Development of a Decision Support System for Turbid Water Management through Joint Dam Operation

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ABSTRACT: In this study we developed a turbidity management system to support the operation for effective turbid water management. The decision-making system includes various models for prediction of turbid water inflow, effective reservoir operation using the selective withdrawal facility, analysis of turbid water discharge in the downstream. The system is supported by the intensive monitoring devices installed in the upstream rivers, reservoirs, and downstream rivers. SWAT and HSPF models were constructed to predict turbid water flows in the Imha and Andong catchments. CE-QUAL-W2 models were constructed for turbid water behavior prediction, and various analyses were conducted to examine the effects of the selective withdrawal operation for efficient high turbid water discharge, turbid water distribution under differing amount and locations of turbid water discharge. A 1-dimensional dynamic water quality model was built using Ko-Riv1 for simulation of turbidity propagation in the downstream of the reservoirs, and 2-dimensional models were developed to investigate the mixing phenomena of two waters discharged from the Andong and Imha reservoirs with different temperature and turbidity conditions during joint dam operation for reducing the impacts of turbid water.

Keywords: Turbidity management, selective withdrawal alternative, SWAT, HSPF, CE-QUAL-W2, joint dam operation

1. INTRODUCTION

In the management of water resources, it is very important to consider both water quantity and water quality. Thus social and economic values of the source water in the reservoir depend on reliable water quality management. Turbid water in reservoir is one of the troublesome water quality issues in Korea and other countries. Main causes of turbid water occurrence include soil loss from excessive rainfall and human activities such as improper construction and irrigation site management.

Turbid water occurred in a basin consists of wash load and suspended load. The wash load induced from upstream basin exists as colloidal forms less than 5μm that do not settle down easily due to stratification or turbulence of reservoir water body, thus causing a long-term turbid water problem in reservoirs. High turbidity current induced from the upstream was found to increase DO consumption and cause reservoir eutrophication since it included nutrients components such as phosphorous and various pollutants. In most cases, the induced turbid water from the upstream of reservoir plunges down to formulate interflow that cannot be easily observed directly from reservoir surface. However, turbid water released from reservoir increases operation costs of water treatment plants located downstream the reservoir.

Generally, the occurrence of turbid water is very sensitive to rainfall intensities rather than rainfall amounts. Recently, due to high concentrated flood resulted from global warming, some reservoirs in Korea suffered from turbid water occurred during high concentrated rainfall. The Imha reservoir located in the upstream of the Nakdong River was suffered from high turbid water occurred during the typhoon 'Rusa' in 2002 and 'Maemi' in 2003. The inflow turbid water had spread out the entire water body through stratification and overturning, resulting in prolonged turbid water problems both in the reservoir and downstream areas.

