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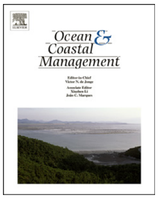

Environmental and ecological effects of Lake Shihwa reclamation project in South Korea: A review

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ABSTRACT

The Shihwa Coastal Reservoir (SCR) was created to supply agricultural water during the construction of dikes for land reclamation, with this project representing a striking example of policy failure regarding tidal flat reclamation in Korea. After the completion of dike construction in 1994, the water quality inside the SCR drastically deteriorated. As a result, in 1996, the sluice gates were opened to dilute water pollution levels through the physical mixing of seawater from outside and freshwater from inside. Over the last 20 years, the Korean government has invested more than US $ 1.5 billion to recover SCR water quality by improving public sewage treatment systems, which is 2.7 times the cost of the original dike construction. Yet, within the reservoir, water quality has minimally improved, sediment pollution continues to be detected, and anoxic layers have been observed, due to stratification in summer. Severe sedimentary pollution caused by heavy metals and trace organic pollutants originating from the upstream regions of the watershed was evident during the SCR project; however, pollution levels appeared to decrease after seawater circulation. In parallel, the pelagic and benthic communities have also been affected by the deterioration of multiple water and sediment quality indices. While the recent construction of the tidal power plant has significantly increased the volume of seawater circulation, it has not been enough to improve the water quality of the upstream region of the SCR, where the water remains polluted. The SCR project presents a clear example that how incorrect policy leads to the mishandling of both coastal ecosystems and substantial governmental budgets.

1. Introduction

Land reclamation is a process of coastal development that involves the construction of a dike across the tidal flat coastal zone to create new land surfaces for multiple uses, and results in the formation of a seawater zone to freshwater reservoir that is used as a water supply (Fig. 1a). The terrestrial national territory of South Korea is about 99,720 km^2, of which 66% is covered in forests; consequently, the percentage of available land for human use is relatively low. To resolve this land shortage, the government actively promoted a policy to increase the extent of agricultural, industrial, and urban land through the large-scale reclamation of tidal flats along the southwest coasts of the Korean peninsula over the last 40 years (Kim, 2010; Koh, 2001). For example, from the late 1960s to 2010, a total of 1,959 dikes were constructed, with the resultant reclaimed lands collectively representing about 1,900 km^2 in 1,612 districts (KRCC, 2010).

The Shihwa Coastal Reservoir (SCR) is a clear example of policy failure in terms of land reclamation, which illustrated the vicious

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Abbreviation: APs, alkylphenols; BOD, biological oxygen demand; Chl-a, chlorophyll-a; COD, chemical oxygen demand; DO, dissolved oxygen; EIA, Environmental Impact Assessment; EMMP, Environmental Management Master Plan; HRWMA, Han River Watershed Management Agency; KORDI, Korea Ocean Research & Development Institute; KIOST, Korea Institute of Ocean Science & Technology; KWRC, Korea Water Resource Corporation; MLTM, Ministry of Land, Transportation and Maritime Affairs; MOE, Ministry of Environment; MOMAF, Ministry of Maritime Affairs and Fishery; MOLT, Ministry of Land and Transport; NPs, nonylphenols; PBDEs, polybrominated diphenyl ethers; PCBs, polychlorinated biphenyls; PAHs, polycyclic aromatic hydrocarbons; PFCs, perfluorinated chemicals; SCMA, Special Coastal Management Area; SCR, Shihwa Coastal Reservoir; SDC, Sustainable Development Committee; STP, Sewage Treatment Plants; TMDL, total maximum daily load; TP, total phosphorous; TPLMS, Total Pollution Load Management System; TPP, tidal power plant; US EPA, U.S. Environmental Protection Agency; WMC, Watershed Management Committee; WQ, water quality.

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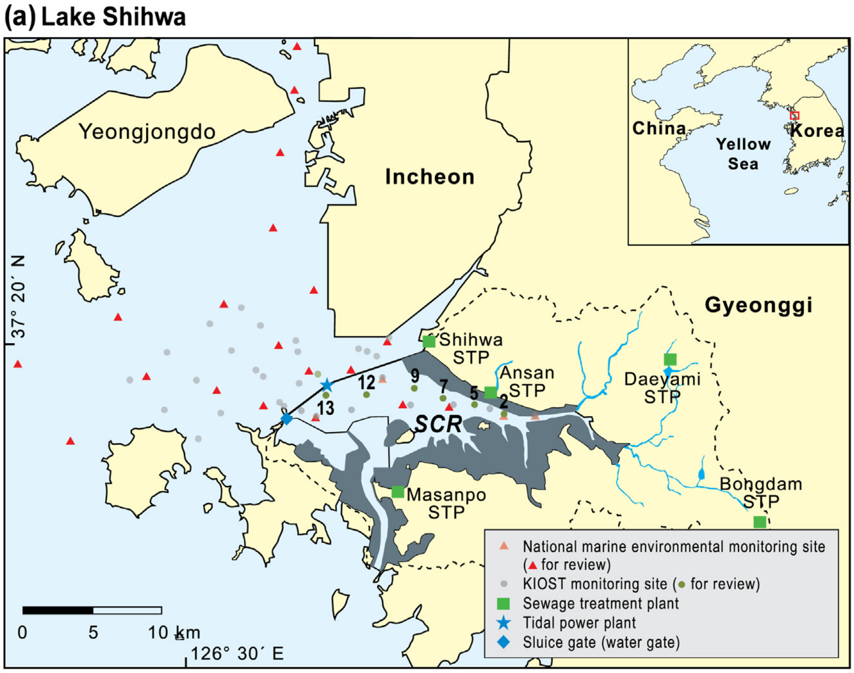

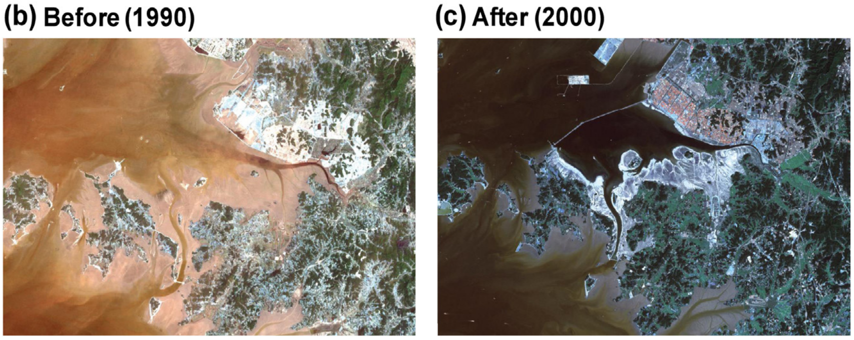

Fig. 1. Map showing the location and watershed boundary of Shihwa Coastal Reservoir (SCR). (a) Monitoring sites at the inner and outer regions of Lake Shihwa and satellite images of (b) before and (c) after the construction of the sea dike (in 1990 and 2000, respectively).

circle of environmental costs. First, coastal development did not take into account the natural environment, which resulted in the rapid deterioration of water quality; consequently, a huge budget was consumed for implementing uncertain water quality improvement techniques. The reservoir was theoretically planned to supply water for agricultural land covering an area of 65 km^2. However, after the sluice of the SCR dike was closed for water desalination, the water quality drastically deteriorated to the point where the Chemical Oxygen Demand (COD) exceeded 20 mg L^{-1} (Hong et al., 1997; Kim et al., 2002). Although the government implemented various short-term measures to improve water quality, including seawater circulation, the SCR desalination policy was officially abandoned, as it inevitably led to the further deterioration of water quality.

In fact, the SCR development was already anticipated to fail because the freshwater volume flowing into the SCR was so low that full desalination would require a longer period of time (KWRC, 2005). In addition, the volume of wastewater in the watershed drastically increased due to the rapid expansion of the adjacent national industrial complexes and the municipal districts. Delay in the construction of the wastewater treatment facilities further aggravated the situation, with the government failing to control untreated wastewater that was discharged into the SCR. However, over a short time frame, the government continued to develop the SCR, due to its tangible economic value, and did not review their policies. While the official decision for the SCR construction project was finalized in 1986, following two years of negotiations among the government parties, construction had already begun, even before the completion of negotiations. In addition, the potential impacts of the construction on the natural environment were not considered through a standard Environmental Impact Assessment (EIA) process. Therefore, the prerequisites of the EIA process were not fully addressed before the start of the SCR desalination project. Such prerequisites included the completion of public wastewater treatment facilities, the discharge of effluents from facilities to outside the dike, the prevention of wastewater inflow into the reservoir, and the operational plan of the dike to replace freshwater with seawater within the reservoir (Choi, 2001).

As a result, the water quality significantly deteriorated, which led to the government implementing various strategies to redress this issue. From the closure of the dike sluice gate (1994) until the abandonment of the desalination policy (2000), the government focused on short-term water quality improvement measures, such as seawater circulation and the discharge of wastewater treatment facilities outside the dike (MLTM, 2011a). These efforts improved the deteriorated water quality by up to 4 mg L^{-1} of COD; however, additional mid and long-term measures, such as the expansion of public treatment facilities, were insufficient to substantially reduce the COD of the SCR, with water quality levels remaining similar over the last 10 years.

