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Review

Effects of Turbid Water on Fish Ecology in Streams and Dam Reservoirs

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Turbid water or suspended sediment is associated with negative effects on aquatic organisms; fish, aquatic invertebrate, and periphyton. Effects of turbid water on fish differ depending on their developmental stage and a level of turbidity. Low turbid water may cause feeding and predation rates, reaction distance, and avoidance in fish, and it could make fish to die under high turbidity and long period. Therefore, it is very important to find out how turbid water or suspended sediment can affect fish in domestic watersheds. The objectives of this study were 1) to introduce international case studies and their standards to deal with suspended sediment, 2) to determine acute toxicity in 4 major freshwater fishes, and 3) to determine in relation to adverse effect of macroinvertebrates and fish. Impacts of turbid water on fish can be categorized into direct and indirect effects, and some factors such as duration and frequency of exposure, toxicity, temperature, life stage of fish, size of particle, time of occurrence, availability of and access to refugia, etc, play important role to decide magnitude of effect. A review of turbidity standard in USA, Canada, and Europe indicated that each standard varied with natural condition, and Alaska allowed liberal increase of turbidity over natural conditions in streams. Even though acute toxicity with four different species did not show any fatal effect, it should be considered to conduct a chronic test (long-term) for more detailed assessment. Compared to the control, dominance index of macroinvertebrates was greater in the turbid site, whereas biotic index, species diversity index, species richness index, and ecological score were smaller in the turbid site. According to histopathological analysis with gills of macroinvertebrate and fishes, morphological and physiological modification of gills due to suspended sediments can cause disturbance of respiration, excretion and secretion. In conclusion, in order to maintain good and healthy aquatic ecosystem, it is the best to minimize or prevent impact by occurrence of turbid water in stream and reservoir. We must make every effort to maintain and manage healthy aquatic ecosystem with additional investigation using various assessment tools and periodic biomonitoring of fish.

Key words : turbid water, suspended sediment, fish, environmental impact assessment, biomonitoring

INTRODUCTION

Not only natural disasters such as flood, typhoon, and snow-melt but also human activities including logging, grazing, agriculture, mining, road building, urbanization, and commercial construction have often played in an important role creating suspended sediment in streams, rivers, and reservoirs (Lloyd *et al.*, 1987; Newcombe and

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MacDonald, 1991; Henley *et al.*, 2000; Bash *et al.*, 2001). Brown (1972) indicated that 12,400, 8,900, 4,600, and 89 ton mi^{-2} yr^{-1} of sediment loading into stream were estimated in four logged watersheds in Oregon, USA after load construction. According to Judy *et al.* (1984), there are 46% of all streams and rivers in the U.S estimated to occur excessive sedimentation.

The suspended sediments depending on particle size have different settling time. Colloidal suspensions, which its particle size ranges between 10^{-9} and 10^{-7} m, are especially suspended in waterbody for a long period of time so that it results in formation of turbid water as the waterbody appears to be muddy. This phenomenon is not only bad for aesthetics but also management of water resources due to requirement of additional treatment for cohesion with alum and gypsum (Boyd and Tucker, 1998). Several investigations estimated that damage cost from soil erosion in and off-stream ranged from 2.1 to 10.0 billion yr^{-1} based on recreation, water storage, navigation, commercial fishing, and property damage without cost of biological impacts (Clark, 1985; Pimentel *et al.*, 1995).

Turbid water or suspended sediment is associated with negative effects on organisms in aquatic ecosystem as well as water quality in water resources (Cairns, 1990; Richter *et al.*, 1997; Henley *et al.*, 2000). Sedimentation and turbidity firstly affect light penetration so that it causes reduction of periphyton and phytoplankton biomass (Kirk, 1985; Steinman and McIntire, 1990; Newcombe and MacDonald, 1991; Ryan, 1991; Hoetzel and Croome, 1994). Thereafter, negative bottom-up effects occur in benthic invertebrates and zooplankton, and further fishes with reduced food availability (Rosenberg and Snow, 1977; Rosenberg and Wiens, 1978; McCabe and O'Brian, 1983; Wagener and LaPerriere, 1985). In addition, excessive suspended sediment can clog gills in filter-feeding invertebrates and fish so that it causes reduced feeding and respiratory efficiency (Herbert and Merkens, 1961; Noggle, 1978; Alabster and Lloyd, 1982; Newcomb and Flagg, 1983). Therefore, an increase in turbidity can be one of significant factors causing negative effects in each trophic level of aquatic ecosystem (Gammon, 1970; Berkman and Rabeni, 1987; Fairchild *et al.*, 1987).