Fig. 1 shows rainfall depth, maximum turbidity, average turbidity, and outflow turbidity in Imha watershed since 2002. As shown in Fig.2, both the maximum turbidity and duration of turbid water dramatically increased in the years of 2002 and 2003 due to the typhoon 'Rusa' and 'Maemi.' Note, however, that the increased turbidity due to the typhoon 'Dienmu', and 'Maegi' during 2004 diminished rather faster than previous years. It shows the possibility to control turbidity through monitoring and water intake tower operation with gate control by releasing high turbid water. Such operation is referred as selective withdrawal in which high turbid water is selectively discharged to shorten the period of turbid water flow in downstream. Fig. 2 shows the turbid water discharged from the reservoir.
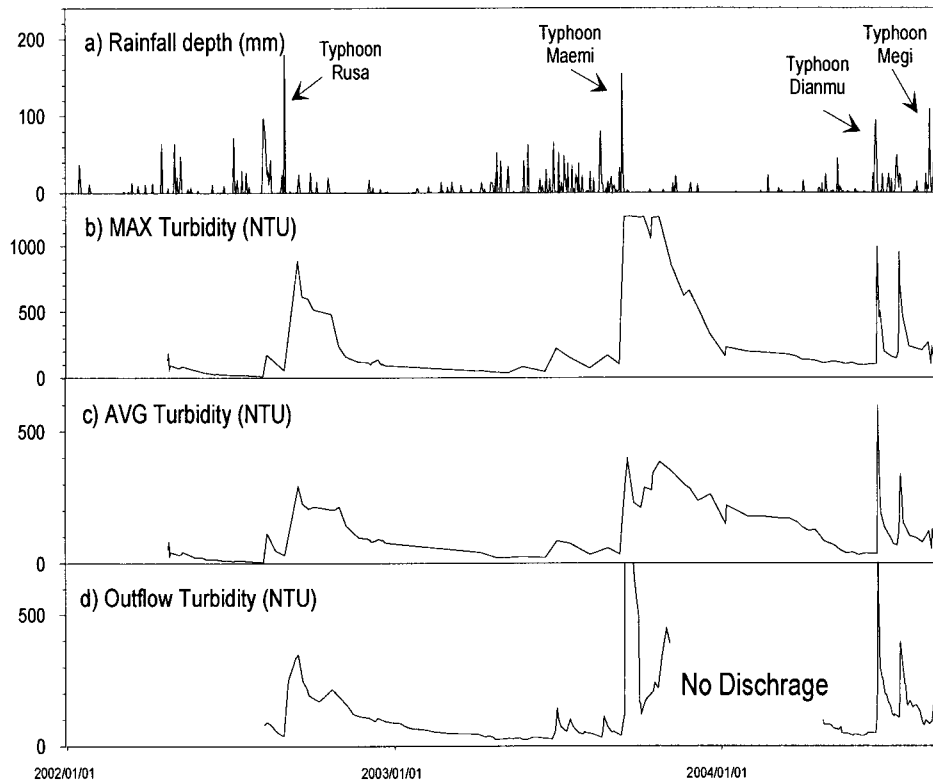

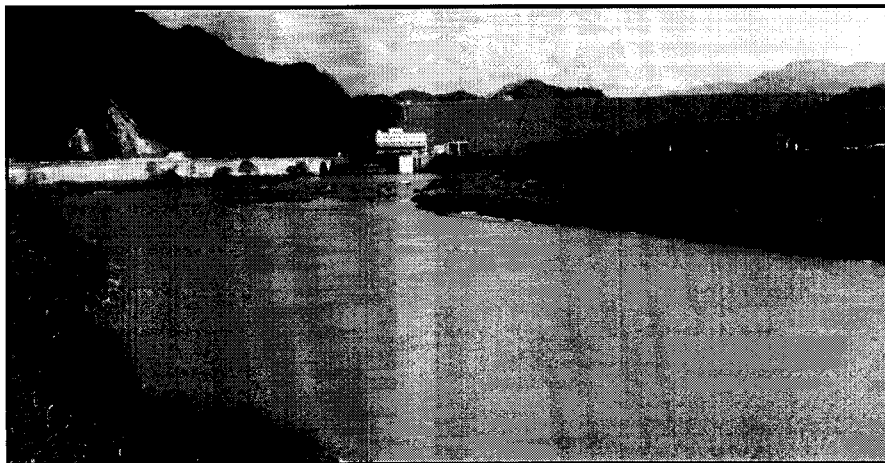Fig. 1. Recent trend of turbidity concentration in NTU and rainfall in Imha Reservoir

Fig. 2. Field photography of high turbid stream water from Imha Reservoir

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In an effort to establish turbid water reduction schemes and deal with arising turbid water problems due to increasing rainfall intensity, the reduction alternative of turbid water has been established and executed in the Imha reservoir. Automatic turbidity monitoring devices were and a selective withdraw facility were installed and under operation.