Previous studies about the SCR focused on two aspects: namely, technology and policy management. The technological perspective included investigations about the causes of the SCR water quality problems after seawater circulation was cut-off, and measures for water quality improvement. In comparison, the policy management perspective included analyses of the causes for policy failure and the lessons learned. Factors considered in the technological studies were the purification capacity of the SCR (Kim et al., 2007), the lack of dissolved oxygen due to stratification (Han and Park, 1999), changes in organic matter and nutrient concentrations (Kim et al., 2002; Park et al., 2003), eutrophication and algal blooms (Shin et al., 2000a, 2000b; Choi et al., 2008), heavy metals concentrations and sediment (Choi et al., 1999; Ra et al., 2011; Won et al., 2012), and the concentration and distribution of sedimentary organic compounds (Khim et al., 1999; Koh et al., 2005; Kim et al., 2005; Hong et al., 2010). The policy management studies analyzed the reasons for the failure of the SCR initiatives from various perspectives, such as the lack of environmental crisis management capability (Ju and Park, 2009), the lack of an adjustment mechanism to promote national projects for multi-purposes (Lee and Hong, 2009), the lack of learning abilities and systematic thinking by the government (Kim, 2003; Yi and Kim, 2005), the lack of awareness about the natural environment among the general population (Kim, 2004), and finally, the deficiency of institutional devices to control such developments (Choi, 2001; Cho, 2005).

Many studies in this area focused on water quality issues, which were considered highly controversial between 1994 (opening of the sluice gate) to 2000, when the government officially declared its abandonment of the desalination policy. After 2000, additional mid- and long-term measures were implemented for water quality management, which consumed a huge budget without satisfactory results. This study aims to integrate various efforts to improve SCR water quality since dike construction in 1994 to the present, and to assess the effects of the SCR on water quality enhancement. Furthermore, we reviewed the associated issues on sedimentary pollution and ecosystem health impacts, such as changes in the community structure of plankton and benthic organisms, by water quality deterioration. The information reviewed here is used to determine the potential negative impacts (such as consumed government efforts and expenses) in the implementation of land reclamation projects without objectively considering relevant environmental parameters.

2. Materials and methods

To analyze the effects of governmental actions aimed toward improving the SCR water quality, all measures and investments were scrutinized in two parts (viz. periods); (1) short-term measures to improve water quality after the construction of the dike (1994–2000), and (2) mid- and long-term measures to improve water quality after the implementation of seawater circulation (2001–2011). In the first part, data from the first SCR environmental management master plan report (MOMAF, 2001) were analyzed (present in Table 1). In the second part, the details and investment results of the second and third SCR environmental management master plan reports (2001–2011) (MOMAF, 2007b; MLTM, 2011b) were analyzed (present in Table 2). In addition, the performance assessment report about the catchment environmental management plan (HRWMA, 2011) and the municipal statistics were referred to regarding the pollutants in the SCR watershed and changes in pollutant load, over the last 10 years (present in Table 3). Point source pollution parameters were examined, such as population of cities, number of plants, volume of wastewater discharge, and biological oxygen demand (BOD) discharge load in the study area. In addition, non-point source pollution parameters were examined, including changes in land use area and BOD discharge load.

National water quality monitoring data were used to determine changes in water quality inside and surrounding the SCR after dike construction. The dataset encompasses data from the Ministry of Environment (MOE) before 2004 and from the Ministry of Land, Transport, and Maritime Affairs (MLTM) after 2005. A total of three sites in the SCR and 18 sites outside the SCR were focused on to evaluate the long term changes in water quality after dike construction (Fig. 1a). COD and chlorophyll-a (Chl-a) were analyzed as SCR water quality proxies. Yearly volumes of seawater circulation were also analyzed, and were compared against changes in SCR water quality.

Sediment data were not available from the National Water Quality Monitoring Network thus, this information was collected from the Korea Institute of Ocean Science & Technology (formerly named the Korea Ocean Research & Development Institute), in addition to related reports and papers (Ahn et al., 1995; Choi et al., 1999; KORDI, 1999, 2000; MOMAF, 2003, 2004, 2005, 2006, 2007a; MLTM, 2008, 2009, 2010, 2011c, 2012a). These data include organic carbon content and certain heavy metals (Cr, Co, Cu, and Cd), which were used to represent sediment pollution. Information about trace organic pollutants, such as dioxins, furans, PBDEs, PCBs, PAHs, alkylphenols (APs), and perfluorinated chemicals (PFCs), were assimilated from peer-reviewed articles, with their spatiotemporal distribution in the study area being analyzed. Finally, to determine the ecological responses to environmental changes in the water column and bottom sediment in and outside the SCR, pelagic and benthic communities, and their temporal changes, were analyzed from information available in the published literature.

In summary, the review of environmental quality and ecosystem health in the Lake Shihwa area during the last 20 years was

Table 1
Causes and impacts of water quality degradation in Shihwa Coastal Reservoir.

Categories	Causes	Impacts
Water	- Dike construction and closed sluices	- Limited tidal mixing (decreased assimilative capacity) - Long water residence time (~300 days) - Water stratification and DO depletion in the bottom layer - Eutrophication and algal blooms
Watershed	- Rapid increase in population size - Rapid increase in numbers of factories	- Increased pollutant loads from watershed
	- Low freshwater input	- Long water residence time (~300 days)
	- Delayed construction of sewage treatment plant - Incorrectly connected sewer pipe system - Illegal wastewater discharge	- Untreated wastewater input (about 314,000 m^3/day)
Management	- Coastal wetland reclamation policy without considering potential environmental impacts	- Irreversible negative impacts on tidal flat ecosystem, water quality, and social conditions

Table 2
Water quality management measures of SCR[a].

Objectives	Year	Major management measures	Expenditure (million US $)
Increase tidal mixing	1997	Test sluice operation to increase seawater circulation	
	1998	Normal sluice operation (0.8 × 10^3 m^3 d^{-1} tidal flushing)	
	1999	Feasibility study of Shihwa Tidal Power Plant (STPP)	3.0
	2004	Onset of STPP construction	426.9
	2011	Test operation of STPP (32–160 × 10^6 m^3 d^{-1} tidal flushing)	
	2012	Full STPP operation (160 × 10^6 m^3 d^{-1} tidal flushing)	
		Subtotal	429.9
Strengthen pollution control	1987	Operation of 1st Ansan STP (cap. 121,000 m^3 d^{-1}, primary treatment)	248.4
	1993	Upgrading of 1st Ansan STP (secondary treatment)	
	1995	Operation of Shihwa STP (cap. 176,000 m^3 d^{-1}, secondary)	168.2
	1996	Diversion of Shihwa and Ansan STP effluents to outside of SCR	
		Construction of oxidation ponds (capacity 128,000 m^3 d^{-1})	15.8
		In-lake WQ management (Allum, Aeration)	4.4
	1997	Construction of wastewater collecting channel (11 km)	5.6
	2001	Expansion of 1st Ansan STP (cap. 385,000 m^3 d^{-1}, secondary)	508.7
	2004	Expansion of Shihwa STP (cap. 103,000 m^3 d^{-1}, advanced)	
	2005	Operation of 2nd Ansan STP (cap. 149,000 m^3 d^{-1}, advanced)	
	2009	Upgrading of 1st Ansan STP (advanced treatment)	
	2006	Operation of Bongdam STP (cap. 8,000 m^3 d^{-1}, advanced)	20.4
	2010	Operation of Daeyami STP (cap. 5,000 m^3 d^{-1}, advanced)	27.5
	2007	Stream sediment dredging and marine debris cleanup	11.7
	2008	Stream maintenance and Tando-ho WQ management	17.3
	2009	Livestock wastewater treatment facilities	24.5
	2010	Nonpoint source treatment and monitoring	24.3
		Groundwater quality monitoring and management	3.7
	2012	Constructed wetland to reduce nonpoint pollution (0.75 km^2)	34.1
		Subtotal	1,114.6
Adaptive management	1988	Finalized environmental impact assessment	
	1996	Establishment of special WQ management measures (MOE)	
	1998	Renunciations of taking irrigation water from SCR (MOMAF)	
	2000	Renunciations of keeping SCR as a freshwater reservoir	
		Designation of SCR as a SCMA (MOMAF)	
	2001	Implementation of 1st phase of SCR EMMP (2001–2006)	0.5
		Establishment of SCR WMC (MOMAF)	0.1
	2004	Establishment of SCR SDC (MOLT)	0.1
	2007	Implementation of 2nd phase of SCR EMMP (2007–2011)	0.5
	2011	Implementation of TPLMS (MLTM)	0.3
		Subtotal	1.5
		Total	1,546.0

[a] Data were referred from MOMAF (2007b) and MLTM (2011b).

presented in the following order. First, general water quality indices, such as COD, Chl-a, and seawater circulation data, were presented in and outside the SCR from the 1990s to date, to determine long-term changes in water quality in the study area. Second, the organic carbon content and major heavy metals (Cr, Co, Cu, and Cd) found in sediment were presented in and outside the SCR for the last 20 years to determine temporal responses to environmental changes associated with dike construction. In addition, we focused on the spatial distribution of certain sediment pollution indices by analyzing data from six sites, both upstream and downstream of the SCR, to determine the presence of a pollution gradient. Third, temporal changes in the concentrations of major trace organic pollutants were collectively presented to compare pollution status and history, with a specific focus on differences in pollutant spatial distributions between inland creeks and the inner lake. Finally, ecological responses were considered, in terms of community structure with respect to changes in the dominant species of marine or brackish organisms for macrofauna, meiofauna, zooplankton, and phytoplankton in the SCR.

