The innovative operation of Imha Reservoir

Le fonctionnement innovant d'Imha Reservoir

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Abstract. Imha Reservoir has both a water transfer tunnel connecting Andong Reservoir and a selective withdrawal facility (SWF), which enable the innovative operation of the reservoir. Although these facilities had not been equipped when constructed in 1993, these structural measures were applied afterward as needed for the effective reservoir operation. The tunnel was constructed in 2015 to minimize the spillway discharge of a reservoir during floods by moving water to the other reservoir with free space. The SWF was installed in 2006 to address problems due to the persistent turbidity of Imha Reservoir. The effectiveness of these facilities was demonstrated through the operational cases in October 2019, while some improvements to non-structural measures were derived simultaneously. To prevent damage to the fish ecosystem of Imha reservoir, the tunnel currently was operated in a one-way water movement. However, a two-way water movement should be allowed as designed in the mid to long term. The SWF was operated effectively based on the prediction of the fate and transport of turbid water inside the reservoir using CE-QUAL-W2. Nevertheless, more action procedures on turbid water are required, such as setting clear criteria for the release timing of turbid water, predicting the downstream turbidity variations, etc.

Résumé. Imha Reservoir dispose à la fois d'un tunnel de transfert d'eau reliant Andong Reservoir et d'une installation de prélèvement sélectif (SWF), qui permettent l'exploitation innovante du réservoir. Bien que ces installations n'aient pas été équipées lors de leur construction en 1993, ces mesures structurelles ont été appliquées par la suite au besoin pour l'exploitation efficace du réservoir. Le tunnel a été construit en 2015 pour minimiser le déversement d'un réservoir lors d'inondations en déplaçant l'eau vers l'autre réservoir avec de l'espace libre. Le SWF a été installé en 2006 pour résoudre les problèmes dus à la turbidité persistante du réservoir Imha. L'efficacité de ces installations a été démontrée à travers les cas opérationnels d'octobre 2019, tandis que certaines améliorations des mesures non structurelles ont été obtenues simultanément. Pour éviter d'endommager l'écosystème halieutique du réservoir Imha, le tunnel

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fonctionnait actuellement selon un mouvement d'eau à sens unique. Cependant, un mouvement d'eau dans les deux sens devrait être autorisé comme prévu à moyen et long terme. Le SWF a été exploité efficacement sur la base de la prévision du devenir et du transport de l'eau trouble à l'intérieur du réservoir à l'aide de CE-QUAL-W2. Néanmoins, davantage de procédures d'action sur l'eau trouble sont nécessaires, telles que l'établissement de critères clairs pour le moment du rejet de l'eau trouble, la prévision des variations de turbidité en aval, etc.

1 Introduction

Along with people's concerns about the deterioration of water resources management conditions due to climate change, interests in environmental preservation and clean water supply are gradually increasing. In particular, as the construction of large dams has become increasingly difficult in South Korea because of the logic of environmental conservation and the opposition from residents ([1]), measures are continuously required to ensure stable water supply and clean water quality without constructing additional large dams. As part of these measures, we may consider structural changes in the facilities, such as a water transfer tunnel between reservoirs for the efficient utilization of existing water resources and a selective withdrawal facility (SWF) ([2]) for water quality control of released water from a reservoir.

Examples of connecting two or more reservoirs include the aqueduct project to connect Ikari and Kawaji Reservoirs in Japan ([3]), and the connection of Trinity Lake and Whiskeytown Reservoir in the United States ([4]). In Australia, the Queensland Water Commission has been operating SEQ Grid since 2008, a system to connect one district where water resources are abundant and other areas where people were suffering from drought ([5]). China has been implementing a project to transport abundant water of the southern Yangtze River to the northern part of the country to address water shortages in the northern region ([6]). In South Korea, a water transfer tunnel connecting Andong and Imha Reservoirs was constructed in 2015 for the optimal utilization of water resources secured through the existing reservoirs ([7]). This tunnel, however, could not be operated until June 2019 because supplementary measures had to be taken to resolve the problems caused by the fish movements between reservoirs such as a reduction in fish diversity.

Also, structural measures using a SWF have been proposed to make clean water quality of reservoirs or downstream rivers considering stratification within reservoirs. We usually use the SWF such as a temperature control curtain, a floating intake facility, a stop-log gate, and a facility for multi-level intake to withdraw water at a specific location, taking into account water temperature or quality by depth in a stratified reservoir ([8]). Sanbanxi Reservoir and Jinping I hydropower station in China have respectively a temperature control curtain ([9]) and a stop-log intake facility ([10]). Grosse Dhuenn Reservoir in Germany has a floating intake facility ([8]). In Imha Reservoir ([11]) and Soyanggang Reservoir ([12]) of South Korea, multi-level water intake facilities were installed and have been operated to reduce damage caused by high turbidity in the water of the reservoirs.

As mentioned in the above cases, Imha multi-purpose reservoir of South Korea is a structure in which both of two facilities, a water transfer tunnel and a SWF were already equipped. Although these facilities were not installed when Imha Dam was constructed in 1993, these structural measures were implemented as needed in the operational process of the reservoir. These facilities can be operated effectively when combined with non-structural measures. In this respect, various studies have been conducted to examine the effects of the installation and operation of these facilities.