As well, the Water Operation Center in K-water established an optimized operation scheme for the Imha multipurpose dam (IMD) and the Andong Multipurpose dam (AMD). According to the scheme, during flood periods (July to September) high turbid water in IMD should be discharged promptly, while during dry period (October to July) turbidity should been less than 30 NTU in the downstream river through joint operation with AMD. Various conditions such as prediction of turbidity, the discharge location of high turbid water, an appropriate discharge timing and rate should be considered for this operation. In this research, we developed an integrated turbidity management system to support the operation for effective turbid water management. The decision-making system includes various models for prediction of turbid water inflow, effective reservoir operation using the selective withdrawal facility, analysis of turbid water discharge in the downstream. The system will be supported by the intensive monitoring devices installed in the upstream rivers, reservoirs, and downstream rivers. The development of integrated system will provide valuable information to reservoir operators.

2. Description of the catchments: Imha and Andong

The study areas include Imha-Andong catchment located the upper drainage area of Nakdong River (Fig. 3). The Imha and Andong catchment's properties are compared in Table 1. The Imha catchment's area is 1,361 km^2 composed of mainly forested area (79.8%), and agricultural area (15.0%). The major soil type is Ma and elevation ranged from 54 to 1215 m. Annual average rainfall in Imha area (2000 to 2004) is 1,158 mm/year. On the other hand, the Andong catchment's area is 1,584 km^2 and the major land use is forest (82.2%) as well, and agricultural area (11.9%) which considered as major source of sediment. The major soil type is Mm and elevation ranges from 105 to 1,550 m relatively higher than Imha catchment. Annual average rainfall in this area (2000 to 2004) is 1,348 mm/year. The soil in the Imha reservoir is classified as very fine colloidal type distributed from 7 to 10 μm in diameter, and thus it does not settle down easily. Generally turbidity and SS are proportionally related, it also is affected by regional factors because the suspended particles in the Imha reservoir are finer than that of the Andong reservoir.

Table 1. Characteristics of Imha and Andong catchement.

| Properties	Imha	Andong
Area (km^2)	1,361	1,584
Major Landcover	Forest (79.8%) Agriculture (15.0%)	Forest (82.2%) Agriculture (11.9%)
Major Soil type	Ms (Lithosols, Micaceous and Hard Siliceous Materials, silty loam or sandy loam)	Ma (Lithosols, Siliceous Crystalline Materials, silty loam or sandy loam)
Avg. Ann. Precipitation (mm, 2000-2004)	1,158	1,348
Total channel length (km)	5,741	5,381
Storage volume (m^3)	424M	1000M
Elevation (m, EL)	54~1,215	105~1,550
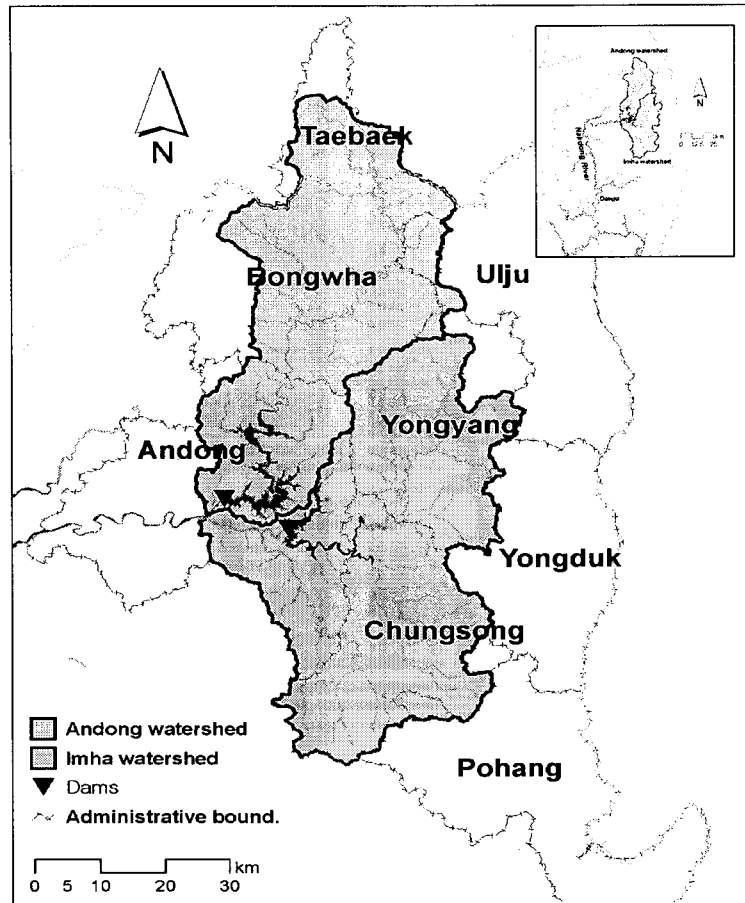
Fig. 3. The location of Imha and Andong catchments.

