ORIGINAL PAPER

Selection of priority management of rivers by assessing heavy metal pollution and ecological risk of surface sediments

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Abstract This study aimed to select rivers of priority management through the assessment of heavy metal pollution of sediments. We investigated the distribution characteristics of heavy metals in surface sediments of the Nakdong River in South Korea and used various pollution indices to assess pollution risk and identify factors influencing pollution. The kriging method was used to determine heavy metal distribution. The pollution load index, potential ecological risk index, mean PEL quotient, and the Canada Council of Ministers of the Environment sediment quality index were used as sediment pollution assessment methods. The toxicity evaluation was performed on sites that appeared to be contaminated, by applying existing methods for assessing sediment pollution level and the national standards for evaluating the pollution level. The toxicity test was performed on *Hyalella azteca,* and a methodology for assessing sediment pollution level was proposed. Ecotoxicity was assessed at seven sites that were found to have heavy metal contaminants. The results showed that sites N1, N8, T28, and T29 were not toxic, while T8, T19, and T21 were. Thus, this study shows that high heavy metal pollution does not necessarily lead to a toxic environment. To assess sediment pollution, an additional assessment of toxicity should be made, along with assessments of existing sediment pollution. Our results demonstrate that streams showing high sediment pollution levels should be granted priority in management. The efforts should particularly focus on Cu at T8, Cr at T19, and Hg at T21.

Introduction

Heavy metals have been continuously produced by human activity, accumulating in the environment and in living organisms. Besides active water quality surveys, geochemical materials (including heavy metals) accumulated in sediments should also be analyzed to understand river environments (Thornton 1983). This is particularly important, as sediments exhibit higher concentrations of heavy metals and smaller spatiotemporal changes than water, due to movement constraints (Ra et al. 2013). Because even small amounts of heavy metals can cause serious harm to aquatic ecosystems and human health, a large number of studies have been conducted to evaluate the intensity of heavy metal pollution. Heavy metals enter

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into surface water bodies via atmospheric deposition and/or industrial wastewater effluents. As they flow into the hydrological system, they also accumulate in sediments. Pollutants stored in sediments can reenter the water body via physical and chemical processes, such as resuspension and oxidation–reduction reactions. Because of this characteristic, sediments are considered as potential pollutant sources. They act both as carriers and sinks for contaminants, reflecting pollution history and providing a record of catchment inputs into aquatic ecosystems (Marvin et al. 2004; Farkas et al. 2007; Cevik et al. 2009; Devesa-Rey et al. 2010). Although heavy metals generally exist in low concentrations in the environment, they are non-degradable, persistent environmental pollutants; therefore, even small amounts can have harmful effects on aquatic ecosystems. However, toxicity tests should be conducted to determine whether heavy metal concentrations have a radical effect on aquatic ecosystems. The degree of sediment pollution is first evaluated using the indexes for assessing the degree of heavy metal pollution. Additionally, a toxicity test is required to determine whether sediments are in a condition that can have a radical impact on aquatic ecosystems. Management of toxic sediments, even those with a low concentrations of heavy metals, should be prioritized compared over sediments with a high concentration of heavy metals but no toxicity.

The behavior of trace metals contained in sediments is useful to understand the sedimentary environment of a river and take efficient countermeasures (Kim et al. 2001). Several methods, including enrichment factor (EF) and geoaccumulation index (Igeo), are predominantly adopted to evaluate the heavy metal concentrations in crustal material or in unpolluted regions that serve as the background (Sekabira et al. 2010). Li (2014) analyzed heavy metals in surface sediments of the Yanghe River and evaluated the pollution levels using the sediment quality guidelines (SQGs) risk assessment method, RI, and Igeo. Ali et al. (2016) analyzed sediments of the Karnaphuli River and applied the contamination factor (CF) and pollution load index (PLI) to assess heavy metal pollution. Effendi et al. (2016) compared the threshold effect level (TEL) and probable effect level (PEL) for the Mahakam delta and used the ecological risk potential index (ERI) for ecological risk assessment of heavy metals in surface sediments. Li et al. (2019) proposed the feasible SQGs by assessing

contamination status and ecological risk determined by EF, Igeo, PLI, and mean probable effect concentration quotients (mPECQs) analyses.

New approaches in the research of river sediments have been emerging in South Korea. Existing studies on the sediments of the Nakdong River mostly focused on the coast, estuary, and delta areas of the river (Lee et al. 2004; Yoon and Lee 2008). Only a few geochemical studies assessed the sediments in the main stream and the tributaries. Since 2013, when the four-river restoration project was completed, studies on stream sediments have been conducted in Korea. Studies are underway to evaluate the contamination level by analyzing the concentration of heavy metals contained in river sediments. The studies on heavy metal contamination in sediments found in the Nakdong River were mainly performed by comparing the results with the standard of sediment environment set in each country: EF, Igeo, and PLI (Kim et al. 2015, 2017). However, previous studies assessed the degree of pollution using only heavy metal concentration. In this study, the degree of surface sediment pollution was analyzed via both heavy metal concentration and a toxicity test using *Hyalella azteca*.