Among the aquatic organisms, fish, which are final consumer in the aquatic ecosystem and belong to vertebrate as human, is the largest organism representing a condition of the aquatic environment. Therefore, it is very important to study survival and protection of fish for management of water resources. Many researches (Noggle, 1978; Reed *et al.*, 1983; Sigler *et al.*, 1984; Lloyd, 1987; Reid, 1998; Bash *et al.*, 2001) on this purpose have been continuously progressed, and Newcombe and MacDonald (1991) grouped the effects of turbid water or suspended sediment on fish into three categories (lethal, sublethal, and behavioral), and subsequently ranked effects on fish and aquatic life into 14 levels based on severity of effect.

The purposes of this review were to introduce international case studies and their standards to deal with suspended sediment, and to determine that direct and indirect effects on macroinvertebrate and fish due to turbid water caused by intensive rainfall and repair works in streams and reservoirs were confirmed using various techniques of impact assessment. This review can provide an understanding of relationship between turbid water and aquatic organisms, and further can recognize the necessity of integrated management of water resources in order to protect healthy aquatic ecosystem as well as water quality.

MATERIALS AND METHODS

Imha Reservoir is located in Andong City, Gyeongbuk Province on the Banbyeon Stream. Imha Reservoir was impounded by the completion of Imha Multipurpose Dam in 1992 to form an approximately 1,367.6 km^2 watershed area and 595 million tons of storage capacity (KOWACO, 1994; Yi *et al.*, 2008). It plays in important role as not only water support for agriculture, industry, living and drinking but also flood control (80 million tons) and hydropower production (96.7 GWh $year^{-1}$).

After Imha reservoir was impounded, there has been an issue continuously on turbid water, and it became a serious problem especially due to the typhoons 'Rusa' in 2002 and 'Maemi' in 2003. Suspended sediments originated from soil erosion have been stayed for a long time in the reservoir resulting in additional treatment with alum for water resources, and further there have been negative effects in aquatic ecosystem such as habitat destruction, food web disturbance when the turbid water was discharged to downstream of dam reservoir. Therefore, Imha Reservoir has provided not only positive factors as water control and utilization but also negative factors as additional management, disturbance of aquatic ecosystem and scenic beauty.

A content of the review was divided into several chapters. In the first chapter, I introduced international case studies due to absence of domestic investigation on a biological impact assessment by turbid water or suspended sediment. With review of these researches, I also confirmed the turbidity standards, which have been applied for protection of fish and wildlife habitats, in developed countries such as America, Canada, and Europe.

In the second chapter, 96-hr acute toxicity test was performed with four freshwater fishes in order to determine whether there was a direct effect by high turbidity to the species of fish; pale chub (*Zacco platypus*), common carp (*Cyprinus carpio*), muddy loach (*Misgurnus anguillicaudatus*), and Japanese medaka (*Oryzias latipes*). In order to reconstruct the phenomenon of turbid water in Imha Reservoir, top soil from the area (Imdong, Imdong-myeon, Andong City) inducing turbid water and discharge water from Imha Dam were collected in October 2004 and brought to the laboratory in Korea Institute of Toxicology. Five different concentrations of turbidity were prepared with grinding, sieving, and mixing of soil and discharge water;

Nominal turbidity: Discharge water, 15.6 (0.08 g), 62.5 (0.31 g), 250 (1.25 g), 1,000 (5 g) NTU
Numbers in parentheses indicates weight of used soil per 1 liter of discharge water

Seven fish of each species were separately exposed to 5 combinations of turbidity without replication. Test conditions during the 96-hr acute toxicity were maintained in accordance with requirement for the standard procedure (OECD, 1998; USEPA, 2002; Yeom *et al.*, 2005) as follows;

Water temperature: 23.7 ~ 24.4°C, Dissolved oxygen: 8.0 ~ 8.3 mg L^{-1}, pH: 8.02 ~ 8.27
Photoperiod: 16 : 8 hr light and dark