3. Methodology

To establish the effective turbidity control measures at catchment scale, the characteristics of a catchment need to be investigated through a broad field survey. As well, areas vulnerable to erosion and priorities of environmental improvement need to be analyzed and defined by using numerical modeling and GIS data analysis.

Fig. 4 shows the schematic of proposed framework to manage the turbidity effectively in Imha-Andong catchment. In this research, to define factors causing turbid water inflowing from Imha-Andong catchment to the reservoirs, filed data during rainfall events were collected and and the catchment models (SWAT, HSPF) were used to estimate the suspended sediment occurring from each subcatchment. Understanding the dynamics of high turbid water inflowing in the reservoir, and proper selective withdrawal schemes with various scenarios were investigated by using CE-QUAL-W2. KORIV1-WIN, dynamic water quality model, was also used to investigate the distance and patterns of turbid water propagations in the downstream. The suspended sediment concentrations measured at the major gauging stations of Imha-Andong catchment were used to calibrate the SWAT, and HSPF. The data from automatic turbidity monitoring stations installed in the reservoir were used to calibrate the CE-QUAL-W2. To measure the turbidity of the downstream, automatic turbidity measurement system was installed in Haepyung, Gumi, and the obtained data were used to calibrate the KORIV1-WIN.
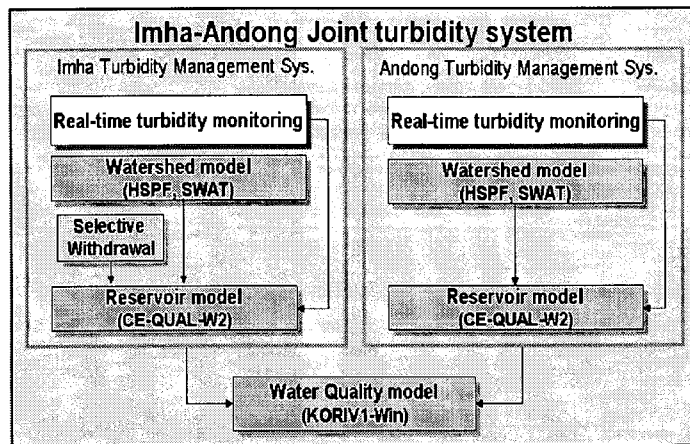
Fig. 4. Schematic diagram of modeling and control system in Joint turbidity system.

4. Result and Discussion

4.1. Establishment of catchment models to predict flow and turbid water inflow.

SWAT and HSPF models were established to analyze the flow and erosion in Imha-Andong catchment. The statistical methods (Nash-Sutclffe equation, R_{eff}, Nash and Sutcliffe, 1970 and R^2) and graphical trend analysis were used to evaluate the efficiency of model prediction. The calibration and validation of two models at daily and hourly scales showed that the models generally reproduced the observed stream flow while they tended to underestimate peak flow. The efficiency of SWAT model prediction was that in case of Imha catchment, R_{eff} ranged from 0.54 to 0.76, and R^2 ranged from 0.53 to 0.79, and in case of Andong catchment, R_{eff} ranged from 0.45 to 0.64 and R^2 ranged from 0.50 to 0.80. The suspended sediment concentrations measured in the three gauging stations (Dosan,Yungyang and Cheongsong) regarding three major events on July, 2006 were used to calibrate the models. The result of HSPF's calibration showed that HSPF reproduced the peak concentration, and temporal trends of the measured data (Fig. 5).