Furthermore, we investigated the impact of the operation of the tidal power plant (TPP) on SCR water quality; however, limited data were available, as TPP operation has only recently been initiated (since 2012). Instead, the predicted effect of the TPP on water quality was inferred from a governmental report on the improvement of marine environments in the SCR (MLTM, 2012b).

Table 3
Pollution sources and estimated BOD loads from the SCR watersheds.[a]

Category		2003	2006	2009
Pollution sources	Population (capita)	856,271	912,642	964,936
	Factory (number)	5,083	6,314	8,449
	Wastewater (m^3 d^{-1})	140,891	254,350	238,767
	Lot area (km^2)	71.5	79.5	83.7
Discharged load	Point source (kg d^{-1})	12,326	9,665	5,518
	Nonpoint source (kg d^{-1})	7,677	8,510	8,877
	Total	20,003	18,175	14,395

[a] Data were referred from HRWMA (2011) and KICOX (2013).

3. Changes in SCR water quality after dike construction

3.1. History of SCR construction

The SCR is located in the southwestern part of Gyeonggi-do (Fig. 1), which is about 40 km southwest of Seoul. SCR construction was initiated in 1987 and completed in 1994. Its fundamental purpose was to expand agricultural land and to secure agricultural water. The reservoir is dammed by a dike of 12.7 km length that extends along a coastal zone, with an area of 56.5 km^2 and average water depth of 3.2 m. The maximum water capacity of the area is

330×10^6 m^3, with a storage volume of 180×10^6 m^3. Before dike construction, the maximum difference between low and high tide along the Shihwa coast reached 10.3 m, with a gentle slope, which generated wide tidal flats. However, after dike construction, the depth of the reservoir near to the discharge sluice gate was 3–13 m, while the depth around the TPP was 5–20 m, and the depth in the main tidal channel was 7 m. Since the ideal water level of the reservoir is a sea level of −1 m, the former 109 km^2 area of total tidal flats (12 km^2 at the northern part and 97 km^2 at the southern part) was converted into bare lands that were free of tidal influences (KWRC, 2005). While the northern part of the resultant reclaimed lands was gradually developed into urban and industrial areas (1996–2001), the southern part was planned for use as agricultural lands (since 2001).

The SCR watershed covers an area of about 477 km^2, which includes four city municipalities: Ansan, Siheung, Hwaseong, and Gunpo. Two national industrial complexes (Banwol and Shihwa), one local industrial complex, and two adjacent cities (Ansan and Siheung) are located in the northeast area of the SCR, whereas agricultural land and forests cover the western and eastern areas of the reservoir. The SCR is connected to nine major watercourses; four courses cross the industrial complexes (Okgu, Gunja, Jeongwang, and Siheung creeks), two courses cross the adjacent cities (Ansan and Shingil creeks), and three courses (Banwol, Donghwa, and Samhwa creeks) cross the agricultural and forest regions. All of these creeks are quite small (about <10 km long each), and collectively deliver freshwater of ca. 340×10^6 m^3 y^{-1} into the SCR, which is a similar amount to the total reservoir capacity of the lake water.

The development of the SCR watershed started in the late 1970s, as part of the population dispersion and industrial rearrangement policy over the metropolitan area. Banwol Industrial Complex (which is about 15 km^2) was constructed to relocate factories that had been previously densely distributed in Seoul. In the mid 1980s, about 1,000 companies moved to this area; therefore, there was no more land available to place additional industrial plants. Later the Shihwa Industrial Complex was constructed, with over 1,600 companies moving into the complex by 1995, as planned. These complexes mainly included industries that require a major water supply, such as food, fabric, paper, print, chemical, wood, rubber, non-metal, machinery, dying, leather, and paper stock industries. These types of heavy industries represented 60% of all industry in these complexes in 1995 and 56% in 2000, and potentially generated heavy pollution loads.

With the facilitation of business activities in the industrial complex, the adjacent cities also rapidly developed. The population reached about 0.3 million at the time of urban planning, and exceeded 0.5 million in the mid 1990s. The expansion of the industrial complexes, and increasing activities from adjacent municipal cities, resulted in the need for the land supply. The ratio of impermeable areas increased from 9.8% of the entire watershed in 1995 to 12.6% in 2000. This drastic increase in population and impermeable areas led to an increase in pollution load. In 1995, COD pollutants from the domestic sewage and industrial wastewater reached ca. 77% of the entire human pollution loads, with untreated or less treated wastewater of 314,000 m^3 d^{-1} being discharged into the SCR (KWRC, 1998).

3.2. Water quality degradation

Although it was planned for the SCR to supply agricultural water, its water quality rapidly deteriorated during the course of desalination. This problem started in 1995, when the dike sluice gates were closed, with it becoming a controversial environmental issue in Korea. A number of studies were conducted to determine the cause of water quality deterioration, and to provide mitigation measures (MOE, 1996; Kim et al., 1998; KORDI, 2000; Hyun et al., 2004). The present study summarizes the reported causes of SCR water quality deterioration based on the findings of these previous studies (Table 1).

The fundamental cause of the water quality problem was excessive development, along with the improper location for a freshwater reservoir. The Shihwa coastal belt had already been subject to a drastic increase in pollutant loads, due to the development of industrial complexes and adjacent populated cities. In addition, dike construction prevented tidal mixing and dilution. Thus, the accumulation of pollutants within the reservoir accelerated, as would be logically expected. The volume of freshwater flowing from the watershed was very small compared to its capacity; therefore, water retention time could potentially rise to 300 days if seawater discharge was blocked. Furthermore, anoxic conditions in the lower layer of stagnant water within the SCR, due to strong stratification, were recorded along the main tidal channel, as large amount of freshwater flowed into the lake and water temperature changed over the seasons.

In fact, during the planning phase of the SCR development project, the potential effects on the environment and ecosystem health were not carefully considered. Furthermore, the dike construction project was initiated one year before the EIA began. In addition, the basic measures required in the EIA were not implemented prior to the completion of the dike. These prerequisite measures included: (1) the proper disposal of effluent from sewage treatment plants (STPs) to the outer sea with controlled water quality management in the open ocean, (2) the prevention of wastewater discharge, which delivers high concentrations of nutrients from the agricultural area into the reservoir, and (3) planning sluice gate operation management strategies for the effective discharge of reservoir water with seawater. If these plans suggested by the EIA had been implemented, the situation would have been much more favorable in terms of environmental and ecosystem health.

Furthermore, it should be noted that the policy drive towards SCR development originated from the governmental reclamation project, with a lack of public awareness about environmental conservation. For example, land reclamation had been promoted as a national project without serious objection, as the project argued to extend agricultural lands that would attain a stable food supply. At the beginning, most people were not particularly interested about the coastal environment and ecosystem in and around the SCR, but were more concerned about the potential benefits of gaining land that could potentially generate economic rewards; however, this concept was naive.

3.3. Governmental measures to improve water quality

The SCR water quality improvement measures have been divided into three categories based on the cause of water quality degradation. These categories include; (1) in-reservoir management (e.g., tidal mixing to enhance water purification capability), (2) watershed management (e.g., pollution control to reduce land driven wastewater), and (3) improvement of the management system to control indiscriminate coastal development, and to alleviate conflicts among stakeholders.

In-reservoir management included both short-term (MOE, 1996) and mid- to long-term measures (MOMAF, 2001, 2007a) to improve water quality through circulation of seawater after dike construction. The MOE facilitated seawater circulation by opening the SCR sluice gate and adjusting the SCR water level from −2 m to −1 m, to increase the seawater circulation. However, there was a limit to which seawater circulation could be increased through the operation of the existing sluice gate; thus, a TPP with 254 MW power generation capacity was planned for construction middle of the dike to increase the seawater circulation rates by about 200 times (KWRC, 2005). The test operation and full scale operation of the TPP were conducted during August 2011 and 2012, respectively.