In the third, distribution, appearance rate, community analysis (Margalef, 1958; McNaughton, 1967; Pielou, 1969), and biological assessment of macroinvertebrates, which play important role on food sources of fish, was compared between control and turbid sites with investigation (September 2004) of macroinvertebrates after discharge of turbid water from Imha Dam;

Control : Site 1 - Mukgye Bridge, Gilan-myeon Mukgye-ri, Andong City
Site 2 - Sindeok Bridge, Imha-myeon Sindeok-ri, Andong City
Turbid : Site 1 - Bulgeoli, Imha-myeon Imha-ri, Andong City
Site 2 - Seoneodae, Songcheon-dong, Andong City

At that time, mean turbidity in control and turbid sites are 0.5 and 66.3 NTU, respectively. In addition, histopathological study on gills of macroinvertebrates and fish was examined to confirm the negative effect of suspended sediment.

RESULTS AND DISCUSSION

1. Investigation of international case studies

1) Literature review

Effects of suspended sediments or turbid water have been found on nearly every trophic level in aquatic ecosystem (Reed *et al.*, 1983). Impacts of turbid water on fish can be categorized into direct and indirect effects. Direct effects include stress responses, increased ventilation rates, gill damage and suffocation, and death. With few exceptions, fish show little direct damage except at very high levels of suspended solids. Indirect effects on fish behavior occur at considerably lower levels. These effects include reduced reactive distance to prey, decreased feeding rates, disruption of spawning migration, reduced activity, and disruption of social hierarchies. More general effects include reduced fish populations and reduced fishing success and effort.

Newcombe and MacDonald (1991) grouped effects of sediment on salmonids into three categories; lethal, sublethal, and behavioral, and Bash *et al.* (2001) summarized in three sections as the following (Table 1). In addition, they indicated the following factors affecting the effects of sediment on salmonids; duration and frequency of

Table 1. Effects of turbidity on salmonids (as cited by Bash *et al.*, 2001).

Physiological	Behavioral	Habitat
Gill trauma	Avoidance	Damage to redds
Osmoregulation	Territoriality	Effect on hyporheic upwelling
Blood chemistry	Foraging and predation	Reduction in BI habitat
Reproduction and growth	Homing and migration	Reduction in spawning habitat

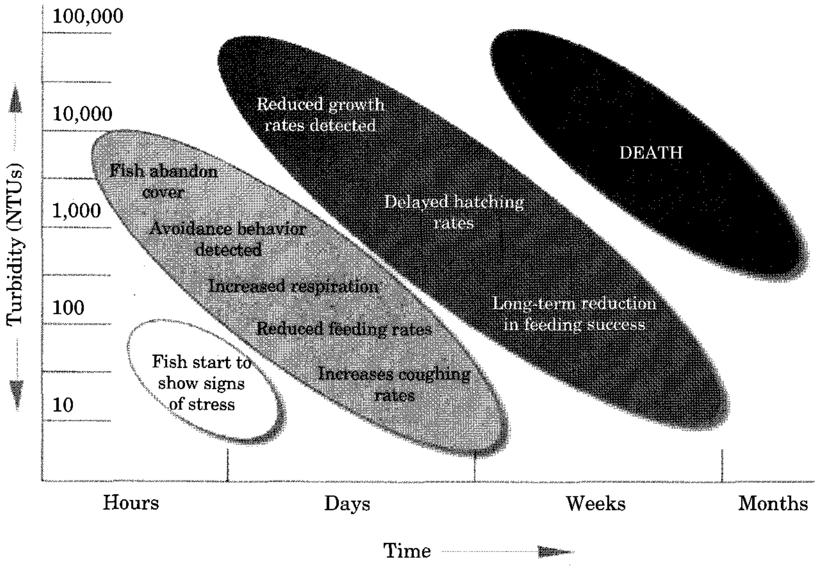

Fig. 1. Levels of negative effects in fish with combination of turbidity and time (as cited by Newcombe and Jensen, 1996).

exposure, toxicity, temperature, life stage of fish, size of particle, time of occurrence, availability of and access to refugia, etc.

Newcombe and Jensen (1996) mentioned that very high levels of turbidity for a short period of time may not be significant and may even be less of a problem than a lower level that persists longer. The Fig. 1 below shows how aquatic organisms are generally affected.