4.2. Establishment of turbid water dynamics prediction model

For efficient turbid water withdrawal in the Imha reservoir, a selective withdrawal facility was recently installed and operated during summer season of year 2006 (Fig.6). In this research, CE-QUAL-W2 model was utilized to assess the efficiency of the selective withdrawal facility, in comparison with the original surface withdrawal, on turbid water management. Model calibration was carried out using the data observed at four automatic monitoring stations in the reservoir. It was found that the model appropriately reproduced, with the RMSE less than 5.2 NTU, the observed vertical and horizontal distributions of water temperature and turbidity as well as the location of maximum turbid water at each monitoring station (Fig.7).

The analysis results showed that selective withdrawal is more effective in removing high turbid water than surface withdrawal as selective withdrawal contributed to reducing 35 Mm^3 of high turbidity water (>100 NTU) in the reservoir by increasing outflows of high turbid water (Fig.7 and 8). Therefore, effective management of turbid water in the reservoir can be achieved by changing locations of intake depending on turbid water distribution conditions. The results of this study will provide some basic information for establishing better operation strategies to cope with turbid water problems.
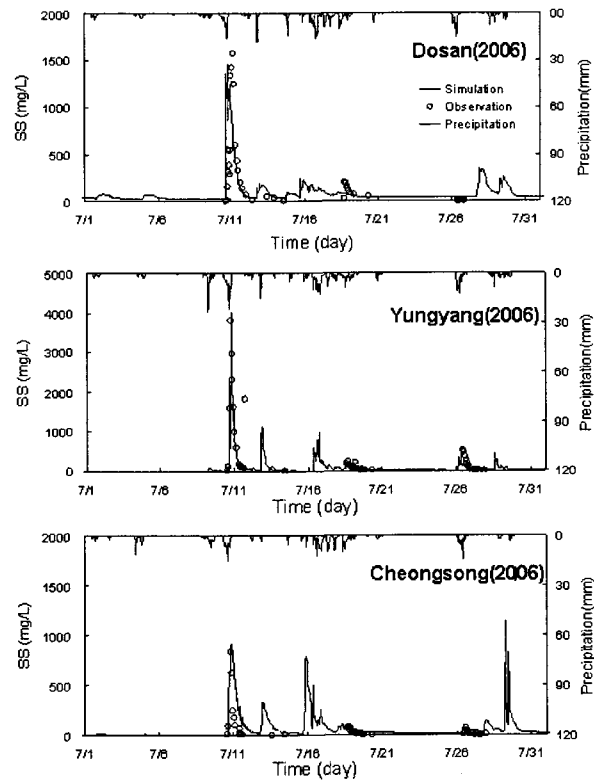
Fig. 5. Results of hourly suspended sediment simulation using HSPF in the catchments.
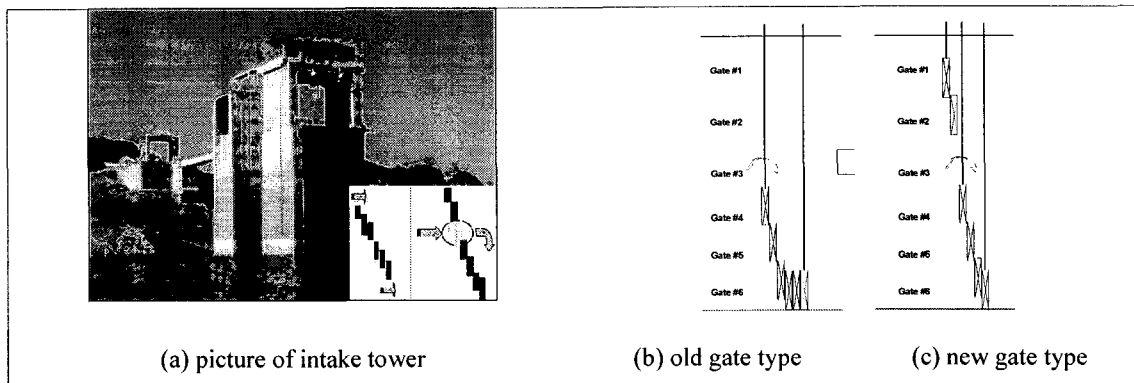