Regarding the water transfer tunnel connecting Andong and Imha Reservoirs, Park et al. ([1]) assessed the environmental, social, and economic benefits owing to the water transfer tunnels between the existing two reservoirs in comparison to the construction of new dams by using reports of a feasibility study, an environmental impact assessment, etc. which were made before the construction of the tunnel. Overall, they concluded that the construction of the tunnel linking existing reservoirs would be profitable in terms of impact on wildlife and plant species, resettling returns, loss of cultural assets, and unit costs for water supply compared to constructing new dams. Ahn ([13]) reviewed the changes in the flow affected by the installation of fish exclusion screens in the intake tower of Andong Reservoir, which is a component of the water transfer tunnel, using Flow-3D, a three-dimensional hydrodynamic numerical modeling system. Through this study, it was concluded that the installation of the fish exclusion screens could prevent the migration of the exotic fish species without interfering with normal operation as designed. Park et al. ([7]) emulated the fate and transport of turbidity flow within Imha Reservoir along with turbidity of released water from the reservoir considering operations of the water transfer tunnel using CE-QUAL-W2. It was based on the data from 2002 and 2006 when high-turbidity water flowed into Imha Reservoir. As a result, there not only were few changes in the turbidity of Andong Reservoir, but there also was a reduction in the turbidity of Imha Reservoir, which has a storage capacity of one-half compared to Andong Reservoir thanks to the operations of the water transfer tunnel. Jeong et al. ([14]) derived the most effective operation rule for the optimal operations of Andong and Imha Reservoirs in tandem with the additional water supply amount through the operation of the water transfer tunnel using historical daily data from 1989 to 2009. It drew that the tunnel operation enabled an additional 12.4×10^6 m^3 of water supply per year. Also, the joint operation using the ER rule was found to be the most optimal one considering the tunnel among the three reservoir operating rules such as the space rule; to maximize storage space when flood inflow to a reservoir is forecasted so that spillway discharge can be minimized, the RA (Revelle's Allocation) rule; to allocate the amounts of water supply by considering storage amount in reservoirs and inflow to reservoirs, and the ER (Equivalent Reservoir) rule; to discharge first from a reservoir with a larger ratio of effective water storage to a total reservoir capacity.

There were some studies related to the SWF of Imha Reservoir. Lee et al. ([15]) quantitatively evaluated the effect of reducing the turbidity in the water of Imha Reservoir through the SWF using CE-QUAL-W2. They used the historical data during the period when the SWF had been operated to release highly turbid water flowed into the reservoir due to Typhoon Ewiniar of July 2006. Consequentially, a reduction of about 13×10^6 m^3 turbid water of over 30 NTU and a decrease of about 35×10^6 m^3 of over 100 NTU in the reservoir were resulted in by comparison with when the SWF had not been installed. Kim et al. ([16]) reviewed the changes in the water flow of Imha Reservoir and the capacity to release turbid water from the reservoir under the varied conditions of the gate opening of the SWF by using FLOW-3D. Similar to the measurement results, the flow velocity of more than 1 m/s was distributed around the opened intake gate. Besides, the turbidity of water released through selective withdrawal increased by 46% compared to the floating intake. Figure 1 is a sketch that presents the difference between a floating intake and a SWF.

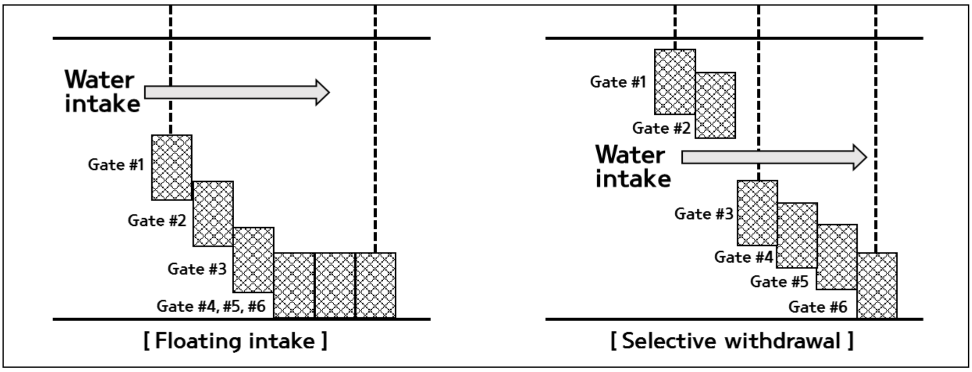

Fig. 1. Difference between a floating intake and a SWF ([15]).

Owing to these two facilities; the water transfer tunnel and the SWF, Imha Reservoir can be operated innovatively and efficiently by applying various non-structural measures. In this paper, we will introduce the operational cases of these two facilities of Imha Reservoir in 2019. Furthermore, some improvements derived from the operational processes will be presented.