2) Current turbidity requirement for protection of fish and wildlife habitats

Turbidity standards used in Alaska and other states in USA is shown in Table 2, and turbidity standards in British Columbia, Canada were classified in accordance with purpose of use as Table 3. European Inland Fisheries Advisory Committe (1965) presented five pathways that fine sediments may harm freshwater fishes as follows;

① By acting directly on the fish swimming in water in which solids are suspended, and either killing them or reducing their growth rate, affecting their resistance to disease

② Preventing the successful development of fish eggs and larvae

③ By modifying natural movements and migrations of fish

④ By reducing the abundance of food available to the fish

⑤ By affecting the efficiency of methods of catching fish

Protective levels established based on EIFAC study was also recommended as Table 4.

Table 2. Numerical turbidity standards for protection of fish and wildlife aquatic habitats in Alaska and other states, USA (as cited by Lloyd, 1987).

State	Turbidity (NTU or JTU)[a]
Alaska	25 units above natural in streams, 5 units above natural lakes
California	20% above natural, not to exceed 10 units above natural
Idaho	5 units above natural
Minnesota	10 units
Montana	10 units (5 above natural)[b]
Oregon	10% above natural
Vermont	10 units (cold water)
Washington	25 unit above natural (5 and 10 above natural)[c]
Wyoming	10 units above natural

[a] Nephelometric (NTU) and Jackson (JTU) turbidity units are roughly equivalent (USEPA 1983).

[b] Montana places the more stringent limit on waters containing salmonid fishes.

[c] API (1980) reports different values in Washington for "excellent" and "good" classes of water.

2. Acute toxicity test on turbid water with freshwater fishes

Four representative species of freshwater fish were selected and tested to determine whether there was a direct effect (acute toxicity) by high turbidity to the species of fish; pale chub (*Zacco*

Table 3. Turbidity standards in British Columbia, Canada (Bash *et al.*, 2000).

Water use	Maximum induced turbidity-NTU or % of background	Maximum induced suspended sediments-mg L^{-1} or % of background	Streambed substrate composition
Drinking water raw untreated	1 NTU when background ≤5	No guideline	No guideline
Drinking water raw treated	5 NTU when background ≤50	No guideline	No guideline
Recreation and Aesthetics	Maximum 50 NTU, secchi disc visible at 1.2 m	No guideline	No guideline
Aquatic Life -fresh- -marine- -estuarine-	8 NTU in 24 hours when background ≤8, Mean of 2 NTU in 30 days when background ≤8	25 mg L^{-1} in 24 hours when background ≤25, Mean of 5 mg L^{-1} in 30 days when background ≤25	Fines not to exceed - 10% as ≤2 mm - 19% as ≤3 mm - 25% as ≤6.35 mm at salmonid spawning sites
Aquatic Life -fresh- -marine- -estuarine	8 NTU when 8≤ background≤80, 10% when background ≥80	25 mg L^{-1} when 25 ≤ background ≤250, 10% when background ≥250	Geometric mean diameter ≥12 mm, Fredle number ≥5 mm
Terrestrial life -wildlife- -livestock water- Irrigation Industrial	10 NTU when background ≤50, 20% when background ≥50	20 mg L^{-1} when background ≤ 100, 20% when background ≥100	No guideline

Table 4. Protective level based on EIFAC study (Bash *et al.*, 2000).

Level of protection	Maximum concentration of suspended solids
High	25 mg L^{-1}
Moderate	80 mg L^{-1}
Low	400 mg L^{-1}
Very Low	over 400 mg L^{-1}

platypus), common carp (*Cyprinus carpio*), muddy loach (*Misgurnus anguillicaudatus*), and Japanese medaka (*Oryzias latipes*). Their characteristics and size were summarized in Table 5.

During the test period, turbidities were gradually declined in chambers of pale chub and Japanese medaka due to low aeration. However, there was no death and any abnormal symptom in all test chambers. Even though Lloyd (1987) indicated fatal (96-hr LC_{50}) turbidity for salmon about 500 NTU or 1,200 mg L^{-1}, four representative species of Korean freshwater fish did not show any fatal effect. However, it would be harmful or critical for fish, especially juveniles when high turbidity in natural environment keeps continued. Therefore, it should be considered to conduct a chronic test (long-term) for more detailed assessment.