| (a) picture of intake tower | (b) old gate type | (c) new gate type |

Figure 6. Selective withdrawal facility built in Imha Dam.

4.3. Establishment of turbidity management system in the downstream

A 1-dimension unsteady-state water quality model was constructed to investigate the reduction of turbidity and pattern of turbidity propagation after high turbidity water is discharged from the reservoir. The model input data include discharge data and turbidity collected in the main stream and tributaries from Andong dam and Gumi. Calibration and validation of KORIV1-Win model were conducted with measured stream flow in Banbuncheon, Naesungcheon, Yonggang, Byongsungcheon, Wicheon and Gamcheon gauging stations. Model result showed that it matched with observed values (Fig.10).

As well, water quality simulation was conducted with the boundary condition of the upstream using outflow's turbidity from the Imha and Andong reservoirs, and mean monthly turbidity in tributaries. The comparison of model prediction and measurement showed that maximum value of turbidity occurred in July of 18, 2006 (Fig.11).
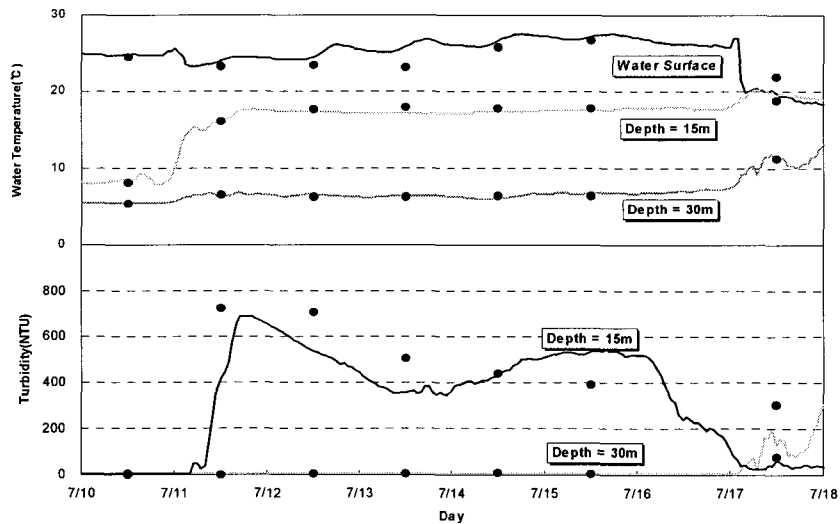

Fig. 7. Temporal variations of temperature at selected depths at the dam site.
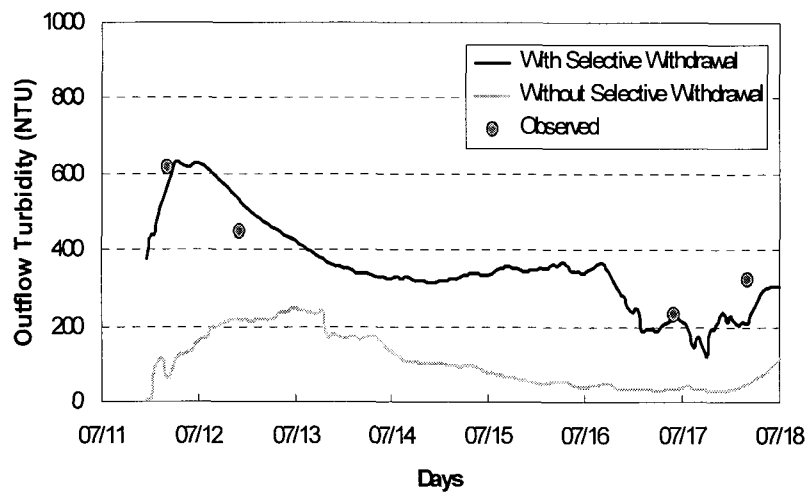((●)observed value; (—) : simulated value).