2 Materials and methods

2.1 Study area

Imha Reservoir, which was constructed in 1993, is located upstream of the Nakdong River basin in South Korea. The reservoir has a storage capacity volume of 595×10^6 m^3 and a catchment area of 1,584 km^2 ([14]). The major tributaries that flow into Imha Reservoir are the Daegok Stream, the Banbyeon Stream, and the Yongjeon Stream ([17]). Soil of the upstream basin of Imha Reservoir consists of fine reddish-brown clay sedimentary rocks that are prone to weathering. Because of this geologic characteristic, it is known that highly turbid water flows into Imha Reservoir when torrential rain occurs especially during the flood season ([15]). Andong Reservoir, which was built in 1977, about 2 km away from Imha Reservoir, has the largest storage capacity among reservoirs in the Nakdong River basin. Andong and Imha Reservoirs are connected through a water transfer tunnel ([7]). Figure 2 shows the location of two reservoirs and the major tributaries flowing into Imha Reservoir. Table 1 shows the detailed information of two reservoirs.

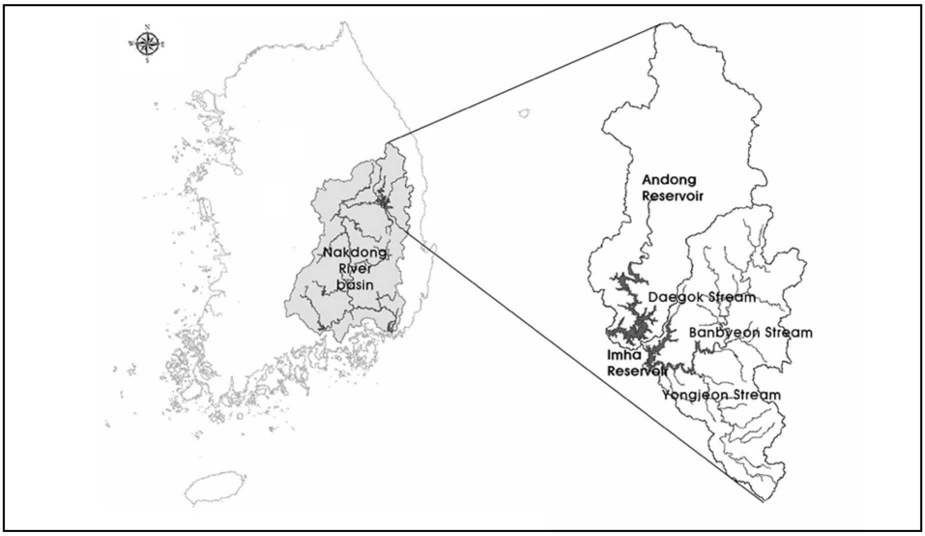

Fig. 2. Location of Andong and Imha Reservoirs and major tributaries flowing into Imha Reservoir.

Table 1. Summary of Andong and Imha Reservoirs characteristics ([7]).

Description	Andong Reservoir	Imha Reservoir
Dam crest elevation (EL.m)	165.4	167.5
Catchment area (km^2)	1,584	1,361
Storage capacity volume (×10^6 m^3)	1,248	595
Normal water level (EL.m)	160	163
Dam height (m)	83	73
Dam length (m)	612	515

2.2 Water transfer tunnel

2.2.1 Purpose of the tunnel

As shown in Table 1, the catchment area of Imha Reservoir is almost similar to Andong Reservoir's one, but the storage capacity volume of Imha Reservoir is only about 47% of Andong Reservoir ([7]). For this reason, Andong Reservoir was released only four times in total for flood control through the spillway, twice respectively in 2002 and 2003 until 2015, but Imha Reservoir discharged 12 times as shown in Table 2 ([18]). Under this circumstance, the installation of a water transfer tunnel connecting the two reservoirs was planned. This tunnel was designed to enable the water of a reservoir to be transferred to the other reservoir with free space. This was expected to secure the additional water resources of 23.7×10^6 m^3 per year by minimizing the released water amount via a spillway for flood control ([19]).

These secured water resources were planned to be used to improve the water quality of a downstream river.

Table 2. Discharge records using spillways of Andong and Imha Reservoirs ([18]).

Andong Reservoir		**Imha Reservoir**			
Period	Released amount	Period	Released amount	Period	Released amount
29/08/2002 - 01/09/2002	39.3×10^6 m^3	10/08/1993 - 11/08/1993	109.3×10^6 m^3	11/09/2003 - 13/09/2003	97.6×10^6 m^3
12/09/2002 - 21/09/2002	95.4×10^6 m^3	13/08/1993 - 17/09/1993	44.4×10^6 m^3	18/09/2003 - 22/09/2003	30.3×10^6 m^3
12/09/2003 - 13/09/2003	5.7×10^6 m^3	16/08/1998 - 20/08/1998	122.4×10^6 m^3	23/06/2004 - 25/06/2004	21.8×10^6 m^3
19/09/2003 - 22/09/2003	26.6×10^6 m^3	23/09/1999 - 26/09/1999	147.6×10^6 m^3	23/08/2004 - 29/08/2004	39.4×10^6 m^3
-	-	29/08/2002 - 05/09/2002	39.3×10^6 m^3	17/07/2006 - 31/07/2006	288.9×10^6 m^3
-	-	12/09/2002 - 21/09/2002	95.4×10^6 m^3	15/09/2012 - 17/09/2012	19.2×10^6 m^3

The project to connect Andong and Imha Reservoirs began in November 2011 and was completed in May 2015 by K-water, which is a state-owned company in charge of the operations of multi-purpose reservoirs including Andong and Imha Reservoirs in South Korea. Through this project, the water transfer tunnel of an internal diameter 5.5m and length 1,925 m was installed along with two intake towers in each reservoir ([14, 19]). This tunnel allows the water of Andong Reservoir to move to Imha Reservoir or conversely, depending on the difference of water level between the two reservoirs. Additionally, the intake tower of Imha Reservoir applied a SWF to minimize damage due to high-turbidity water flowing frequently into Imha Reservoir ([19]). Figure 3 shows the location and the concept diagram of the water transfer tunnel.