As a short-term watershed management measure, the entire volume of Shihwa and Ansan STPs effluent was discharged to the outer sea to reduce the pollutant loads flowing into the SCR. In addition, to prevent wastewater flowing into the SCR, due to the poorly constructed sewerage system and illegal discharge, sub-collection watercourses were installed at the end of the four major watercourses crossing the industrial complex, and the collected wastewater was delivered to the STPs. As industrial and municipal activities increased more rapidly than expected in the watershed areas of the SCR, the expansion and upgrading of public STPs was urgently required to prevent the deterioration of seawater quality outside the SCR. However, such planning required high expense and a long construction period; thus, instead, the government abandoned the desalination plan of the SCR in 1998, with it officially being canceled in 2000.

The authority for the environmental management of the SCR was transferred from the MOE (in charge of watershed management) to the Ministry of Maritime Affairs and Fisheries (MOMAF) (in charge of coastal and maritime area) when the desalination plan of the SCR was canceled. Based on the Marine Environment Management Act for the integrated management of maritime and inland areas, the MOMAF designated the SCR and the related watershed areas as the SCR Special Coastal Management Area, and established the SCR Environmental Management Master Plan (EMMP), which is carried out every 5 years. The second phase plan of the SCR EMMP ended in 2011, with the third phase being currently in progress. In terms of the integrated management of the coastal area, the MOMAF established the SCR Watershed Management Committee to promote an investigation about public opinion, to coordinate conflicts regarding environmental management, and to provide institutional support for the participation of stakeholders in management.

As the water quality of the SCR was maintained and stabilized to a certain level after seawater circulation, development of the reclaimed land at the northern and southern parts of the SCR was initiated. In 2004, to prevent the reclaimed land development causing another possible cause for the water quality problem, the Ministry of Land and Transport (MOLT), which is the agency in charge of land development, formed the SCR Sustainable Development Committee (SDC), which contained the stakeholders involved in the SCR development. After consultation of the SDC, it was agreed to form a state-of-the-art industrial complex in the northern part (9.8 km^2), with a 37% reduction in the original planned area for agricultural land, which was reallocated for the development of a city and park.

Meanwhile, the MLTM introduced the SCR Total Pollution Load Management System (TPLMS), because another concern about the water quality problem was raised, due to the change in the SCR reclaimed land use plan, followed by the progression of development. TPLMS is similar to Total Maximum Daily Load (TMDL), and was implemented by the U.S. Environmental Protection Agency (USEPA, 1997), and was recently tested in the successful case study of Masan Bay, Korea (Chang et al., 2012). This system was introduced to set a target for water quality management, and to control the increase in pollutant discharge, caused by development, to meet the water quality target. According to the first TPLMS master plan, the target was to improve the SCR water quality to 3.3 mg L^{-1} for COD and to 0.065 mg L^{-1} for total phosphorous (TP) by the end of 2017 (MLTM, 2012b).

It was estimated that until 2011, US $1.5 billion had been invested in projects to improve the SCR water quality, which includes the construction and expansion of Shihwa and Ansan STPs, the construction of the TPP, and the establishment of artificial wetlands. These expenses are 2.7 times greater than the cost of the original Shihwa dike construction (US $565.5 million). Out of these expenses, US $248.2 million (16%) was spent prior to desalination, US $197.0 million (13%) was spent during the period of implementing short-term measures (1995–2000), and US$ 1.1 billion (71%) was invested in mid- to long-term measures. This expenditure shows that the advance investment for the protection of the natural environment in the SCR development accounted for just 16% of the entire budget. When looking at the investment by category, the expansion of the public treatment facilities accounted for 63% (US $973.2 million), of expenditure, while the construction of the TPP accounted for 28% (US $429.9 million).

4. Changes in SCR water quality after seawater circulation

4.1. Pollution loads

Pollutant sources continued to increase because of SCR development, even after the initiation of seawater circulation; however, the actual pollutant load flowing into the SCR decreased with the implementation of various measures within the watershed (Table 3). The human population affected by the point source pollution was 11.6% larger in 2009 compared to 2003. At the same time, the number of factories in the industrial complex increased by 66.2%; however, wastewater discharge from industrial complex decreased, because the government implemented strict measures to control the demands for industrial water use.

Despite increasing pollution loads from the pollutant sources, BOD discharge load decreased with the expansion and implementation of advanced environmental treatment facilities, such as STPs. In contrast, BOD discharge load from non-point sources increased by about 15.6% in 2009 compared to data from 2003, due to the conversion of lands that were previously forests, rice paddies, and dry paddies into high density land use, such as industrial, commercial, and urban lands through industrialization and urbanization. The land use for siting, having the greatest unit load compared to other land uses, increased from 72 km^2 in 2003 to 84 km^2 in 2009. These findings indicate that, while the total pollutant load continued to decrease, the influence of non-point source pollution on water quality increased relatively more rapidly compared to point sources pollution after 2009.

4.2. Stratification and DO depletion in the water column

One of the common environmental issues related to reservoir formation after the construction of dikes is the stratification and lack of dissolved oxygen (DO) in the lower water layer (Fig. 2). After the attempt to desalinate the SCR, stratification (due to the difference in vertical salinity) led to a lack of DO in the lower water column; however, this problem remains, despite various follow-up measures for water quality improvement.

In 1996, when seawater circulation had yet to be initiated, the influence of freshwater resulted in 12–16 psu of salinity at a depth of 8 m and 25 psu at a depth of 10 m or deeper, while continuous desalination resulted in the stratification of deeper areas. In 1997, when seawater circulation was initiated, the salinity of the surface water decreased to 10 psu, while that at 6 m depth exceeded 20 psu, indicating severe stratification. Since 1998, vertical differences in salinity were observed with continued seawater circulation; however, the salinity level in 2004 was similar to that of 1997. While the vertical distribution of DO varied over the years, the basic pattern remained same. The DO saturation on the surface layer

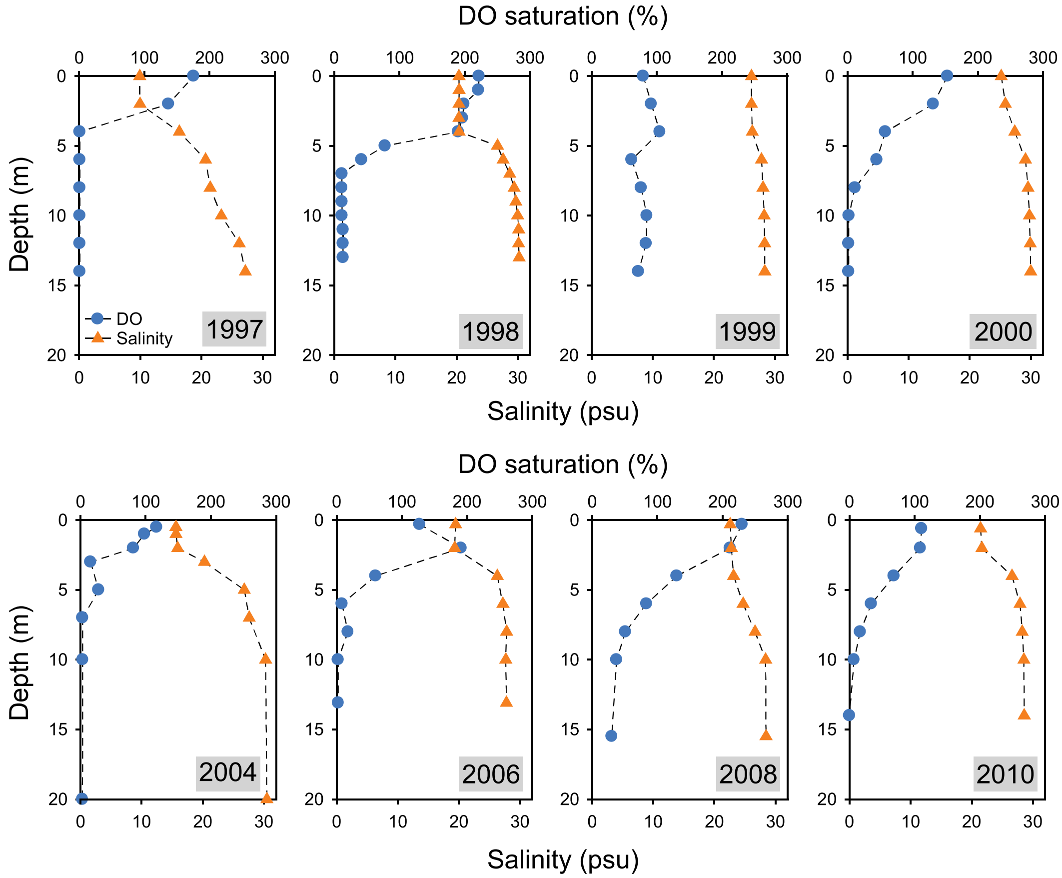

Fig. 2. Vertical profiles of dissolved oxygen (DO) and salinity at the center of the inner region of Lake Shihwa (at site 12, see Fig. 1) during the summers (July or August) of 1997–2010 (after the construction of sea dike) conducted by KIOST.

exceeded 100%, but decreased to 0% at a depth of 2–6 m, which clearly represented an anoxic layer.