3. Effects on macroinvertebrates and fish

1) Investigation of macroinvertebrates

In order to examine distribution, appearance rate, community analysis, and biological assessment of macroinvertebrates, which play important role on food sources of fish between control and turbid sites, a field investigation was performed in September 2004. Sampling sites were located in Gilan Stream and Banbyeon Stream. Two control sites were located in Gilan Stream, which was upstream of the point Imha Dam discharge flows to, and other two of turbid sites were located in Banbyeon Stream.

The total number of macroinvertebrates caught from two control sites was 903 individuals representing 4 phyla, 5 classes, 8 orders, 17 families, and 33 species, whereas only 142 individuals (2 phyla, 3 classess, 8 orders, 13 families, and 20 species) was found in two turbid sites (Table 6). Numbers of species and individuals in the controls were 1.65 and 6.36 times greater than those of turbid water sites.

According to community analyses by sampling

Table 5. Characteristics and size of four test species.

Test species	Characteristics	Total length (mm)	Total weight (g)
Pale chub (*Zacco platypus*)	Tolerant, Most common	91±6	5.3±1.3
Common carp (*Cyprinus carpio*)	Tolerant, Economic	43±2	0.9±0.1
Muddy loach (*Misgurnus anguillicaudatus*)	Bottom dwelling, Economic	54±2	0.9±0.1
Japanese medaka (*Oryzias latipes*)	International test species	25±2	0.12±0.03

Table 6. Taxonomic composition of macroinvertebrates in control and turbid sites.

Phylum	Class	Order	Family		Species		Individuals	
			Cont.	Turb.	Cont.	Turb.	Cont.	Turb.
Platyhelminathes	Turbellaria	Tricladida	1	0	1	0	1	0
Mollusca	Gastropoda	Mesogastropoda	1	0	1	0	5	0
Annelida	Hirudinea	Arhynchobdellidae	1	1	1	1	1	1
Arthropoda	Crustacea	Amphipoda	1	0	1	0	3	0
		Decapoda	0	1	0	1	0	1
	Insecta	Ephemeroptera	6	4	14	6	467	13
		Hemiptera	0	1	0	1	0	1
		Megaloptera	0	1	0	1	0	1
		Coleoptera	3	3	4	3	9	5
		Diptera	2	1	2	1	154	30
		Trichoptera	2	1	9	6	263	90
Total 4 (2)	5 (3)	8 (8)	17	13	33	20	903	142

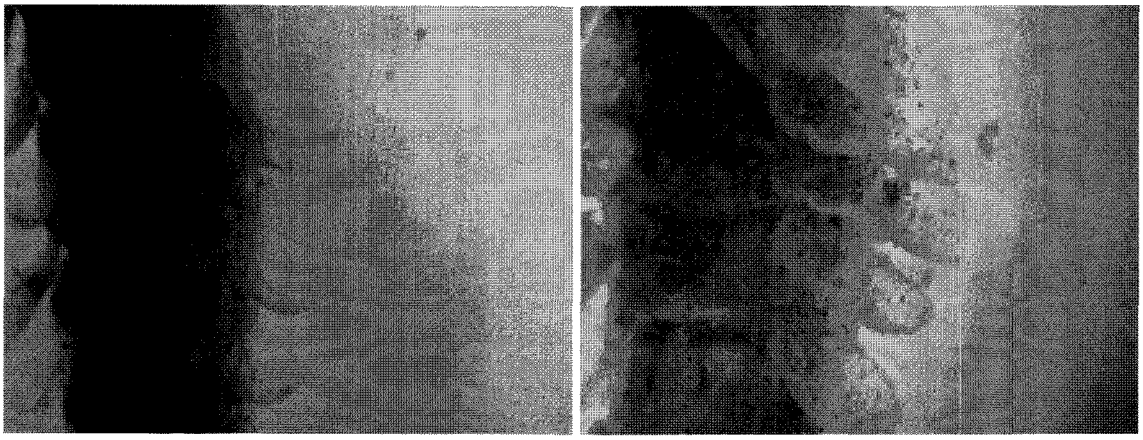

Fig. 2. Tracheal gills of *Siphlonurus chankae* in control (left) and turbid (right) sites.

site, mean of dominance index (DI) was greater in the turbid site (0.627) than the control (0.308). On the other hand, means of biotic index (BI), species diversity index (H′), species richness index (RI), and ecological score of benthic macroinvertebrate community (ESB) were smaller in the turbid site (27, 2.814, 3.834, 57) than the control (51, 3.893, 4.702, 110). The results indicated that there was decline of species diversity and change of species composition due to destruction of microhabitats by sedimentation of suspended sediment particles.