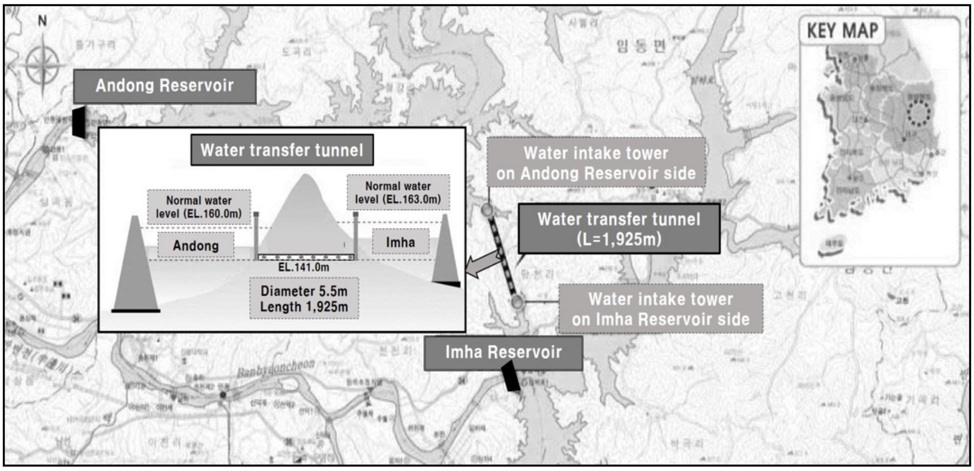

Fig. 3. Location and concept diagram of the water transfer tunnel ([7, 19]).

2.2.2 Operational guideline of the tunnel

In the design phase of the water transfer tunnel at first, the operational guideline was established to ensure a two-way water movement using the water level difference between Andong and Imha Reservoirs by opening the tunnel at all times. Additionally, during a flood, floating intake from Imha Reservoir was planned to be implemented to prevent the highly turbid water of Imha Reservoir from being transferred into Andong Reservoir ([19]). Figure 4 shows a flow chart of the tunnel operation procedures.

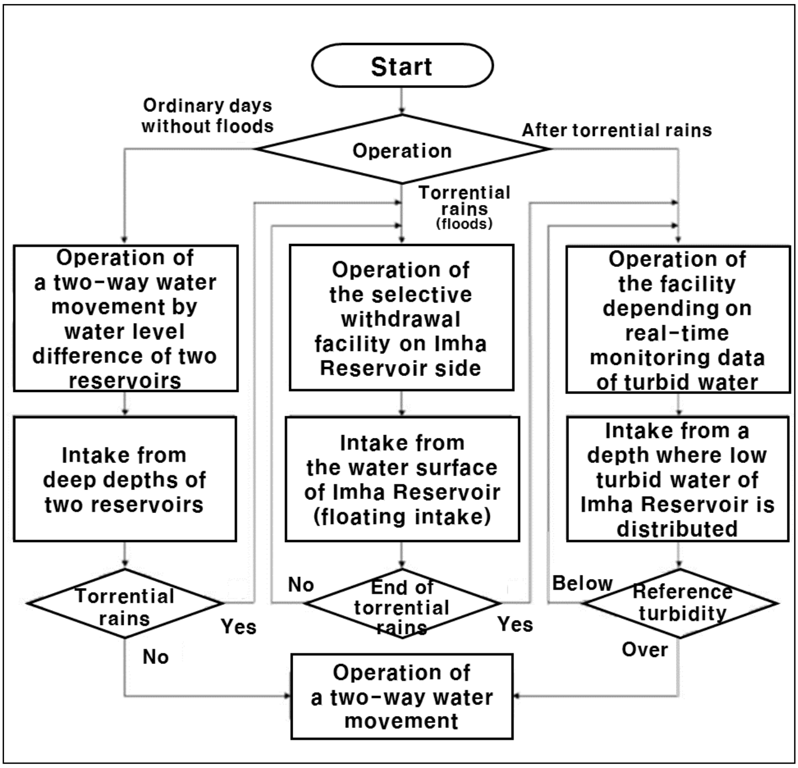

Fig. 4. Flow chart of the tunnel operation procedures for a two-way water movement ([19]).

However, during the construction of the tunnel, residents who were earning a living by collecting fish from Imha Reservoir filed a complaint that exotic fish species in Andong Reservoir were likely to enter Imha Reservoir through the tunnel, resulting in damage to the fish ecosystem. Hereby, K-water established measures to prevent the fish movement from Andong Reservoir to Imha Reservoir. First of all, a structural method was applied by installing meshed screens at the entrance of the tunnel ([13]). Simultaneously, non-structural measures were established, such as the tunnel operation of a one-way water movement from Imha Reservoir to Andong Reservoir and the set-up of the water level difference between reservoirs of more than 1m considering the critical flow velocity of fish (0.93 m/s) ([19]). Figure 5 schematizes these measures.