4.3. General water indices

General measures of water quality (such as COD, seawater circulation, and Chl-a) inside and outside the SCR was evaluated using national water quality monitoring data, as described in the methods (Fig. 3). In 1993, before dike construction, the annual average COD in the SCR was 3.2 mg L^{-1}. In 1994, after dike construction, COD rapidly increased to 5.9 mg L^{-1}, and reached a maximum of 17.4 mg L^{-1} in 1997, just before the onset of seawater circulation. In 2000, COD rapidly declined to 4.3 mg L^{-1}. Although COD concentrations have fluctuated annually since 2000, no distinct improvement has been observed in the last 10 years. In 2011, a COD concentration of 3.7 mg L^{-1} was recorded, which was still greater than the target of 2.0 mg L^{-1}.

Chl-a is another algal-based organic material index, with its concentrations showing a similar temporal pattern to COD. In 1997, Chl-a concentrations reached the highest level, but have since drastically decreased, with no sign of improvement since 2000, although slight fluctuations have been observed.

The relationship between water quality and seawater circulation located in the southern part of the SCR dike showed that COD and Chl-a concentrations drastically decreased after 1998, when full-scale seawater circulation was implemented. Meanwhile, it was found that decreases in the volume of seawater circulation caused the deterioration of water quality in 2002. This observation indicates that seawater circulation seems to represent one effective measure to generally control water quality, at least to a certain extent.

The water quality outside the dike remained at 2 mg L^{-1} for COD (unlike the inside), with no significant change being observed after the onset of seawater circulation. This observation might indicate that the water inside the dike was not completely exchanged with the outer seawater. The Chl-a concentration outside the dike was smaller compared to inside, with relatively minimal change over the years. However, the greatest concentration of Chl-a that recorded during the early years of seawater circulation (around 1999) might indicate the influence of pollutants inside the dike, where eutrophication presented a serious threat.

5. Sediment quality in the SCR

5.1. Organic carbon content and heavy metals

Apart from the serious water quality problem, several indices of the sedimentary environment also supported the effects of pollutant loads as a sink. The organic carbon content in sediments drastically increased after dike completion, reaching the greatest value in the SCR during the late 1990s (Fig. 4). In early 2000, immediately after the policy was abandoned, as expected, the sediment organic carbon content decreased, with minor fluctuations being recorded in the following years. The spatial distribution analysis indicated that organic carbon content was relatively high in areas adjacent to known pollution sources (e.g., site 9); thus, the sediments reflected the pollution loads in the overlying water column. Meanwhile, annual comparisons of organic carbon content showed an increasing

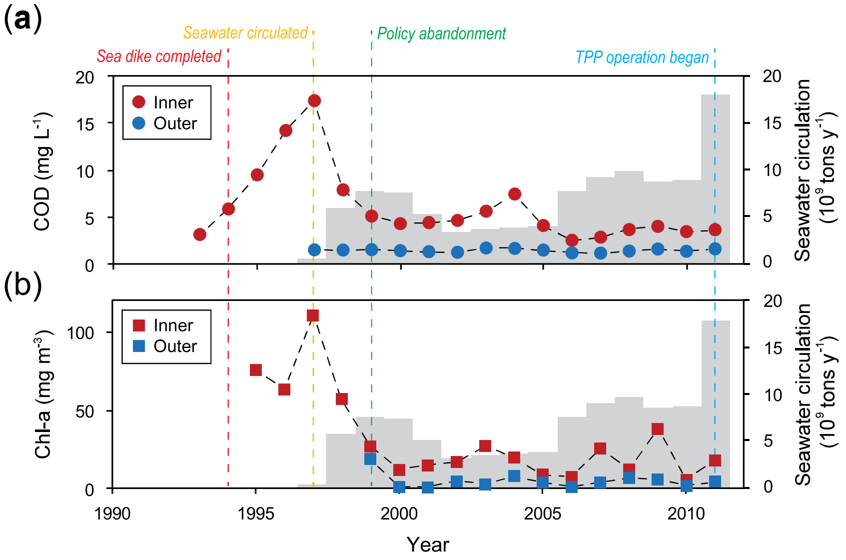

Fig. 3. Temporal trends of (a) COD and (b) Chl-a concentrations of the inner and outer regions of Lake Shihwa (see Fig. 1). Dotted lines indicate major events and shaded bars show the amount of seawater that circulated through the watergate and tidal power plant (TPP).

trend at some locations, such as site 2 (upstream) and sites 12 and 13 (downstream). In contrast, organic carbon content also showed a clear decreasing trend at site 9. Thus, sediment organic carbon did not fully explain spatial pollution loads.

Analyses of the heavy metals in sediments (Fig. 4) indicated that the concentrations of all target chemicals in the SCR were relatively high during the early and middle 1990s. After 1997, when seawater circulation began, these levels appeared to decrease. However, after

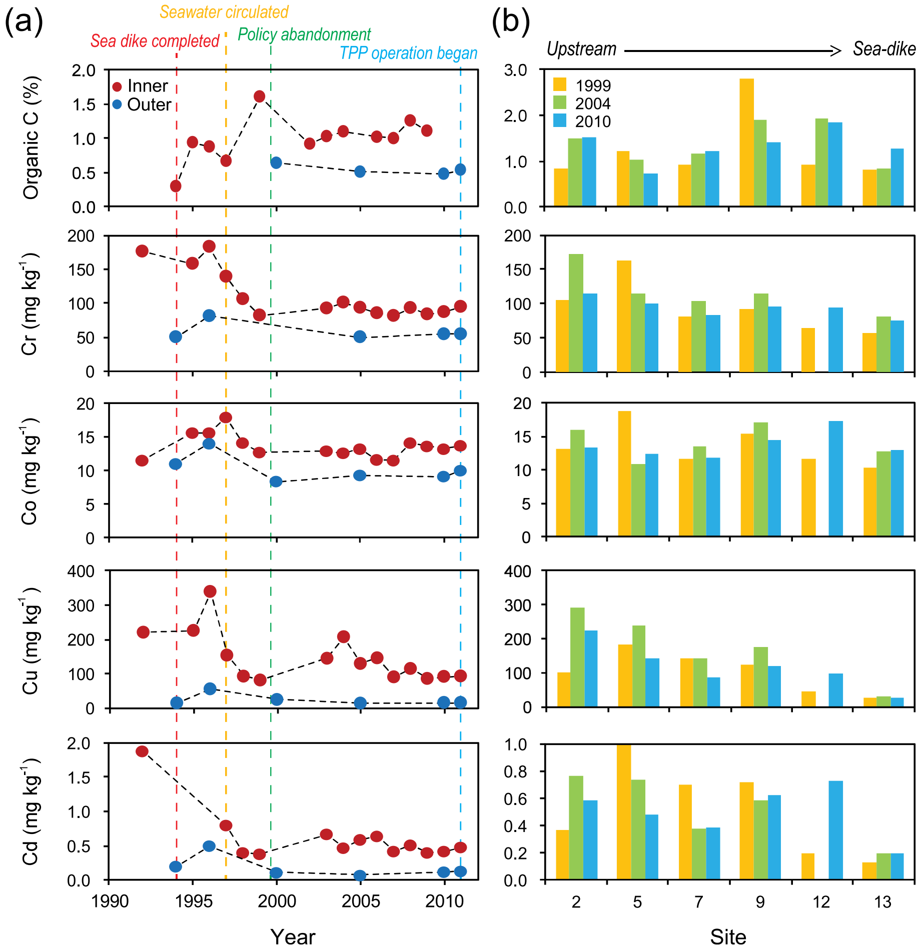

Fig. 4. Organic carbon contents and heavy metals in sediment of Lake Shihwa. (a) Temporal trends in the inner and outer regions and (b) spatial distribution at selected sites (from the upstream to sea dike, see Fig. 1) of the inner regions of Lake Shihwa surveyed in 1999, 2004, and 2010.

dike completion in 1994, the concentrations of all target chemicals also increased in the outer locations of the SCR, which might indicate time-lagged pollution effects to the outer sea areas. Six locations were selected and compared to further investigate the significant effects of heavy metal pollution inside the lake. A decreasing trend from the watershed towards the dike was observed for all target metals. Although the concentrations of target heavy metals in the SCR sediments varied with location, the clear and consistent increase in heavy metal concentrations after dike construction in the uppermost location of site 2 indicated excessive pollution loading from the watershed into the SCR.

5.2. Trace organic pollutants

Periodic monitoring data is not available for the concentrations of trace organic pollutants in the water and sediments within the SCR; therefore, available reports and published papers were used (Fig. 5). In the late 1990s and early 2000s, the presence of classic organic pollutants (such as PCBs, PAHs, and nonylphenols (NPs)) in the SCR sediments were primarily reported (Khim et al., 1999; Lee et al., 2001; Li et al., 2004a, 2004b; Koh et al., 2005; Choi et al., 2011). More recently, emerging pollutants, such as perfluorinated compounds (PFCs) and polybrominated diphenyl ethers (PBDEs), were monitored (Rostkowski et al., 2006; Yoo et al., 2008, 2009; Moon et al., 2012a). These studies showed that most organic pollutants originated from the surrounding industrial complexes and cities, with a clear location-dependent spatial distribution. In particular, NPs, PBDEs, dioxins, and furans exhibited high accumulations in the upstream sites and inland creeks located near the industrial complexes and residential areas. In contrast, the concentrations of these chemicals were relatively low near the downstream sites, approaching the dike. Hence, similar pollutant behavior was observed to that of the heavy metals (Li et al., 2004a, 2004b; Oh et al., 2010; Moon et al., 2012a, 2012b).

