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Dynamics of Turbid Water in a Korean Reservoir with Selective Withdrawal Discharges

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This study intended to understand movements of turbid water in selective withdrawal reservoirs before and after summer monsoon. Mean rainfall during November-May was low, compared to that during June-October. The reservoir water was discharged through watergates when previous rainfall and inflow exceeded 50 mm and 80 $m^3 s^{-1}$, respectively. Intake towers were generally used except for the period of the high runoff. Average turbidity in down-reservoir showed a difference of 29.9 NTU between premonsoon and postmonsoon. Diameter of particles of turbid water ranged between 0.435 and 482.9 μm. Fine particles such as clay were much denser than the larger particle. In the whole stations, clay component was relatively higher with a proportion of that in the particle distribution. Particle composition of turbid water showed that clay consisted of 94.4-98.9% and silt made of 1.1-5.6%. Analysis on turbid water movements derived from particle distribution showed a linear increase from the deep layer toward the surface layer in lower area of a reservoir. This was closely related with the hydraulic behavior of the reservoir, and heavily affected by the discharges through selective withdrawal towers and watergates. Turbid water originated from stream sediments in the middle area then resuspended in the down-reservoir causing a movement between the surface and middle layers of the reservoir. Therefore, such phenomenon needs to be understood for reservoir water quality management.

Key words : selective withdrawal, turbid water, turbidity, particle, reservoir, monsoon

INTRODUCTION

Selective withdrawal methods in reservoir are used widely in the agricultural and industrial parts (Imberger and Patterson, 1990; Kataoka *et al*., 2001). For example, warm surface water is used for irrigating peddy fields to minimize the cold damage, while cold deep water is opted as cooling water agent of various power generation equipments such as engines in power plants. In Korean inland areas, the method of selective withdrawal is utilized mostly for the former type.

Turbid water, which is also called "Heuktang-mul" (muddy-water), has emerged as an important environmental issue in the aspect of the use and management of water resources in Korea (Shin and Hwang, 2004). Turbid water occurs naturally by watershed uses or from various constructions as a result of an anthropogenic effect. The level of turbid water is higher during summer, when heavy rainfall cause more active soil erosion, than in any other seasons (Shin *et al*., 2003). Soil erosion and wash-out of the land

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surface from rainfall are considered non-point sources of turbid water. Point sources include various construction sites of land development, road and housing projects, installation mining, and stream remodeling projects; turbid water generation from point sources has been steadily increasing (Ward *et al*., 1994; Shin *et al*., 2003).

Turbid water moves down from the upstream to downstream or reservoirs. Mechanism of turbid water outflow into downstream from a reservoir is closely related to structure and type of watergate discharge, power generation discharge, and intake. Turbid water inflow from stream into reservoirs consists mostly of soil components, humic substance and dead debris (Wotton, 1994). Turbid water can bring about changes to water environment such as deterioration of water clarity and productivity, increase of allochthonous organicmatters, supply of water nutrient, and change in sediment property. Moreover changes heighten economic losses through heavier burden of water treatment cost (AWWA, 1999).

Reservoir is a standing water environment created by building a dam in a river. It is not only the fragments of the entire river but also brings about various formative, structural, and functional changes (Hannan and Young, 1974; Baxter, 1985; Thornton *et al*., 1990; Wetzel, 2001). Particle composition of water inflow into a reservoir can include biotic and abiotic factors. Introduction of abiotic factor is prevalent in times of frequent rainfalls (Wotton, 1994; Winston and Criss, 2002). During the summer monsoon inflows rapidly cause the water turbid; turbidity of water immensely heightens to add up to natural water pollution occurred every year. Taking movement and transportation caused by water flow into consideration, particles that can suspend for a long period of time lies at the center of this research (Shin *et al*., 2003).

This research aims to facilitate the reservoir water quality management effort by thorough studying the distribution of turbid water layers before and after intense monsoon season using the selective withdrawal methods commonly used in major dam reservoirs of South Korea.