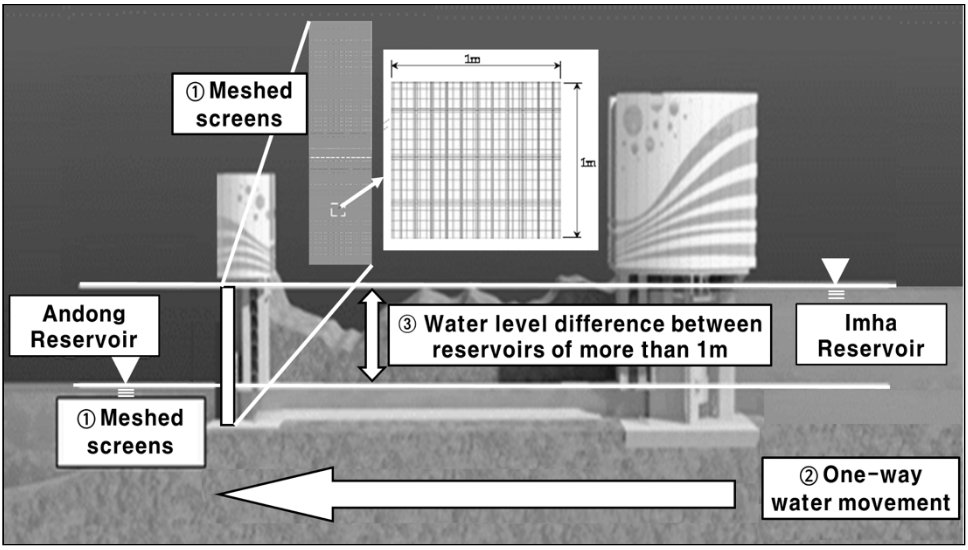

Fig. 5. Measures to prevent the movement of exotic fish species to Imha Reservoir ([19]).

2.2.3 Operational cases of the tunnel

Despite the establishment of such measures, the tunnel had not been operated since its completion in 2015 due to continuous concerns among residents. In June 2019, K-water operated to test the structural stability of the tunnel for the first time. Following the one-way operational guideline, 13.4×10^6 m^3 of water was transferred from Imha Reservoir to Andong Reservoir for 57 hours as shown in Table 3. During the operation of the tunnel, the water level of Imha Reservoir was kept over 1 m than the Andong Reservoir's one. Through the test operation, it was confirmed that the tunnel was in good condition and could be operated if necessary.

Table 3. Test operation result of the water transfer tunnel.

Reservoir	**Starting water level (09:30 13/06/2019)**		**Ending water level (18:50 15/06/2019)**		**Transferred water quantity**
Andong	EL.148.40m	Difference 2.70m	EL.148.70m	Difference 1.00m	13.4×10^6 m^3
Imha	EL.151.10m		EL.149.70m		

Afterward, the tunnel was operated on October 14, 2019, as the water level of Imha Reservoir reached a maximum of EL.162.65m on October 9, due to heavy rain caused by Typhoon Mitag. However, the tunnel was operated only for six hours because of concerns over the inflow of the high-turbidity water from Imha Reservoir into Andong Reservoir despite the water level difference between the two reservoirs was still 9.63m. Table 4 shows the operation result of the tunnel at that time.

Table 4. Operation result of the water transfer tunnel on October 14, 2019.

Reservoir	**Starting water level (11:40 14/10/2019)**		**Ending water level (17:50 14/10/2019)**		**Transferred water quantity**
Andong	EL.152.46m	Difference 9.86m	EL.152.54m	Difference 9.63m	3.4×10^6 m^3
Imha	EL.162.32m		EL.162.17m		

2.3 SWF

2.3.1 Purpose of the facility

After the completion of Imha Dam in 1993, the turbidity of Imha Reservoir had not been such high (100-250 NTU) and not remained for long periods in each year, but in 2002 and 2003, due to torrential rains caused by Typhoon Rusa and Maemi, the high-turbidity water flowed into Imha Reservoir. In 2003, the turbidity of more than 30 NTU, which is an indicator to figure out the severity of turbidity ([12]), continued for 315 days, as shown in Table 5. This was because the high-turbidity water could not be released entirely only through the surface water intake and the turbid water was spread to the whole layer of the reservoir due to the turn-over phenomenon in the fall. The persistent turbidity causes various problems such as a decrease in the utility value of water resources, deterioration of water quality, disturbance of the aquatic ecosystem, and an increase in water treatment costs ([2, 12]). In 2006, the SWF and the turbidity measuring devices of Imha Reservoir were installed as part of measures to reduce the damage caused by this highly turbid water.

Table 5. Annual peak turbidity and turbid water periods (days with over 30 NTU) of Imha Reservoir.

Year	**'96 - '01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**···**	**'17**	**'18**	**'19**
Peak turbidity (NTU)	248	882	1,221	994	500	1,050	90	···	51	211	473
Days	-	170	315	365	178	49	6	···	0	0	42

When Imha Reservoir was constructed, the water intake was possible at the water surface like a type of floating intake or in deep depth of the reservoir. It was improved to the multi-level intake facility as a SWF in 2006. In addition to this facility, automatic turbidity measurement devices were installed at nine points, including the water intake tower, the dam, Doyoun Bridge, Jichon Bridge, etc. for real-time monitoring ([15]). After that, measuring devices at two more points, including the intake tower of the water transfer tunnel, were installed. Therefore, a total of 11 turbidity measuring devices are currently in operation. Figure 6 shows the location of the major turbidity measuring devices in Imha Reservoir.