The annual comparison of changes in the concentrations of trace organic pollutants was difficult because of inconsistency in monitoring sites and limited availability of temporal data. Thus, temporal variations of trace organic pollutants in the SCR might not be fully explained; however, the collected data indicates clear inter-annual differences between inland creeks and the inner lake. For example, there was a slight decrease in NP concentrations over the years, both in the water and sediments, with relatively lower concentrations being found in the downstream and lake areas compared to upstream regions (Fig. 6). This trend appeared to be associated with efforts to restrict NPs, and water quality improvement through seawater circulation. Overall, the studies about trace organic pollutants in the water and sediments of Lake Shihwa indicated that sediment quality was possibly improved by the pollution control and/or restriction of chemicals in recent years. However, major levels of emerging pollutants, such as PFCs and PBDEs, were recently reported at some inland sites (Rostkowski et al., 2006; Moon et al., 2012a, 2012b; Naile et al., 2013). Thus, it is important to continue monitoring efforts and environmental management planning in relation to existing and emerging substances.

6. Ecosystem responses in the SCR

6.1. Benthic communities

With respect to changes in the distribution of aquatic organisms (Fig. 5), it was observed that benthic communities were directly affected by the anoxic environment in the lower layer, which had formed as a result of dike construction (Fig. 7). The benthic habitats of the SCR were originally similar to the surrounding coastal areas before dike construction, but rapidly changed during the desalination processes. As a result, certain benthic species completely disappeared, whereas, the number of opportunistic species significantly increased. After seawater circulation, the benthic habitat seemed to recover in the middle and downstream areas, as a result of improved water quality. However, at upstream sites, the extent of pollution was severe, because these areas were directly affected by inland pollutants. The shallow depth of the water further aggravated the situation, with a prevalence of opportunistic species, particularly polychaetes (Jung et al., 2012).

Only one study exists about the community changes of benthic fauna before and after dike construction in Lake Shihwa (Hong

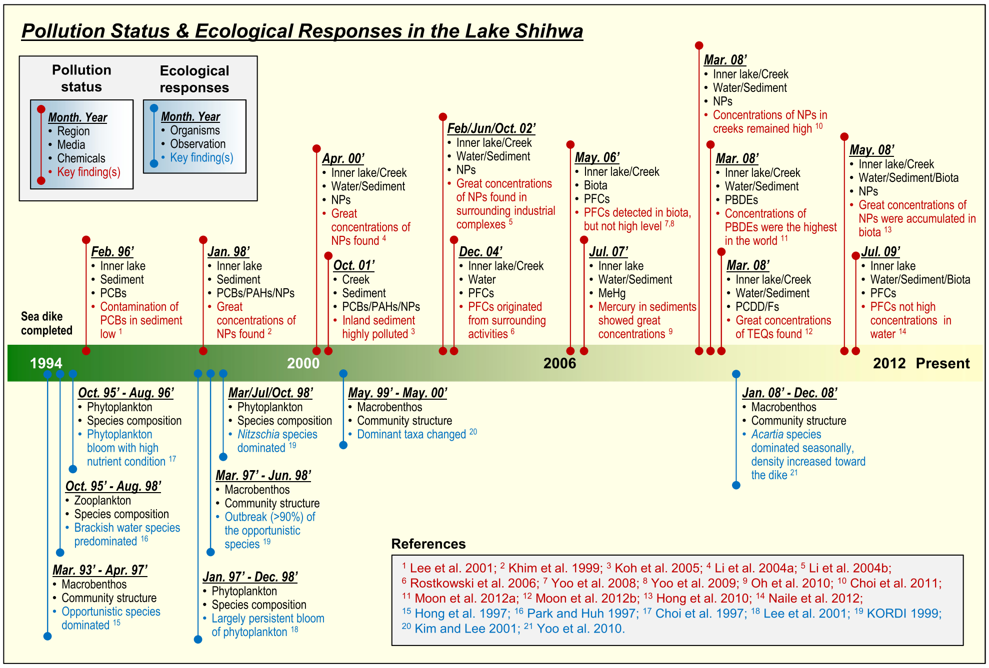

Fig. 5. Summary of pollution and ecological studies, with key findings, conducted in the Lake Shihwa environment.

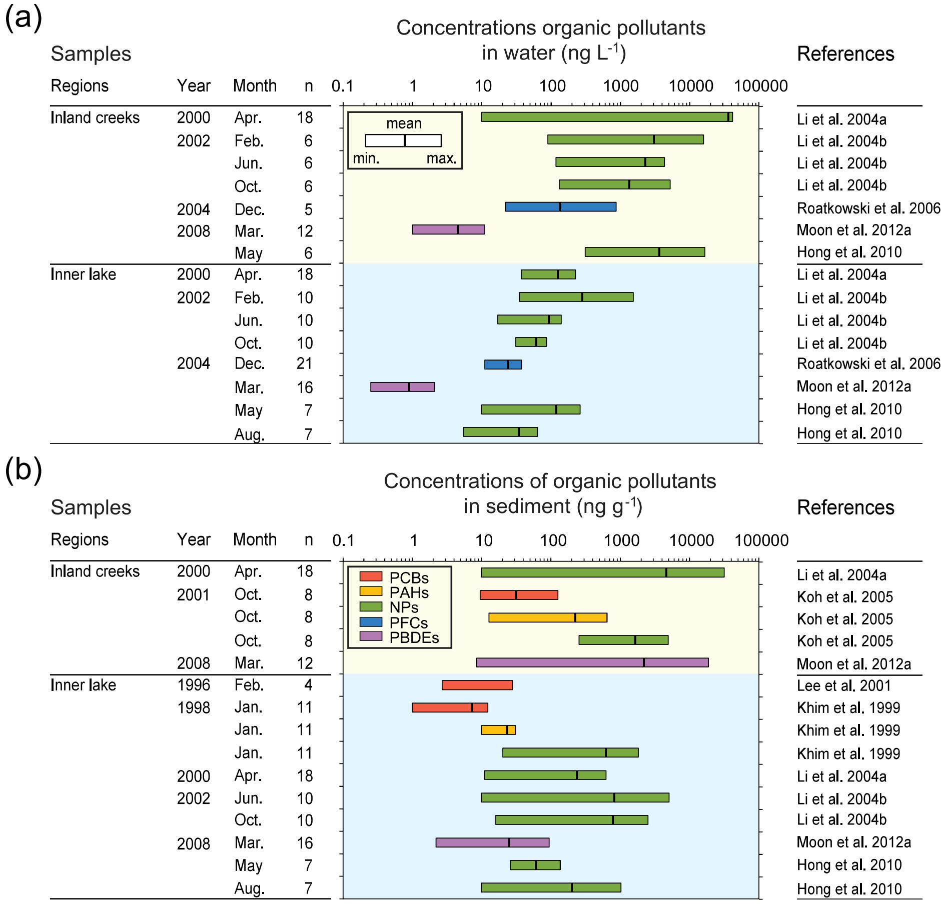

Fig. 6. Concentrations of organic pollutants (including PCBs, PAHs, NPs, PFCs, and PBDEs) in (a) the water and (b) the sediment of the inland creeks and inner regions of Lake Shihwa.

et al., 1997). The authors reported the formation of an anoxic layer that was associated with the increased influx of the organic matter after the completion of the dike, particularly at water depths of less than 6 m. Opportunistic species, such as *Pseudopolydora kempi* Southern, 1921 and *Polydora cornuta* Bosc, 1802 dominated the communities near the dike. Subsequent studies investigated the macrobenthic fauna of the lake (Lee and Cha, 1997; Ryu et al., 1997; KORDI, 1999; Lee et al., 2003). Overall, until the sluice gate was opened and the water partially circulated in 1997, the number of polychete species tended to decrease, whereas opportunistic species increased. After water circulation, the number of meiobenthic species greatly increased; however, there was limited focus on changes to their community. Only Kim and Lee (2001) studied this issue between May 1999 and May 2000. The predominant animals were nematodes, followed by sarcomastigophorans, crustacean nauplii, benthic harpacticoid copepods, and polychaetes. The ratio of nematodes to benthic harpacticoids (N/C) was lower around the dike and higher in the inner area of the lake. This observation indicates that the inner areas of the lake became unsuitable habitats for meiobenthos due to major pollution levels, with similar results being obtained for the macrobenthos.