As the multifunctional weirs constructed in the Four Major Rivers Project maintained the management of the water level, the current velocity of the river changed, the retention time increased, and silt was redistributed. River sediments are carried by river flow from regions upstream and deposited on the river bed. With slower current velocity, a larger number of particles are deposited. As the weirs increase both the water level and the river retention time, sediments (mostly sand) become finer, and heavy metals tend to accumulate more in fine sediments.

The necessity for efficient sediment management has become increasingly recognized because bottom sediments should be maintained and pollution sources should be determined and controlled. However, sediment research has been limited in South Korea. The operation plan of the water environment monitoring network was included in notification No. 2017-74 of the Ministry of Environment (MOE 2017) and has been upgraded every year since. The sediment monitoring network has been surveying surface sediments in streams since 2012. Basic data to determine the effects of sediment pollution on water quality and aquatic ecosystems have been collected as part of this survey and for the assessment of the environmental

quality of subaqueous sediments. However, as yet, there are no reports on heavy metal pollution in surface sediments of the Nakdong River. This study attempts to evaluate the influence of sediments as potential pollutants on the river environment. In this study, sediments from the Nakdong River basin were analyzed by (1) an ecotoxicology evaluation test, (2) a toxicity test using *H. azteca*. Based on the results of the analysis, the degree of heavy metal pollution was evaluated using the heavy metal evaluation technique. The pollution levels and risks were evaluated by applying various pollution indices (PLI, RI, mPELQ, and CCME SeQI) to data collected in 2015 at 38 points in the streams of the Nakdong River system. Finally, this study used toxicity tests to show that high heavy metal pollution does not necessarily lead to a toxic ecosystem environment. This type of sediment quality assessment is vital, as sediments play a major role in determining pollution patterns in aquatic ecosystems. An ecotoxicology evaluation was performed using *H. azteca* on stream sediments that were known to be highly polluted, and a methodology was proposed for a comprehensive evaluation of sediment pollution in river systems. The ultimate goal of this study is to provide basic data for middle- and long-term policy of selecting streams that require priority management.

As the significance of sediment management and water quality is realized, the results of this study will be used to evaluate streams and sites with high pollution levels and determine sites that require priority management. Such assessment and analysis will provide useful data for establishing a relevant policy concerning priority management.

Materials and methods

Study area and sediment sampling

The Nakdong River basin has an area of 23,384.21 km^2, a river length (main stream) of 400.7 km, and a flow path length of 510.36 km. It is located at 127°29′19″–129°18′00″ East and 34°59′41″–37°12′52″ North, in the southeastern Korean Peninsula. The Nakdong River originates in Hwangji in the Taebaek Mountains and flows to the South Sea. It passes through most parts of the Yeongnam region and some parts of Gangwon-do and Jollabuk-do. The Nakdong River is the second largest river in Korea, occupying 24% of the territory (Ministry of Land, Infrastructure, and Transport 2009). The river flows through three big cities (Busan, Daegu, and Ulsan) and parts of five provinces (Gyeongsangnam-do, Gyeongsangbuk-do, Jollanam-do, Jollabuk-do, and Gangwon-do) (NIER 2008). Other major hub cities, such as Andong, Gumi, Daegu, and Busan, which are experiencing significant industrial development, are located along the Nakdong River basin. Nakdong River is the main source of drinking water for 13 million people; it is also used for agricultural activity (51.0%), for domestic and industrial purposes (21.6%), and for river maintenance (27.4%). The Four Major Rivers Project aimed to manage the limited water resources and achieve effective flood control. As part of the project, the rivers were dredged and 16 multifunctional weirs were constructed. The Nakdong River has eight weirs, which is the largest number among the four rivers.

Surface sediments in the study area were collected between March and May (the dry season in Korea) in 2015. The effects of heavy rains, rainy season, and typhoons on the sediment environment during this season are considered to be weak. Surface sediments were collected from the upper 3 cm using a Ponar Grab sampler at 38 points in the streams of the Nakdong River basin (Fig. 1). "N" indicates the main stream of the Nakdong River, and "T" indicates the tributaries joining the Nakdong River or the other branches of the Nakdong River. The points marked "T" are located at the end of each unit basin for the management of the Nakdong River.

Analysis of sediment samples

At each point, more than five sediment samples were collected, mixed, and strained through a nonmetal sieve (sieve size of 0.15 mm). Next, the samples were dried and ground by a crusher down to < 0.063 mm. Nitric acid (HNO$_3$), perchloric acid (HClO$_4$), and hydrofluoric acid (HF) were added to the dry and pulverized samples. The mixture was then heated until both the oxides and the sediments were completely decomposed. Next, 20 mL nitrate solution (2%) was added to volatilize and remove HF, then again for dissolution. After the pretreatment, the contents of eight metals: Al, Li, Zn, Cr, Pb, Ni, Cu, and Cd, were analyzed using inductively coupled plasma-atomic emission spectrometry (ICP-AES, Varian, 720-ES).