Fig. 8. Temporal variations of temperature at selected depths at the dam site.
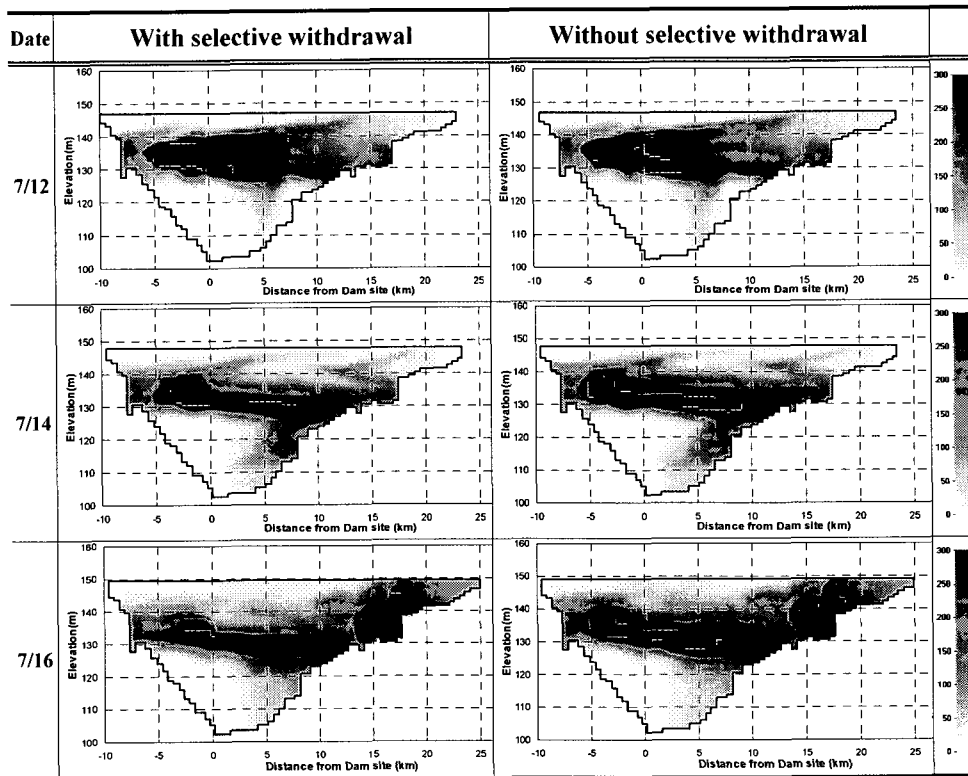
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Fig. 9. Simulation results of turbidity variation in the Imha reservoir:
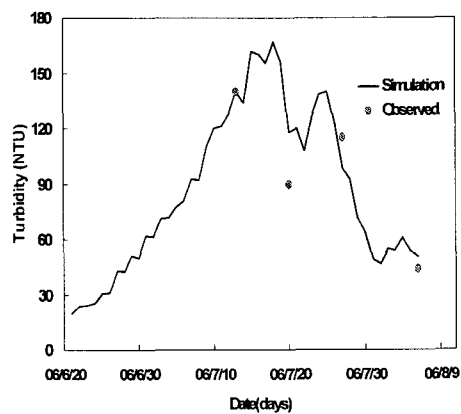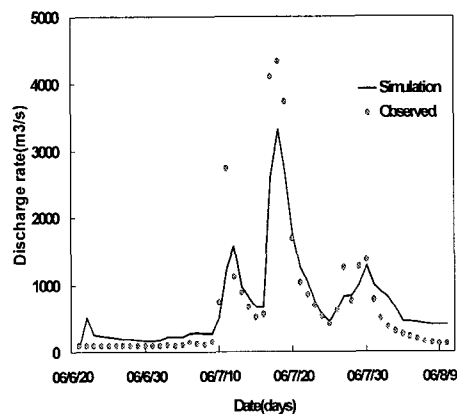(Contour line indicates turbidity exceeding 500 NTU).