2) Histopathological analysis with gills of macroinvertebrate and fish

Most nymph or larval stages of aquatic insects have tracheal gills for obtaining oxygen. These gills are mainly located on abdomen. When sus-

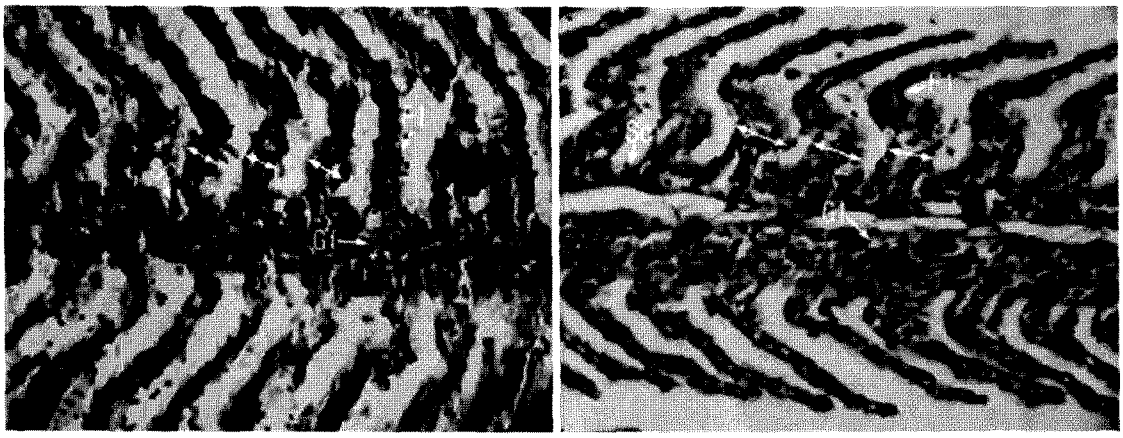

Fig. 3. 2^{nd} gill lamella of *Culter brevicauda* in control (left) and turbid (right) sites (× 400).

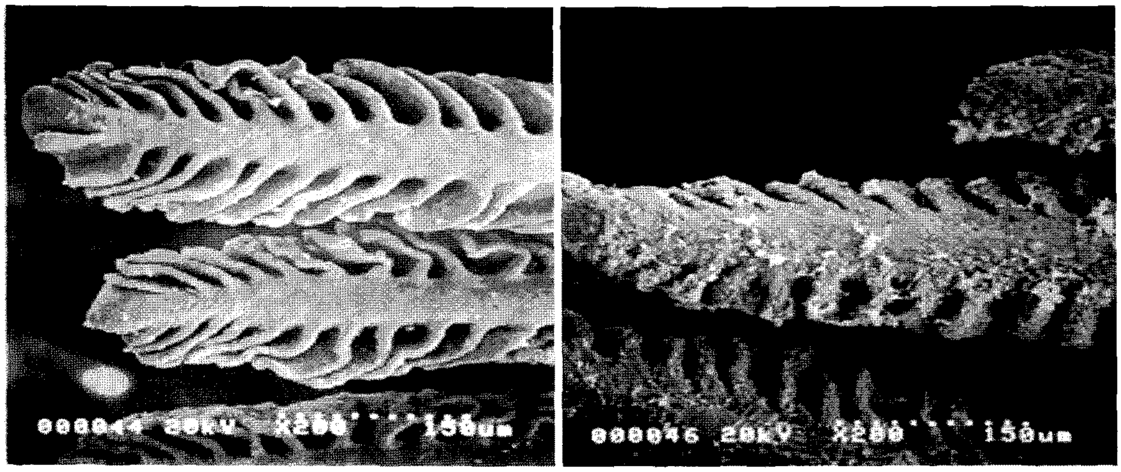

Fig. 4. Gill of *Carassius auratus* in control (left) and turbid (right) sites (× 200, SEM).