MATERIALS AND METHODS

Descriptions of study sites

The research was conducted in Hoingsong Reservoir (37° 32′N, 128° 05′E) located in the upstream of the Som River, which is a tributary of the Namhan River (Fig. 1). Hoingsong Reservoir has been used for multi-purposes including hydropower generation, water supply, and impoundment for flood control since late 2000. The total watershed area is 209 km^2 and the storage area is 5.82 km^2, so the watershed-to-storage area ratio is 36 (Table 1). Average annual rainfall is 1,301 mm, and the average daily rainfall for days with precipitation is 12.2 mm. The average inflow and outflow is 6.1 m^3 s^{-1} and 6.1 m^3 s^{-1}, respectively. The storage capacities of total and active are 86.9×10^6 m^3 and 73.4×10^6 m^3, respectively (KOWACO, 2001-2003). The average water depth is 16.7 m with the maximum depth of 33.0 m; water in influent zones is mostly shallow, and it gets the deepest in near the dam. Water introduced into Hoingsong Reservoir flows into the downstream and water treatment plants through spillways, power generation discharge gates, and intake tower.

Sampling and water survey

Water turbidity and particle diameter were

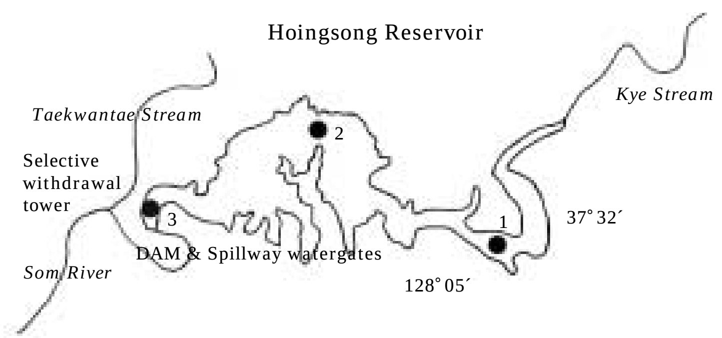

Fig. 1. Map showing sampling stations in Hoingsong Reservoir located in Kangwon Province, South Korea.

measured for different water layers in upper area (HS1) near the river, middle area (HS2), and lower area (HS3) close to the dam (Fig. 1). Daily rainfall measurements from the Weonju Meteorological Office and the daily inflow and outflow measurements from KOWACO (2001–2004) were used. Site investigation utilized a mini boat and GPS (global positioning system), and basic water quality was measured using YSI–6600 meter every 1.0 m interval from the surface layer to the deep–water layer.

Analyses of turbidity and particles

Epilimnetic, metalimnetic, and hypolimnetic waters were sampled from each station of survey for the turbidity measurement. Samples for turbidity were taken from the 0.5 m depth at each station, placed in polyethylene bottles, and measured with HACH 2100N turbidimeter after returning of the laboratory. Particle density and size in the turbid water were determined by a particle analyzer armed with Model LE400–05 sensor (AccuSizerTM 780: Particle Sizing Systems Inc., USA). Particles were measured duplicate in the range of 0.4–500.0 μm, and the average values were used for the data analysis.

RESULTS AND DISCUSSION

Rainfall and hydrological conditions

Daily rainfall varied from 0.1 to 305.0 mm during 2001–2004 and averaged 12.2 mm (Table 2). The total rainfalls varied year–to–year measured at 775.7 mm in 2001, 1,481.7 mm in 2002, 1,745.0 mm in 2003, and 1,201.3 mm in 2004, respectively, with an average of 1,300.9 mm (Table 2). Rainfall during the period between November and May fell short than that from the period between June and October showing a particularly drastic change in the transition period from summer into autumn (Fig. 2A). Rainfalls of more than 50 mm were scattered in 2001 and 2002, and they were dense in August in 2003. During the period between June and October directly and indirectly influenced by seasonal monsoon and typhoons, and frequent rainfall were the highest in mid–to–late August 2003 and mid–July 2004, when both inflows and outflows exceeded 100 $m^3 s^{-1}$. The highest daily rainfalls were observed in the period between August and

Table 1. General hydrological and limnological parameters in the Hoingsong Reservoir watershed.