6.2. Planktonic communities

With respect to zooplankton, Park and Huh (1997) reported a predominance of *Sinocalanus tenellus* (Kikuchi K, 1928) when the lake was desalinated during 1995–1996. After the desalination policy was abandoned, by 2008, the zooplankton species composition was similar to that of the seashore outside of the dike; however, the dominant taxa from April to September of 2008 were brackish water copepods (Yoo et al., 2010). However, a dense phytoplankton bloom with an average value of 168.6 μg Chl-a L^{-1} was recorded in both 1995 and 1996 (Choi et al., 1997). In 1997–1998, freshwater species of phytoplankton were dominant, whereas brackish species became abundant when seawater circulation treatment was initiated (Shin et al., 2000a). In particular, the water quality deteriorated during the rainy summer season, because of a massive input of nutrients from industrial complexes and adjacent cities (Shin et al., 2000b). In addition, phytoplankton species diversity appeared to increase from 1998, following the onset of seawater circulation (KORDI, 1999; Kim and Kwon, 2004). Overall, temporal changes in the dominant species of Lake Shihwa, including benthic macro- and meio-fauna, zooplankton, and phytoplankton, collectively reflected the direct effects associated with the environmental changes in this area.

To improve water quality by increasing seawater circulation, the government implemented a new TPP construction project at the center of the SCR dike in 2011. As a result, seawater circulation increased to 0.16 billion ton d^{-1}, which represented about 50% of the entire capacity of the SCR (0.33 billion). The Korea Water Resources Corporation anticipated that TPP operation would improve the water quality within the SCR to similar levels of that outside the dike (KWRC, 2006).

Based on the ocean water quality model established for the TPLMS master plan of the SCR, it was anticipated that the water quality in the middle and downstream areas of the SCR would

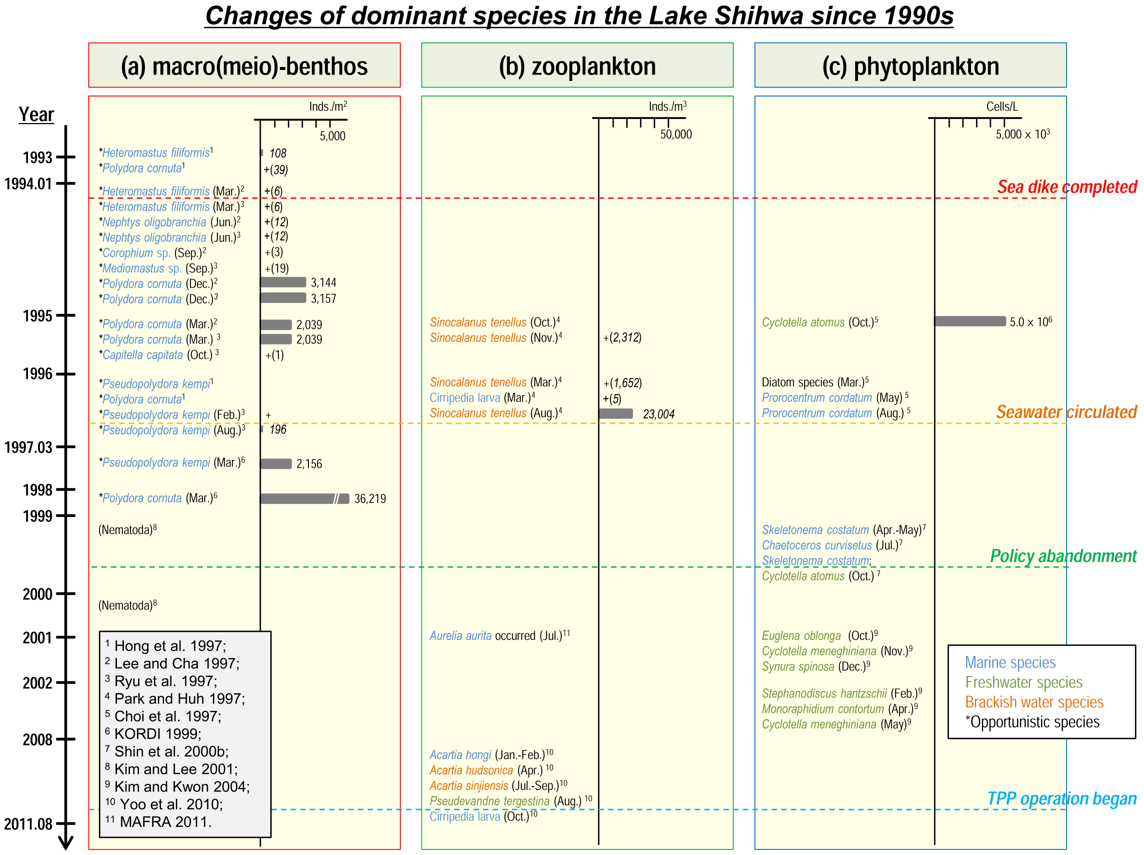

Fig. 7. Temporal trends of dominant species, including (a) macro (meio) benthos, (b) zooplankton, and phytoplankton in Lake Shihwa.

improve, in terms of COD. The model estimated that COD would decrease from the 5.58 mg L^{-1} recorded in 2001 (average of May and August when water quality was at its lowest) to 3.30 mg L^{-1} after TPP construction in 2011. Hence a 2.28 mg L^{-1} reduction in COD was estimated just from the effect of TPP seawater circulation (Fig. 8). However, there was limited improvement in the water quality of the upstream area of the SCR, where pollution was more serious, despite the increased volume of seawater circulation. In fact, the reservoir water surface level decreased to that of average sea level (−4 m) as a result of TPP construction. This drop in water level caused major changes in the reservoir capacity of the upstream region. Furthermore, while TPP construction resulted in increased seawater circulation, it also caused the upper region to stratify, as the increased volume of seawater expanded to upstream sites. Therefore, during the rainy season, pollutants from the watershed had a much greater effect on upstream water quality, as a result of stratification.

7. Discussion

Dike construction blocks seawater circulation and mixing, which inevitably causes stratification in water column, because of increased water retention time, and represents a common environmental problem of artificial reservoirs. The case of the SCR in South Korea was no exception. In this instance, it was observed that the inflow of sufficient organic matter from the watershed, in addition to the on-site production of organic materials through algal growth and accumulation in the reservoir, produced anoxic conditions through the consumption of DO in the water column (Fig. 2). Under these conditions, pollutants, such as nutrients from sediments, tend to be released, leading to a further deterioration in the water quality of the lower layer (Heo et al., 1999; Choi et al., 2008), which generates a vicious cycle. Such conditions could remain unchanged, even after the implementation of follow-up remedial measures, such as seawater circulation and pollutant control (Fig. 3). The anoxic or oxygen deficient layers that form because of stratification might have adverse effects on the ecosystem, almost eliminating existing benthic communities in the SCR, with the survival of only certain opportunistic species (Gray et al., 2002) (Fig. 7).

After the desalination of the SCR, there was evident deterioration in both water and sediment quality (Figs. 2–6). These environmental changes were the collective result of multiple causes (Table 1). One of the fundamental causes of environmental deterioration was the blockage of seawater circulation, preventing the proper control of pollutants. The wastewater discharged from the industrial complexes, cities, and cattle sheds around the SCR was not properly treated because of the delayed construction of public treatment facilities and poorly designed sewage piping, which did not connect with water directly flowing into the SCR. Pollution further increased with the formation of anoxic and/or oxygen deficient layers in the water column, along with algal growth and pollutants released from the sediments. Both organic matter concentrations and Chl-a exhibited similar fluctuations in the SCR over the last 10 years (Figs. 3 and 4), which supported previous work suggesting that organic matter in the SCR loaded from the watershed facilitated algal growth (MOE, 1996; Kim et al., 2002; KWRC, 2005).