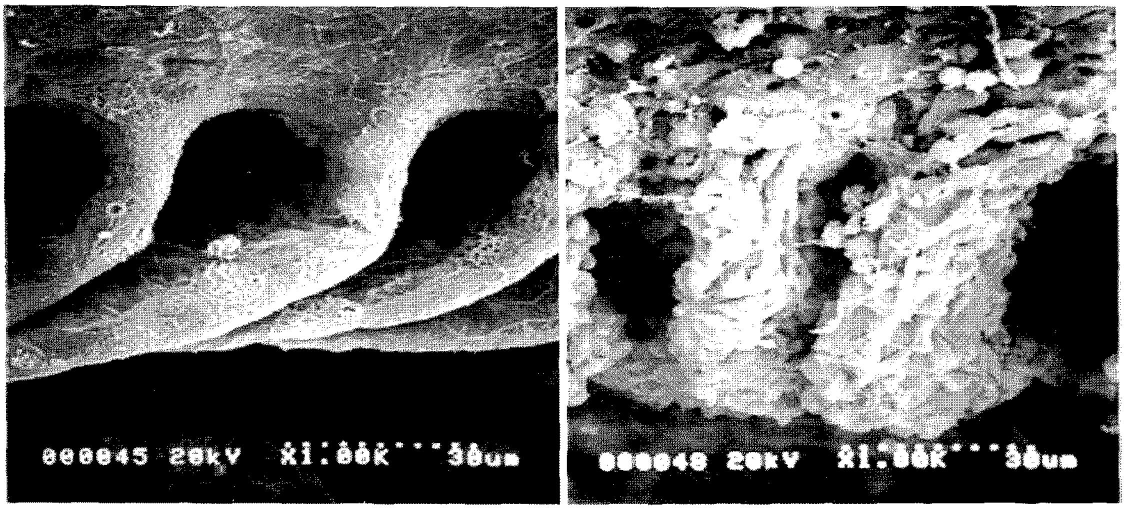

Fig. 5. 2^{nd} gill lamella of *Carassius auratus* in control (left) and turbid (right) sites (× 1,000, SEM).

pended sediments in aquatic environment are high, gills of macroinvertebrates are covered by them, and thereafter efficiency of gas exchange in gills declines gradually. It eventually results in serious impact on their survival. Therefore, it is very important to make gills clean to not only enhance oxygen absorption but also have healthy condition.

When the tracheal gills of *Siphlonurus chankae* (Ephemeroptera) in control and turbid sites were observed, body including gills was fully covered by much fine sediment particles in turbid site (Fig. 2). It was considered that the *Siphlonurus chankae* might have difficulty on gas exchange and could have functional problem.

Fish also have gills for not only respiratory function but also osmoregulation and excretion of waste matters. Therefore, morphological and physiological modification of gills due to suspended sediments can cause disturbance of respiration, excretion and secretion.

The species of *Culter brevicauda* and *Carassius auratus* were examined in order to distinguish any difference of histological structure on their gills in the control and the turbid sites. The secondary gill lamellae in *Culter brevicauda* gill from the turbid sites were formed as thicker layers compared to those in the control sites, and there were many salt cells on their surface (Fig. 3). When the secondary gill lamellae tend to be thicker, spaces between them get shrunk so that it makes gills difficult on CO_2 exchange followed by decline of respiration rate. In addition, gills of *Carassius auratus* were examined with a scanning electron microscope (SEM), and the secondary gill lamellae were fully covered by much fine sediment particles (Figs. 4 and 5). It might result in respiratory acidosis due to decline of CO_2 exchange, and it would affect fish's life.

In conclusion, in order to maintain good and healthy aquatic ecosystem, it is the best to minimize or prevent impact by occurrence of turbid water in stream and reservoir. There are many ways to prevent factors causing turbid water; self-control of unnecessary stream rehabilitation works, reduction of exposed land without vegetation or forestation, and construction of debris barriers in regular flooded streams, and so on. Currently, Korea Water Resources Corporation (K water) built a selective withdrawal facility in Imha Multipurpose Dam in 2006 to withdraw turbid water immediately when intensive rain brings about suspended sediment loading from watershed (Lee *et al.*, 2007). In addition, the K water installed floating islands, which provides artificial spawning habitat, in Imha Reservoir to enhance fishery. Therefore, it is very important to understand whether aquatic ecosystem is affected by turbid water, and must perform periodic and systematic investigation using various assessment tools in order to make every effort to maintain and manage healthy aquatic ecosystem.

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