Attributes	Hoingsong Reservoir
Latitude	37° 32′N
Longitude	128° 05′E
Dam elevation (m)	EL. 184.0
Project period of dam construction	January 1990 to January 2000
Impoundment of reservoir	October 2000
Functions	Multi–purpose
Trophic state	Meso–eutrophic
Average rainfall (mm day^{-1})	12.2
Average inflow ($m^3 s^{-1}$)	6.1
Average outflow ($m^3 s^{-1}$)	6.1
Watershed area (km^2)	209.0
Reservoir surface area (km^2)	5.82
Maximum depth (m)	33.0
Mean depth (m)	16.7
Reservoir storage volume ($\times 10^6 m^3$)	86.9
Active storage volume ($\times 10^6 m^3$)	73.4
Dam hight (m)	46.5
Dam length (m)	205.0

Table 2. Mean values of hydrological factors in Hoingsong Reservoir during January 2001 to August 2004. Plus–minus and parenthesis values indicate standard deviation and maximum vs. minimum, respectively.

Factors/Years	Hoingsong Reservoir				
	2001	2002	2003	2004	Total
Rainfall (mm)	8.6±13.2 (65.8/0.1)	12.5±33.2 (305.0/0.1)	13.8±21.7 (111.0/0.1)	13.1±22.51 (112.0/0.1)	2.2±24.3 (305.0/0.1)
Discharge ($m^3 s^{-1}$)					
Inflows	3.3±23.0 (421.5/0.1)	4.5±24.0 (402.5/0.1)	9.1±18.2 (151.4/0.1)	8.2±26.8 (274.6/0.1)	6.1±23.0 (421.5/0.1)
Outflows	3.7±12.6 (185.5/0.4)	3.9±12.0 (128.5/1.1)	9.4±19.5 (153.0/0.5)	8.0±26.0 (240.7/1.4)	6.1±17.7 (240.7/0.4)

September, and daily rainfalls over 100 mm were limited to 1-3 times yearly. In distribution of the annual rainfall, rainfalls within the range of 0.5 -15.8 mm (Shin *et al*., 2003), that do not greatly affect the inflow/outflow dischange in a long-term absence of previous rainfall accounted for 76.0%; 8.7% of rainfall were over 50 mm.

Seasonal fluctuations of inflows and outflows reflected the intensity and frequency of precipitation. The heaviest inflow/outflow occurred in 2001 and 2002, and it was the lowest in 2003; volume of the inflow and outflow in 2004 fitted in the middle (Fig. 2C). The range and average of inflow between 2001 and 2004 were 0.1-421.5 $m^3 s^{-1}$ and 6.1 $m^3 s^{-1}$, respectively, with the range and average of discharge during the same period amounting for 0.4-240.7 $m^3 s^{-1}$ and 6.1 $m^3 s^{-1}$, respectively (Table 2). Outflows over 100 $m^3 s^{-1}$ took place between July and September, demonstrating a heavy dependence of the water flow on the rainfall (Fig. 2C).

Outflows from the reservoir dam occur through either watergates or selective withdrawal towers. Watergate discharges were controlled when the previous rainfall and inflow exceeded 50 mm and 80 $m^3 s^{-1}$, respectively. Otherwise, intake towers were used for uncontrolled discharge into the river and the reservoir. Average discharge through watergates and surface withdrawal accounted for 38.7% and 2.9% of the total discharge, respectively. There were periodical differences to the discharge every year. Change in climate and watergate uses can have a heavy influence on occurances and movements of turbid water in reservoirs.