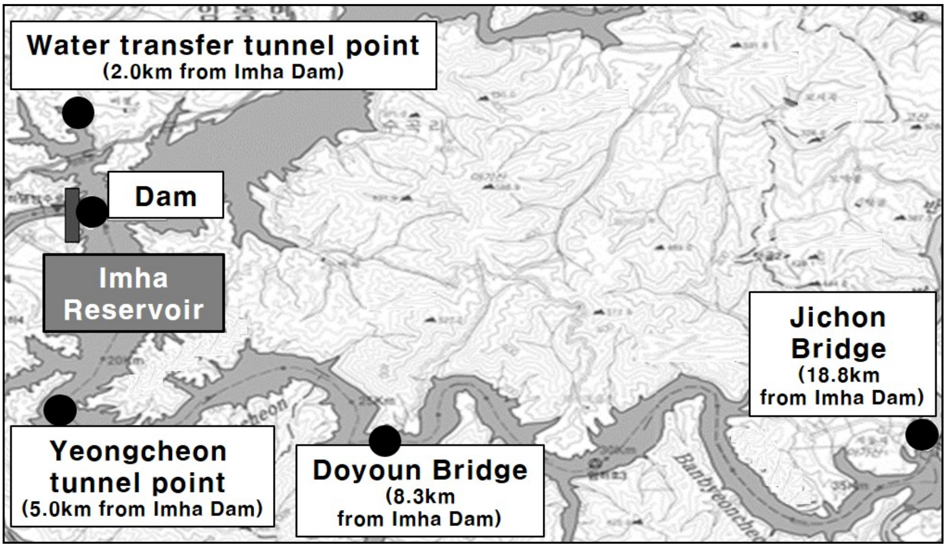

Fig. 6. Location of the major turbidity measuring devices in Imha Reservoir ([15]).

2.3.2 Operational cases of the facility

In addition to the geological characteristics of Imha reservoir, the highly turbid water flowing into the reservoir is caused by torrential rains ([2]). Since the installation of the SWF in Imha Reservoir, the high-turbidity water flowed into Imha Reservoir during Typhoon Ewiniar in July 2006. Due to this turbid water, the highest turbidity of 1,050 NTU was recorded in the reservoir as shown in Table 5. At that time, as the highly turbid water distributed around the middle level of the reservoir was released using the SWF, the persistent turbidity could be prevented.

Since then, few problems had occurred due to the inflow of high-turbidity water until 2018, but in October 2019, turbid water flowed into Imha Reservoir during Typhoon Mitag's invasion. Due to torrential rain, the maximum inflow into Imha Reservoir was 3,534 m^3/s, which was the largest one since Typhoon Maemi in 2003. With that torrential rain, the highest turbidity of 473 NTU was recorded in the reservoir on October 5th. Table 6 shows the hydrological data of Imha Reservoir in the event of major torrential rains in the past, including Typhoon Mitag.

Table 6. Hydrological data of Imha Reservoir in the event of major Typhoons.

Typhoon	**Rusa (2002)**	**Maemi (2003)**	**Ewiniar (2006)**	**Mitag (2019)**
Precipitation (mm)	183 [Aug 30-Sep 1]	185 [Sep 11-Sep 13]	147 [Jul 9-Jul 10]	166 [Oct 2-Oct 3]
Maximum inflow (m^3/s)	7,113 [Aug 31, 22:00]	6,836 [Sep 13, 03:00]	2,304 [Jlu 17, 01:00]	3,534 [Oct 3, 04:00]
Highest water level (EL.m)	164.42 [Sep 4, 04:00]	163.61 [Sep 16, 06:00]	158.93 [Jul 19, 10:00]	162.65 [Oct 9, 10:00]

To cope with the problem proactively and effectively due to highly turbid water, K-water simulated and predicted the turbidity variation by the depth of the reservoir using CE-QUAL-W2, which is a two-dimensional (longitudinal and vertical) hydrodynamic modeling system that is suitable for emulating the water temperature stratification, the fate and transport of turbidity flow, etc ([2, 12, 20]). According to the modeling results, the turn-over phenomenon would occur in November and the persistent turbidity problems of the reservoir would be following when the turbidity was not ruled out, as in 2002 and 2003. For this reason, the highly turbid water had to be released quickly.

Simultaneously, K-water had to decide how much water should be released, exceeding the demand for water use, to exclude the highly turbid water from the reservoir rapidly considering the stability of the water supply. The prediction of the fate and transport of turbidity flow inside the reservoir depending on the scenarios with different discharge amounts and periods, shown in Table 7, by CE-QUAL-W2 supported K-water's decision-making. As a result, K-water selected the third scenario of Table 7 and it could obtain the most effective result to resolve the turbidity problem of the reservoir. Figure 7 shows the simulation results of turbidity by the third scenario of Table 7.

Table 7. Scenarios by the different release amounts and periods to predict turbidity.

