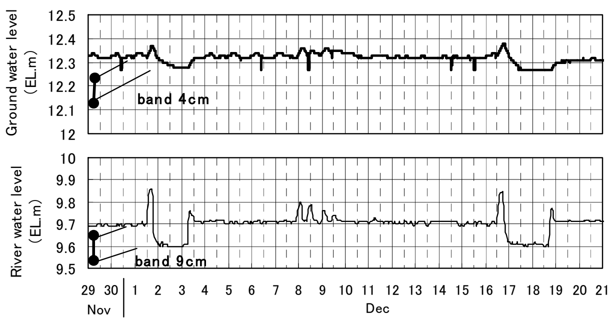


Figure 19 Change in river and ground water levels

5.3 Comparative study of approaches to reduce turbid substance in Hitotsuse Reservoir

1) Conditions to be examined

In order to evaluate the effect and influence level of each proposed measure, analysis results was checked by comparing with actual data and a comparative study was done through simulation analysis[3),4)] using a perpendicular one-dimensional model.

The effect and influence level were evaluated in terms of changes of water temperature and turbidity profile , and amount of turbid substance. The cases studied were based on the following three types of the discharge facilities operation method and final water level of the dam after discharging (see Figure 15)

CASE 1: Discharge for power generation through selective intake (conventional method)

CASE 2: Discharge from emergency discharge equipment in addition to CASE 1

CASE 3: Discharge from assumed turbid substance removal equipment (conduit with discharge position of EL.135m, diameter φ3m, and max discharge capacity of $230m^3/s$) in addition to CASE 2

2) Effect of removing turbid substance

Table 2 shows the results of comparative study making this value the target for countermeasures. Shaded values are cases that could not achieve the target.

(1) It's comprehended that in either case, more turbid substance can be discharged by lowering the water level of the dam.

(2)For amounts of up to 100,000t of turbid substance, the amount generated in 1997 when the amount of turbid substance was the second largest in the history of observation, it was possible to achieve the 3,000t target by the end of October by lowering the water level to maximum EL.160 m through discharge in CASE 2.

(3)For amounts up to 200,000t of turbid substance, the amount generated in 2005 when the amount of turbid substance was largest in the history of observation, it was not possible to achieve the target through discharge even in CASE 3, and it comprehended that the effect had little difference from CASE 2.

Taking these results into consideration, in order to further reduce the turbid substance from Hitotsuse Dam, the decision was made to apply power generation discharge by means of selective intake, as well as discharge using emergency discharge equipment.

3) Effect of reducing turbidity

We then performed analysis to confirm by how much downstream discharge turbidity would actually be decreased. The effect of reducing turbidity, shown in Figure 16, about one month after 100,000 t of turbid substance is trapped in Hitotsuse Dam, is that the discharge turbidity of Sugiyasu Dam is reduced to 10 ppm or less, which proves that long-term turbid water effluence can be controlled.

6. Impact assessment for downstream region

6.1 Issues relating to additional countermeasures for turbid water effluence

As shown in Table 3, KEOPCO is required to perform responsible discharge downstream. However, the additional countermeasures just developed require the water level of the dam to be lowered to EL.160 m at the maximum, on the assumption that the amount of water discharged from the dam can be reduced below the responsible discharge for a few months from October. Because no such plan has ever been implemented, it is necessary to check whether or not there are any serious effects on operations that utilize water such as agriculture and water supply as well as on fauna and flora in the downstream region.

6.2 Content of investigation and review

Investigation and review were carried out by the work group for the mid- and downstream regions, a section subordinate to the Advisory Committee. Figure 17 shows the water utilization map in the downstream region.

The work group for the mid- and downstream regions selected items for evaluation by referring to relevant literature[5),6),7)] (see Table 4). The evaluation was conducted by first studying the current conditions, such as level and quality, followed by conducting a paper-based study, and then by verifying the findings in a discharge test.

6.3 Current condition of ground water

The reduction of discharge from Hitotsuse Dam could have an impact on ground water in the surrounding areas. Thus, the work group studied existing wells at about 50 locations to understand their conditions including ground water level and quality, and seasonal changes. The results are listed below:

- Since ground water level is higher than river water level, ground water flows down from the mountains towards the river.
- Ground water level is lower in general from summer to fall by about 0.4m-3.0m
- Chloride ion concentration is 25mg/l or less and meets the water quality standard of 200mg/l for tap water.