The drastic decrease of COD and Chl-a in the SCR after 1997 was caused by the implementation of short-term water quality measures, such as the installation of wastewater collecting facilities, the discharge of effluent from Shihwa and Ansan STPs to the outside of

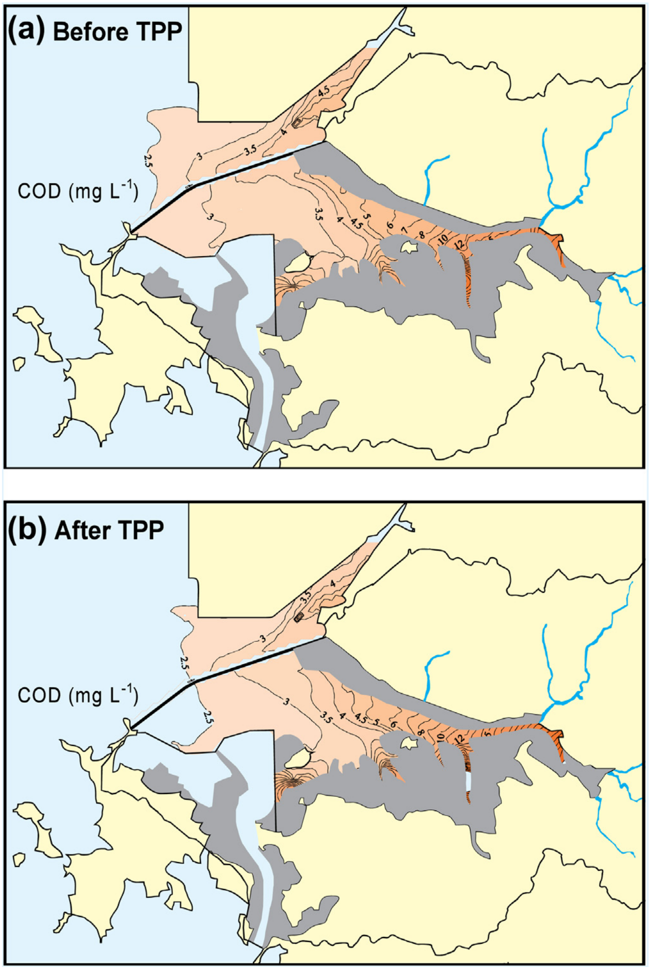

Fig. 8. Prediction of water quality (COD) change caused by the operation of the tidal power plant (TPP). (a) before (2010) and (b) after the onset of TPP operation (MLTM, 2012a). COD in SCR after TPP (lower) was predicted using the average value of COD observed during May to August of 2010 (upper).

the dike, and the physical mixing of seawater. It was difficult to quantitatively determine the effects of individual measures; however, a clear relationship was observed between the amount of circulated seawater and COD concentration (Fig. 3). Thus, the improvement of SCR water quality was largely attributable to seawater circulation (Kim et al., 2004).

Although the short-term measures implemented to improve water quality until 2000 generated significant changes, the subsequent implementation of mid to long-term measures did not contribute to any further recovery of water quality after 2001. Since 2000, more than US $556 million was invested in the expansion and advancement of the STPs (Table 2); yet, the concentration of COD in 2011 was 3.7 mg L^{-1}, which, while improved from 4.5 mg L^{-1} recorded in 2001, it did not meet the target of 2 mg L^{-1}. In particular, the concentrations of COD and heavy metals in the upstream region of the SCR were higher compared to those in downstream region, because the effect of seawater circulation could not reach the upstream region due to the geomorphological features.

The improvement of water quality in the SCR after seawater circulation also led to the improvement of sediment quality (Figs. 3–5). The level of pollution from organic carbon content and heavy metal concentrations in the sediments drastically increased when seawater circulation was blocked after dike construction; however, levels declined, particularly from the late 1990s to early 2000s, when sewage and wastewater were discharged outside of the dike. Similar temporal trends were observed for trace organic contaminants, both in the water column and bottom sediments. In addition to seawater circulation decreasing the level of sediment organic pollutions, it also had a general positive influence on the pelagic and benthic communities (Fig. 7).

However, despite consistent investment in water treatment facilities, further improvement in water quality has not been observed since 2000 to present. Although treated water from Shihwa and Ansan STPs was discharged to outside of the dike, loadings from non-point sources continued to increase. At present, Shihwa and Ansan STPs represent most of the SCR watershed loadings from point sources; yet, the reduction of general loads after the expansion of their treatment capacities and advancement of treatment facilities appeared relatively small (MLTM, 2011a).

Organic carbon content and heavy metal concentrations in the sediments were relatively high in the upstream region, which was directly caused by pollutants from the watershed, in addition to being high in some of the regions in the middle of the SCR, where fine sediments had accumulated because of seawater circulation and geomorphological features (Fig. 4). The central area of the SCR was deep enough to cause oxygen deficiency in the lower layer, because of stratification; thus it is possible that the released nutrients caused the mass production of phytoplankton (Kim et al., 2002; Park et al., 2003; Hyun et al., 2004; Kim et al., 2007). In addition, the analysis of sediment heavy metal concentrations showed an increase in all pollutant parameters at site 12 (located in the middle of the SCR) in 2010 compared to 1999, because the sediments also flowed from upstream to downstream, followed by a long period of sink in deeper water (Ra et al., 2011). Therefore, as most of the point sources were being properly regulated, it is necessary to control non-point sources properly to generate any notable improvement in water and sediment quality in the future.

After 2000, it was found that point source loads within the watershed significantly decreased because of the continuous expansion of treatment facilities and maintenance of sewage systems. In comparison, non-point source loads continued to increase, because of the excessive utilization of reclaimed lands (Table 3). Therefore, measures implemented to improve water quality were not effective. The investment in non-point source control within the SCR watershed accounted for US$ 2.9 million, which represented just 5% of the entire investment for the watershed (Table 2). Furthermore, a large portion of this amount was used for non-point source monitoring, rather than for implementing practical load reduction plans. Thus, further improvement in SCR water quality could be limited, unless non-point source loading during the rainfall period is controlled (Kim et al., 2002; Jang et al., 2011; Ra et al., 2011). The contamination of sediments by heavy metals and trace organic pollutants was also closely associated with point sources, whereby greater concentrations were usually found near to industrial and urban regions (Figs. 4 and 6). However, certain volatile chemicals, such as low molecule PAHs, might be released from non-point sources via atmospheric deposition, after combustion in and around the industrial areas (Shin, 2008); thus, future management plans should focus on addressing non-point sources.

After 2000, Chl-a concentration tended to fluctuate annually (Fig. 3), reflecting the changes in organic loads generated by the lake, which were caused by changes in non-point source loads and the mass reproduction of algae, with these factors also being dependent on the level of precipitation in a given year (Kim et al., 2004; Choi et al., 2008; MLTM, 2011c). With respect to the distribution of sediment pollutants, limited seawater circulation prevented organic matter and pollutants from the watershed or those generated within the reservoir to flow to areas outside of the dike.

Consequently, these contaminants remained in the reservoir for a much longer period of time. When taking the geographical characteristics of the SCR into consideration to improve water quality, it is necessary to increase seawater circulation, control stratification, and enhance the natural pollutant purification capacity. Furthermore, practical measures must be implemented to reduce non-point loads from the watershed, by designating management areas to control them. Finally, to improve water quality, it is vital to dredge sediments to reduce the influence of various pollutants, such as polluted sediments, to control algal blooms (Park et al., 2003; Kim et al., 2007).

It was difficult to assess the effects of TPP on water quality, because there is a lack of accumulated water quality monitoring data after the onset of TPP operation in 2012; however, the modeling results indicated that plant operation has had an insignificant effect on water quality in the upstream region of the SCR (i.e., the origin of pollution). To improve the water quality of the SCR in the future, it is vital to reduce non-point source loads within the watershed; however, to date, the government has not taken any practical measures towards this end. The plan to dredge polluted sediments in the SCR to improve water quality was considered in the third SCR environmental management master plan (MLTM, 2011b); however, the expected effect might not be significant, due to the comparatively small size of the dredging area.

The fundamental cause of SCR water quality deterioration was found to be the blockage of seawater circulation through dike construction, without the implementation of any practical water quality control measures. In the early stages of dike construction, the inflow of untreated pollutants was the largest source of water pollution; however, after seawater circulation and the discharge of treated effluent outside the dike, non-point source discharge from the watershed and limited circulation of seawater became the main issues. As a result, the government invested about US $1,546 billion to increase seawater circulation (viz., TPP construction), the expansion of STPs, sewage system improvement, livestock night soil treatment, non-point source treatment, and artificial wetland formation, among other techniques. However, to date, the water quality target has not been achieved, and needs to be improved to match that of background levels, namely, the levels recorded before dike construction. A simulation model was run, in which all of the measures were considered (including TTP operation), that produced an estimated COD value of 2.3 mg L^{-1} in the far western area of the SCR, where the largest improvement in water quality was expected. This model indicates that US $479 million might have been misused in various initiatives, as just an 1 mg L^{-1} improvement in COD over the last 10 years (from 2001 to present). At present, the upstream region of the SCR is still subject to major water quality problems, with it being unclear as to whether any improvement is possible in the near future; thus, fundamental efforts to address this issue are urgently required.

8. Conclusions

The SCR is an artificial reservoir that was created from the sea dike constructed in 1994; however, the lack of management initiatives to address the accumulation of pollutant loads from the watershed, due to reduced tidal mixing, led to a major deterioration in water quality. Multiple lines of evidence demonstrating water quality deterioration clearly confirm the significant adverse effects of blocking seawater circulation in combination with the continual accumulation of pollution loads from the watershed into the SCR, due to the long residence time of water. The Korean government has invested US $1.546 billion to facilitate tremendous efforts to improve the water quality of the SCR through various schemes over the last 20 years. Yet, the implemented measures could not resolve the fundamental flaws generated by dike construction. The SCR is an example of a grand land reclamation project in Korea; however, this project demonstrates that the major changes to the natural environment caused by this major development could not be artificially reversed to reflect original conditions. If such a project is inevitable, strict and consistent management, along with the implementation of relevant policies, should be taken, to minimize the time and efforts to redress any negative effects, along with unforeseen economic costs.

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