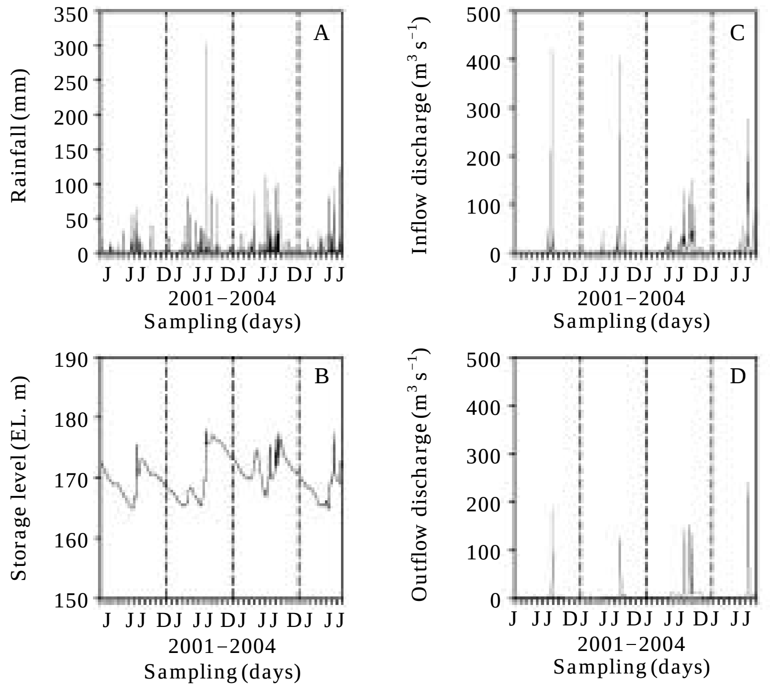

Fig. 2. Daily variations of hydrological variables in Hoingsong Reservoir Basin from January 2001 to August 2004.

Table 3. Comparison of turbidity between premonsoon and postmonsoon in major stations of Hoingsong Reservoir.

Factors \ Stations	Premonsoon			Postmonsoon								
	Lower area			Upper area			Middle area			Lower area		
	EPI	MET	HYP	EPI	MET	HYP	EPI	MET	HYP	EPI	MET	HYP
Turbidity (NTU)	3.21	1.24	3.45	43.8	-	51.5	10.2	68.6	65.3	11.5	80.0	6.3

EPI: epilimnion, MET: metalimnion and HYP: hypolimnion

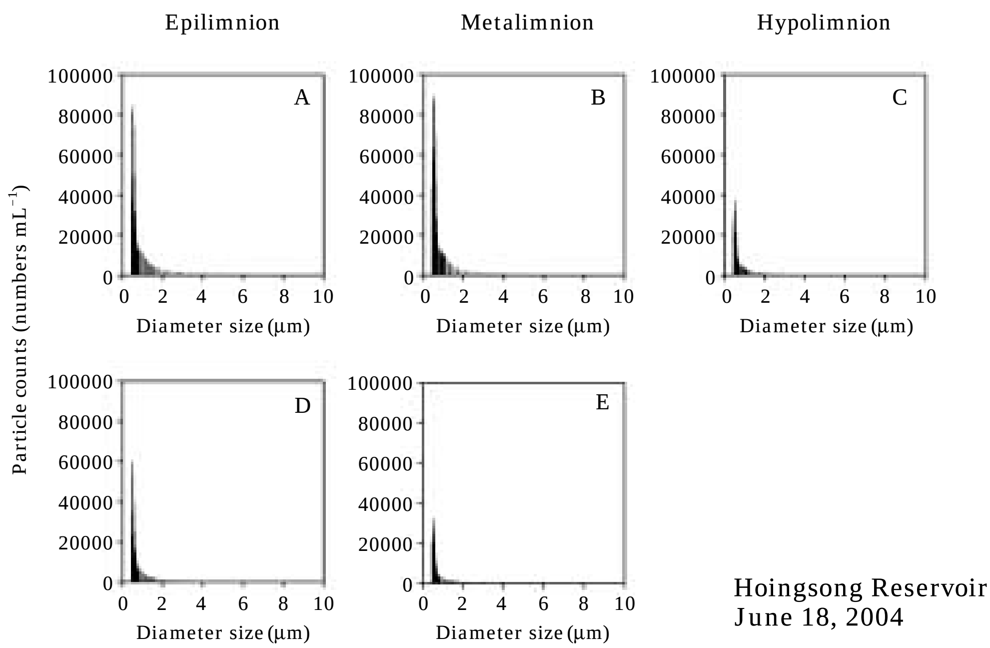

Fig. 3. Size distribution of suspended particles before summer monsoon in the down-reservoir of Hoingsong Reservoir in June 18, 2004.