Table 4 Content of investigation and review

Investigation and review items			Understanding of impact		Investigation and review method		
			Short-term investigation	Long-term investigation	Survey of current status	Analytical review	Discharge testing
Water environment	Flow condition	Flow velocity, water depth, width of water surface	○		○		○
	Water quality	Water temperature, DO, BOD, pH, SS, turbidity		○	○		
	Saltwater intrusion	Electrical conductivity, salinity	○		○	○	○
	Underground water	Water level, synchronization with river, salinity	○		○		○
Water utilization	Waterworks, irrigation water		○		○		○
Bottom quality, river form, other environment	Bottom quality	Particle size composition, strength loss in weight, COD, T-N, T-P, odor		○	○		
	River morphology	Blockage of estuary, sedimentation in river channel	○			○	
	Subsidence		○		○		
Agriculture	Adhesion of turbid substance to farm products			○	○		
Fishery	Sweetfish	Egg laying and flowing larval fish		○	○		
	Elver	Eels running upriver (quantity of catches)		○	○		
	Japanese common fresh water clam	Distribution		○	○		
Fauna	Fish and benthic animals	Phase, distribution, important species, habitat		○	○		
Flora	Aquatic fauna	Phase, important species		○	○		
	Eelgrass (Zostera japonica)	Distribution		○	○		
	Attached algae	Phase, amount in existence		○	○		
Ecosystem	Features of ecosystem that characterize the region			○	○		
Landscape, place for activities where people can come into contact with nature	Conditions of main view points and landscape resources		○		○		○
	Conditions of places used for social activities		○		○		○
Sailing			○		○		○
Protection of river management facilities			○		○		
Protection of other facilities			○		○		

6.4 Investigation of saltwater intrusion range

The work group predicted the change in intrusion range of saline wedge due to reduced discharge, by applying three-dimensional analysis. Analysis was conducted for the end of October when the tidal level is the highest over a year. The flow rate for the river was $4m^3/s$. The result showed the expansion of the intrusion range by about 0.7km upstream.

6.5 Investigation of flow rate secured for Hitotsuse River

The flow rate to be secured means the minimum flow rate needed to maintain the river environment downstream. The flow rate to be secured was calculated to be $4m^3/s$ based on the items excluding salt damage prevention.

6.6 Verification test for discharge reduction

1) Outline of test

- Objective: Verification of flow rate to be secured for Hitotsuse River at $4m^3/s$
- Test dates: Dec. 1-3 and Dec. 16-18, 2007
- Discharge amount: Responsible discharge reduced from $9m^3/s$ to $6m^3/s$ ($6m^3/s$ ≒ flow rate to be secured $4m^3/s$ + water use $1.3m^3/s$)

2) Test results

(1) Flow condition

No significant change was observed in flow condition (flow rate about $5m^3/s$, velocity decreased by 0.01-0.67m/s, water depth decreased by 5-10cm, water surface width: decreased by 0.35-4.75m)

(2) Saltwater intrusion

The comparison of the measured and calculated chloride ion concentration is shown in Figure 18. The figure shows that the measured and calculated values fluctuate in a similar manner around 12:00 at the time of high tide, even with a slight difference between the values. The range of saltwater intrusion was also similar to the result of the prior analysis. Thus, the work group judged the analysis model to be adequate. Our findings indicate that the saltwater intrusion range expands towards upstream when the river flow rate is $4m^3/s$ as stated in 7.4, and that a discussion of measures and monitoring is needed with regard for the problem of water intake for tap water and saltwater contamination of ground water.

(3) Ground water

The work group for the mid- and downstream regions selected 12 wells among about 50 for which the current conditions were investigated, and measured them continuously with automatic meters. At four locations, the ground water level was found to drop due to the river water level drop. Figure 19 shows the locations where the drop in ground water level was the greatest. The decrease in ground water level was about 4cm at the maximum, which is extremely small. The work group judged that the impact from the lower river water level was insignificant.

(4) Water utilization

There was no problem caused to water utilization.

(5) Scenery and navigability of river

Scenery and navigability of river were not affected.

Based on results of the verification test, the work group determined that there is no serious impact from reduced discharge for items that can be evaluated over a short term. However, investigation will continue for items that require evaluation based on long-term examination such as agriculture, fisheries, flora and fauna.

7. Consolidated plans for dam countermeasures

7.1 Countermeasures for dam equipment

(photo 1,photo2)

KEPCO plans to rehabilitate the emergency discharge equipment installed at Hitotsuse Dam over 40 years ago, which has not been used and has suffered deterioration due to age, to become regularly-used discharge equipment with sufficient safety and operability. KEPCO also plans to install discharge equipment in Sugiyasu Dam, since the dam has a spillway gate and an intake at high position, and does not have a structure that will allow sufficient removal of turbid water from the dam.