Scenario	**S1**	**S2**	**S3**	**S4**
Discharge (m^3/s)	12.8-12.9	42.9	95.2	95.2
Release period	Until Jun 30, 2019	Until Feb 12, 2020	Until Oct 30, 2019	Until Nov 9, 2019
Predicted maximum turbidity (NTU), as of Dec 31, 2019	40.8	32.2	25.8	22.8
Selection			√	

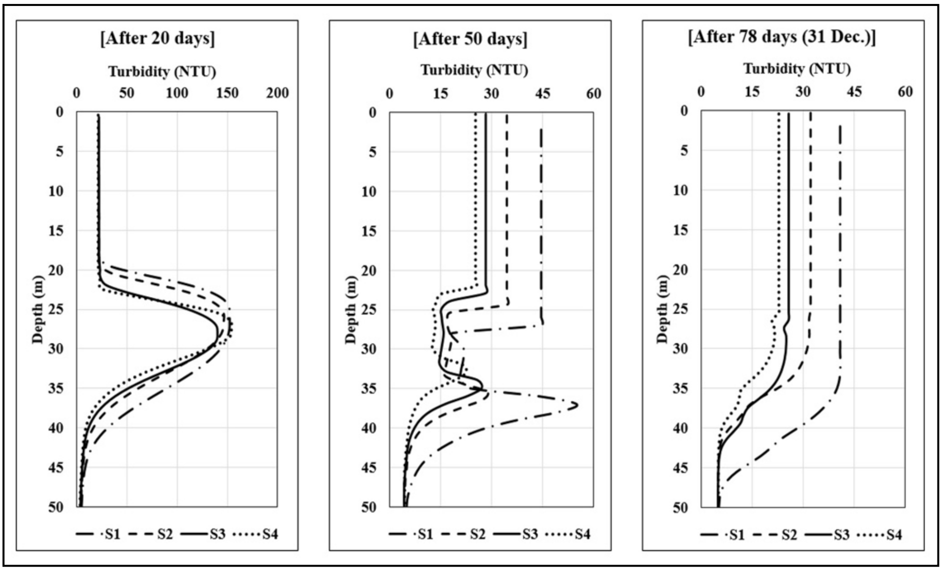

Fig. 7. Simulation results of turbidity by the third scenario of Table 7.

Based on these simulation results, the SWF was used to release the high-turbidity water around the middle layer of the reservoir. Through these processes, the period when the turbid water over 30 NTU in Imha Reservoir had remained was only 42 days as shown in Table 5 of the annual peak turbidity and turbid water periods. Consequentially, the problems which would be caused by the persistent turbidity were prevented in advance.

3 Results and discussion

3.1 Improvement requirements of the water transfer tunnel operation

Through the first operation of the water transfer tunnel in 2019, the structural stability for its regular operation was confirmed, but there are still a couple of improvement requirements in the non-structural measures for the effective operation of the tunnel.

In the mid to long term, a review for the two-way water movement should be made as planned in the original design phase, although the one-way operation is inevitable under the current circumstances to prevent damage to the diversity of fish ecology in Imha Reservoir. The one-way movement of water from Imha Reservoir to Andong Reservoir also enables the additional water resources of 23.7×10^6 m^3 per year to be secured ([19]). However, the operation for the two-way water movement is needed in terms of the optimal utilization of the existing water resources in two reservoirs. To achieve it, monitoring the ecological change of the reservoirs must be preceded.

Moreover, it is necessary to supplement the operational guideline of the tunnel to prevent the movement of high-turbidity water from Imha Reservoir to Andong Reservoir due to tunnel operation during the flood season. After Typhoon Mitag had hit in October 2019, the tunnel operation was attempted in tandem with the intake of the water at the surface layer of Imha Reservoir on 14 October, but it was suspended within six hours due to a sudden increase in the turbidity of Imha Reservoir as shown in Figure 8. When judging by the gradual decrease in turbidity after the tunnel was been shut down, it is assumed that the change of flow velocity inside the reservoir due to the tunnel operation had caused this variation in turbidity. To address this problem, the decision support system is required to predict the fate and transport of turbidity flow inside Imha Reservoir due to the tunnel operation.

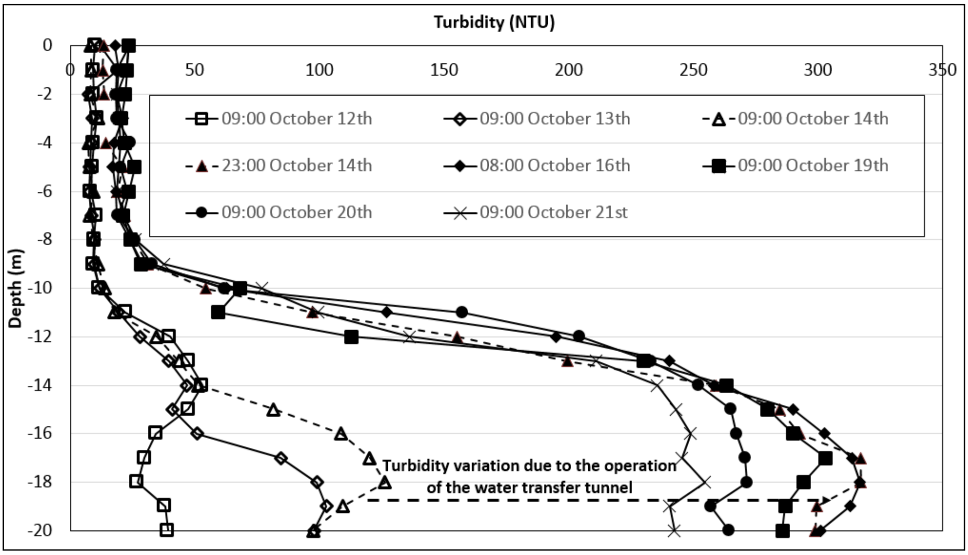

Fig. 8. Turbidity variation graph by depth of Imha Reservoir due to water transfer tunnel operation.