Distributions of turbidity and particles

Prior to the June, turbidity in the down-reservoir was 3.21 NTU in the epilimnion, 1.24 NTU in the metalimnion, and 3.45 NTU in the hypolimnion, respectively. Measurements in the epilimnion and hypolimnion in the upper area (HS1) however showed 43.8 NTU and 51.5 NTU, respectively; epilimnion, metalimnion, and hypolimnion layers in the middle area (HS2) marked 10.2 NTU, 68.6 NTU, and 65.3 NTU and the lower area (HS3) recorded 11.5 NTU, 80.0 NTU, and 6.3 NTU, respectively. Water turbidity increased by 29.9 NTU after the intense monsoon in the lower area, and the increase was the most noticeable in the metalimnion layer (Table 3).

Particle diameters of turbid water ranged from 0.435 to 482.9 μm. Concentration of micro-particles of clay component was relatively higher with a bigger particles proportion (Fig. 4, Table 4). Total number of particles measured in a standing point of the lower area from June was 6.69×10^5, 2.67×10^5, and 2.34×10^5 numbers mL^{-1} in the epilimnion, metalimnion, and hypolimnion demonstrating a clear number drop with an increase in depth (Table 4). Measurement from the upper area in July was 7.33×10^5, −, and 6.96×10^5 numbers mL^{-1}; number from the midstream were 8.97×105, 7.86×10^5, and 8.46×10^5 numbers mL^{-1} finally, from the lower area recorded 8.64×10^5, 8.89×10^5, and 4.49×10^5 numbers mL^{-1} (Table 4). Number of particles were 4.8–26.4% bigger in epilimnion water than in metalimnion and hypolimnion water. Particle composition of turbid water was consisted of 94.4–98.9% of clay and 1.1–5.6% of silt; sand only made up for 0.003% of the total (Table 4).

Turbid water dynamics in a selective withdrawal reservoir

Particle density was higher in epilimnetic and metalimnetic waters than that in the hypolimnetic water in the down-reservoir before the intense monsoon (Fig. 3). Abundance of phytoplankton in the epilimnion layer and zooplankton in the metalimnion layer contributed to the biotic composition in water during this period. Nevertheless, it was noted that the content of mineral particles from soil considerably increased in reservoir water after the intense monsoon. There was more difference in turbidity and particle numbers for different water layers in lower area than in upper area of reservoir. Same measurements were taken from all water layers in the upper area (Figs. 4A–B). In the middle area, particle density was significantly higher in the epilimnion and hypolimnion than in the metalimnion, reflecting the high content of large particles in the process of sedimentation and small particles with a smaller propensity to do so (Figs. 4C-E). In the lower area, particle distribution showed a different pattern from the upper and middle area; particle density marked a linear increase moving from the hypolimnion layer to the epilimnion layer (Fig. 4F-H). This result is closely related to the hydraulic environment of the reservoir while reflecting the effect from discharge through selective withdrawal towers and watergates directly and indirectly.

Turbid water movement, based on particle distribution, is summarized in the Fig. 5. Turbid water from the river submerged in the middle area to resuspend in the lower area. Turbid density current, which is often observed in a large reservoir with metalimnion/hypolimnion water discharge system and a large water depth, did not occur. Most turbid water passed through the epilimnion and metalimnion of the reservoir. Further studies need to be done for turbidity dynamics and particle movements in relation to the hydrology in the reservoir.