Fig. 10. Discharge simulation result at Kumi. Fig. 11. Turbidity simulation result at Kumi.

4.4.   Implication through the joint operation of Imha (IMD) and Andong dam (AMD)

The Water Operation Center at K-water established an optimized operation scheme for the Imha reservoir to effectively manage high turbid water problems. According to the scheme, during flood periods (July to September) high turbid water should be discharged promptly, while during dry period (October to July) turbidity should be controlled less than 30 NTU in the downstream of IMD and AMD through joint operation of IMD and AMD.

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In case of year 2006, the turbidity of outflow has been less than 30 NTU without joint operation of IMD and AMD in the mostly period since the 25th of September, 2006 (Fig.12). High turbid water flowing in the reservoir was well removed because selective withdrawal facility was operated and outflow rate was increased in IMD which had relatively higher turbid water than AMD. Its result implicated the importance of turbidity management through removal of high turbid water in the flood period.
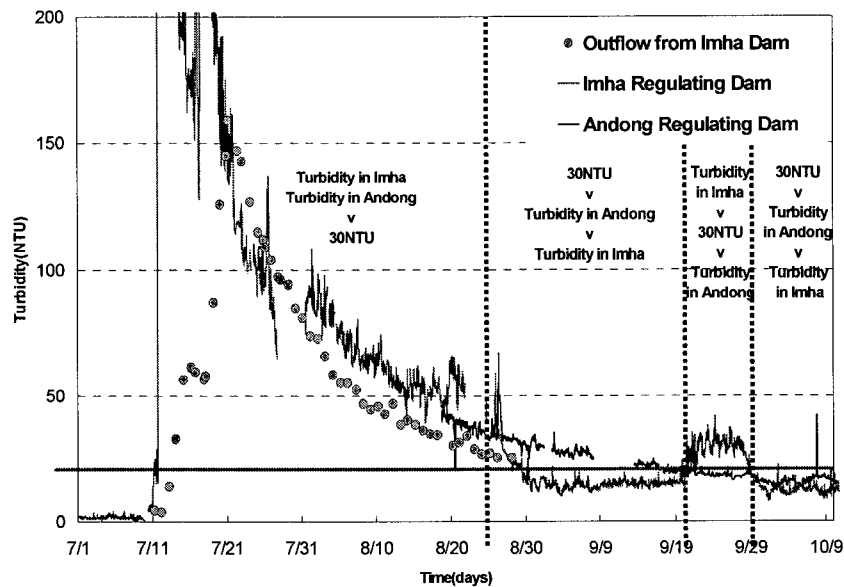

Fig.12. Turbidity discharged from regulating reservoirs from IMD and AMD

5.   Conclusion and future plan

In this research we developed a decision support system to predict turbid water inflow from the catchments of IMD and AMD, to analyze the dynamics of turbid water for selective removal of high turbid water from the reservoir, and to analyze the influence of turbid water discharge in the downstream. The system consists of SWAT and HSPF for turbid water generation, CEQUAL-W2 for turbid water dynamics in the reservoirs, Ko-Riv1-WIN for turbid water propagation in the downstream, and many real-time flow and turbidity measurement stations. It is expected that the operation with the current established system will help manage turbid water problems in the reservoirs and the downstream through timely removal of high turbid water flowing into the reservoir during heavy rainstorm considering various conditions of downstream areas.

Reference
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