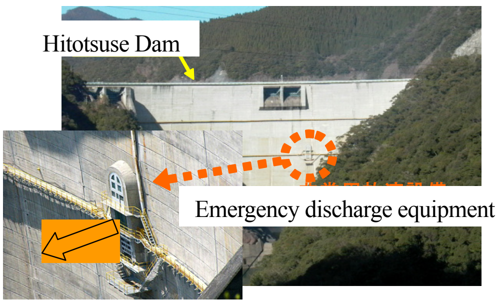
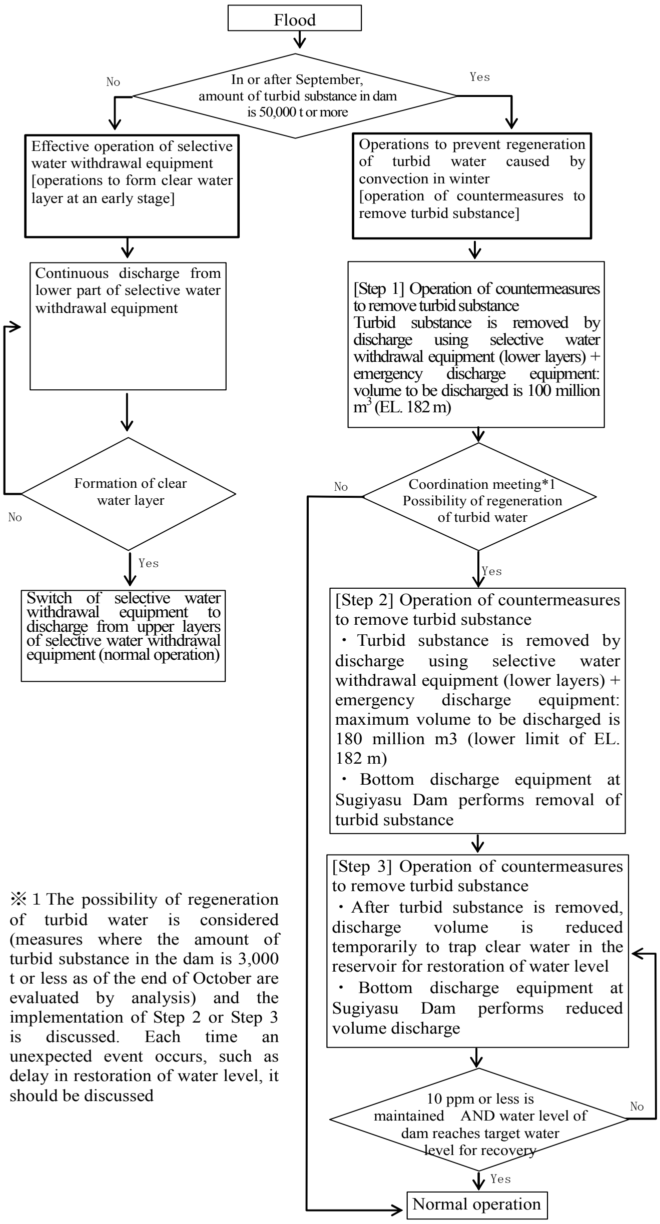


Photo 1 Emergency discharge equipment at Hitotsuse Dam

Photo 2 Sugiyasu Dam

7.2 Operation of dam countermeasures

The flow of countermeasure operations is given in Figure 20. If the amount of turbid substance in the dam is 50,000t or more in or after September, additional countermeasures will be implemented. As the method of operation, countermeasures will be implemented in three stages. Especially before the amount of discharge downstream is reduced in Step 2, a coordination meeting will be held promptly, with the participation of Miyazaki Prefecture, municipalities in the basin and water users, to decide on the countermeasures to follow after thorough discussion and coordination.



※1 The possibility of regeneration of turbid water is considered (measures where the amount of turbid substance in the dam is 3,000 t or less as of the end of October are evaluated by analysis) and the implementation of Step 2 or Step 3 is discussed. Each time an unexpected event occurs, such as delay in restoration of water level, it should be discussed

Figure 20 Flow chart of countermeasure operations

7.3 Countermeasures for upstream region

As stated in 3 above, even with additional countermeasures for the dam, reoccurrence of turbid water due to winter convection cannot be avoided if the amount of turbid substance is of the order of 200,000t. Therefore, the control of turbid water generation must also be actively pursued. The work group for the upstream region investigated the sources and mechanisms of turbid water generation. The findings revealed that bare land resulting from landslides and access roads is the source of turbid water, which imposes a large impact, since a mixed layer with fine soil that does not precipitate easily is seen in the surrounding areas upstream. Based on the investigation results, related organization including prefecture plans to implement measures for the upstream region, for example, by the leading of forest with various species , age mixed and appropriate periodic thinning; by provision of guidance for construction work in accordance with the instructions and standards for access roads in Miyazaki Prefecture that set standards for turbid water prevention; early restoration of failed slopes through forestation, and development of forests and greening of bare land.

8. Conclusion

Whether this plan for countermeasures to reduce turbid water effluence in Hitotsuse River will be developed to into more effective measures or not depends on industry-university-government cooperation to continuously implement, evaluate and improve the plan. KEPCO will proceed with equipment installation, countermeasure operation and monitoring based on the new countermeasure plan. It will also improve data measurement such as that for the distribution of turbidity and water temperature in the reservoir, and actively provide information to local residents to enhance their understanding of the situation.

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