3.2 Additional requirements for the effective operation of the SWF

During Typhoon Mittag's invasion which caused torrential rain, the turbidity of Imha Reservoir exceeded 30 NTU on October 2, 2019, but it was stabilized below 30 NTU on November 14 by releasing turbid water rapidly using the SWF. As shown in Figure 9, the turbidity was decreasing while the temperature of the water body was becoming constant to about 25 m below the water surface of the reservoir because of the turn-over phenomenon. Accordingly, K-water adjusted the discharge at Imha Reservoir from 95.2 m^3/s to 12.9 m^3/s, which was the demand amount of the reservoir.

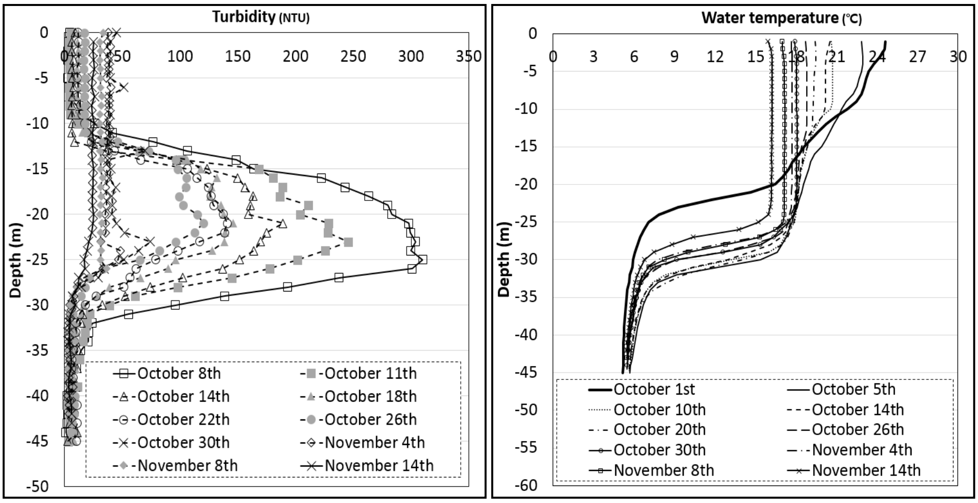

Fig. 9. Variation graphs of turbidity and water temperature by depth of Imha Reservoir (Measurement data from October to November 2019).

This case shows that the structural measures using the SWF of Imha Reservoir were combined effectively with the non-structural measures such as the prediction of the fate and transport of turbidity flow to cope with the highly turbid water flowing into Imha Reservoir. Two more things, however, are required to improve the action system on turbid water more effectively as follows.

First, a procedure should be added to set clear criteria for determining whether or not the turbid water should be released from the reservoir along with the release timing. The real-time turbidity measurement data at the point of Jichon Bridge located in 18.8 km upstream from Imha dam can be utilized. The data can give K-water enough time to decide on releasing turbid water from the reservoir considering the travel time of turbid water from Jichon Bridge.

Furthermore, water quality modeling to predict the turbidity variations for a downstream river as well as for the reservoir has to be implemented. A more systematic action on turbid water will be possible when the changes in turbid water of the downstream river are considered at the same time.

4 Conclusions

Imha Reservoir is a hydraulic structure with both a water transfer tunnel and a SWF. To maximize the installation effect of these facilities, non-structural measures have been applied. Starting with the test operation of the tunnel in June 2019, the water transfer tunnel was operated during typhoon Mitag's invasion in October 2019. In the same period, the SWF was also in operation to quickly release the high-turbidity water flowing into Imha Reservoir. These operations demonstrated the effectiveness of the facilities, while improvements to some unstructured measures were derived as below.

- The operation of the tunnel in October 2019 followed the one-way water movement guideline from Imha Reservoir to Andong Reservoir. Inevitably, this one-way operation will be conducted until it is proved that the two-way water movement does not affect the fish ecosystem of the two reservoirs. However, the two-way water movement will be necessary for the optimal coordinated operations of the two reservoirs. To achieve it, monitoring variations in the fish ecosystem of the reservoirs should be preceded in the mid to long term.
- In October 2019, the SWF could be used effectively based on real-time turbidity monitoring data of the reservoir, simulation of the fate and transport of highly turbid water within the reservoir through water quality modeling, and selective intake of the middle layer inside the reservoir with highly turbid water. However, to cope with turbid water more effectively and systematically, some additional procedures can be required as follows; setting up clear judgment criteria on the release timing of turbid water from the reservoir, securing the stability of water supply from the reservoir, predicting the turbidity changes of the downstream river due to turbid water released from the reservoir, and simulating the turbidity variations of the reservoir by the operation of the water transfer tunnel.

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