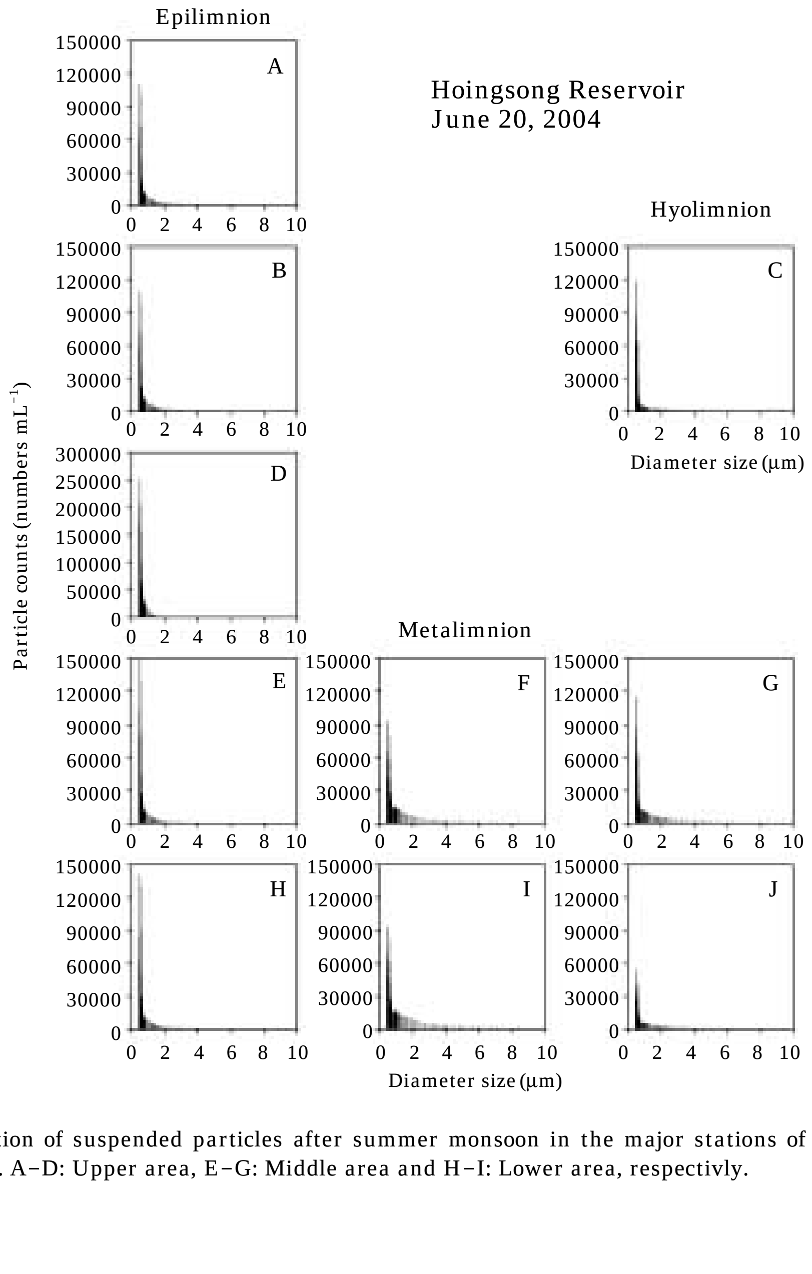

Fig. 4. Size distribution of suspended particles after summer monsoon in the major stations of Hoingsong Reservoir in July 20, 2004. A-D: Upper area, E-G: Middle area and H-I: Lower area, respectivly.

Table 4. Composition of density of suspended particles in high turbid water of Hoingsong Reservoir Basin in 2004. Parentheses indicate percentage among total particles. (Unit: numbers ml^{-1}). EPI: epilimnion, MET: metalimnion and HYP: hypolimnion, respectivly.

Factors \ Stations	Premonsoon			Postmonsoon								
	Lower area			Upper area			Middle area			Lower area		
	EPI	MET	HYP	EPI	MET	HYP	EPI	MET	HYP	EPI	MET	HYP
CLA*	658,695 (98.4)	263,884 (98.7)	226,638 (96.9)	715,927 (97.6)	–	666,252 (95.7)	887,187 (98.9)	749,572 (95.3)	799,642 (94.5)	848,355 (98.1)	839,456 (94.4)	428,142 (95.3)
SIL	10,699 (1.6)	3,351 (1.3)	7,355 (3.1)	17,479 (2.4)	–	29,612 (4.3)	9,765 (1.1)	36,962 (4.7)	46,267 (5.5)	16,234 (1.9)	49,611 (5.6)	20,969 (4.7)
VFS	ND	ND	7.6 (3.2×10^{-3})	2.6 (4.0×10^{-3})	–	16.7 (2.4×10^{-3})	ND	21.7 (2.8×10^{-3})	21.8 (2.6×10^{-3})	17.2 (2.0×10^{-3})	22.3 (2.5×10^{-3})	1.6 (0.3×10^{-3})
FIS	ND	ND	ND	ND	–	ND	ND	ND	ND	3.4 (0.4×10^{-3})	3.2	ND
MES	ND	ND	ND	ND	–	ND	ND	ND	8.1 (0.4×10^{-3})	3.4 (2.5×10^{-3})	22.3	ND
COS	ND	ND	ND	ND	–	ND	ND	ND	ND	ND	ND	ND

* CLA : Clay (<3.9 μm), SIL: Silt (3.9–62.5 μm), VFS: Very fine sand (62.5–125.0 μm), FIS: Fine sand (125.0–250 μm), MES: Medium sand (250.0–500 μm), COS: Coarse sand (500–1,000 μm)

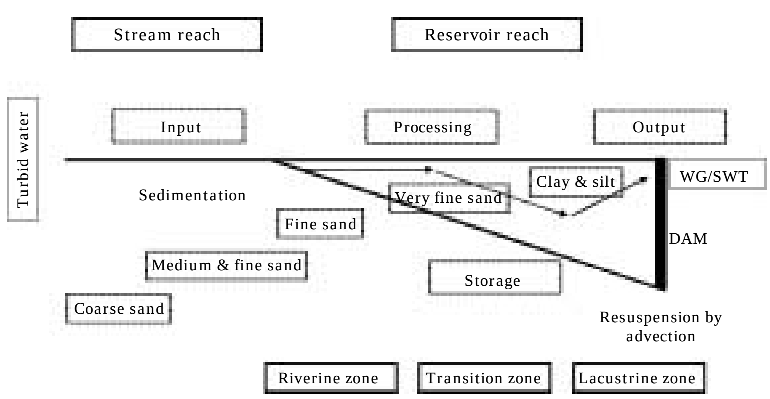

Fig. 5. Dynamics of turbid water after the monsoon rainfall in Hoingsong Reservoir applicable selective withdrawal discharge. WG: watergates, SWT: selective withdrawal tower.

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< 국문적요 >

선택 취수하는 저수지에서 탁수의 동태

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본 연구는 선택 취수하는 저수지에서 장마 전후에 탁수의 거동을 파악하고자 하였다. 강수량은 11월-5월에 적었고, 6월-10월에 풍부하여 대비가 되었다. 수문에 의한 방류는 선행 강수량과 유입량이 각각 50 mm, 80 $m^3 s^{-1}$ 이상일 때 조작되었고, 그 외 기간은 대부분 취수탑을 통해 배출되었다. 하류부를 중심으로 비교할 때, 장마 전후 수중 탁도 차이는 평균값이 29.9 NTU로서 장마 후에 크게 증가하였다. 탁수에 포함된 입자 크기의 범위는 0.435-482.9 μm이었고, 전 정점에서 clay성분의 미세립자로 갈수록 크기 분포가 더욱 조밀하였을 뿐만 아니라 상대적으로 차지하는 비율도 높았다. 탁수의 입자 분포에서 clay는 94.4-98.9%, silt는 1.1-5.6% 범위로서 총 입자수의 대부분을 차지하였다. 입자 분포에 의한 탁수의 흐름을 분석한 결과, 저수지의 하류부에서 총입자수는 저층에서 표층으로 갈수록 선형적인 증가가 뚜렷하였다. 이것은 저수지의 수리학적 환경과 밀접한 관련성이 있었고, 선택취수탑과 수문을 통한 방류에 의한 영향이 큰 것으로 추정되었다. 하천으로부터 유입된 탁수는 중류부에서 침강되다가 하류부에서 재부유하는 현상이 발생함으로서 표층-중층을 통한 탁수 이동이 현저하였다. 따라서, 향후 저수지 수질관리 측면에서 이에 대한 육수학적 영향을 규명할 필요성을 제시하고자 한다.