Fig. 1 Basin setting and location of streams in the study area
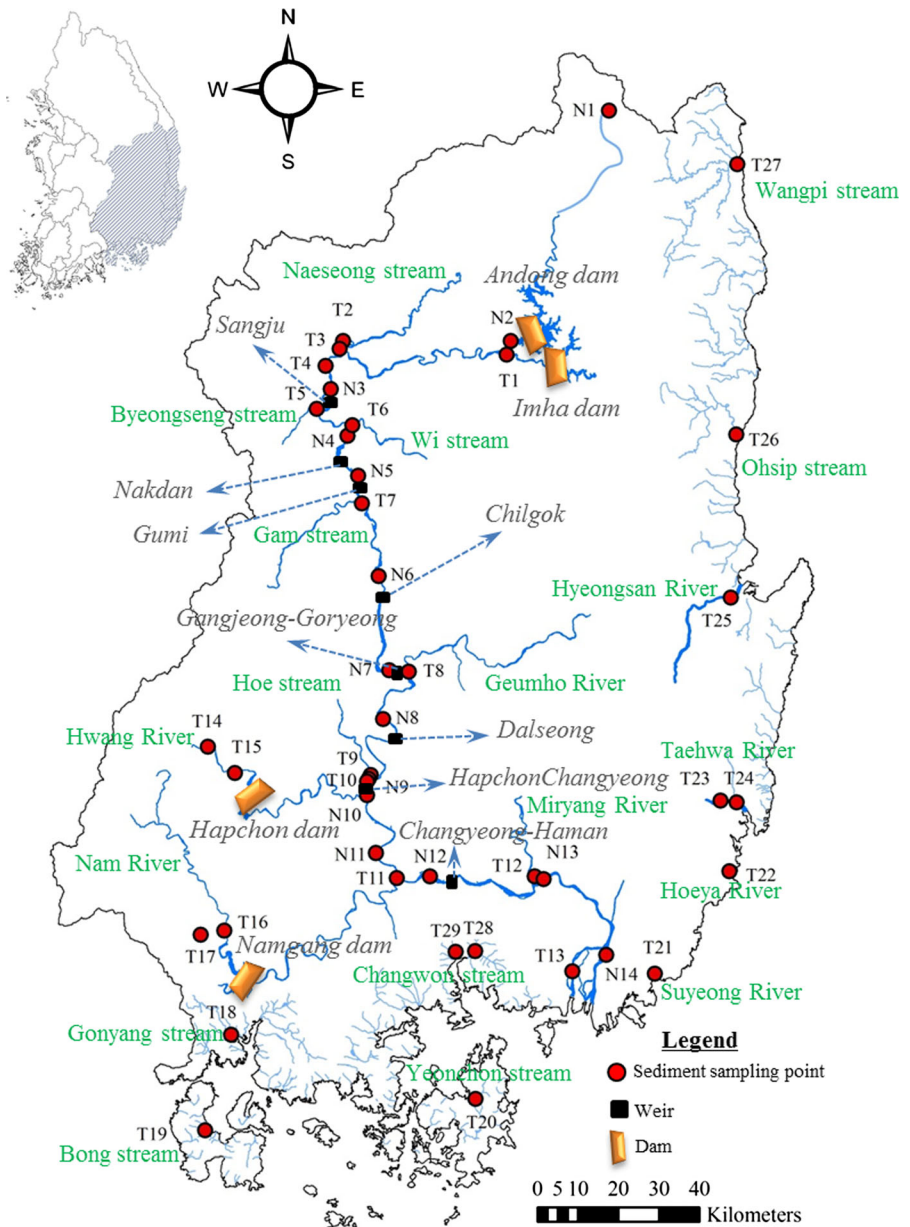
Heavy metals were pretreated with nitric acid (HNO₃; Kanto chemical, Japan, 60%), perchloric acid (HClO₄; Junsei, Japan, 70%), and hydrofluoric acid (HF; Fluka, Germany, 47–51%), order in parentheses (manufacturer, country, concentration). Every analysis procedure and method used in this study conformed to the process test for rivers sediments for water pollution prepared by the National Institute of Environmental Research (MOE 2012).

Assessment of sediment pollution

The background concentration of sediments is essential to assess sediment pollution. The global average concentration of metals, as reported by Taylor (1964) and Onyari et al. (2003), was considered as the background value in the computations. This study adopted the background values of river sediments, proposed by the NIER (National Institute of Environmental Research (NIER) 2011): 50.2 mg/kg for Pb,

215 mg/kg for Zn, 43.9 mg/kg for Cu, 83.3 mg/kg for Cr, 39.3 mg/kg for Ni, 14.9 mg/kg for As, 0.4 mg/kg for Cd, 0.065 mg/kg for Hg, and 54 mg/kg for Li.

In this study, PLI, RI, the mPELQ, and CCME SeQI are recommended as indicators of heavy metal contamination. The PLI can be used to collect the total pollution level at a site by combining the concentration of heavy metals with the background concentration. The RI can determine the degree of toxic contamination caused by each heavy metal. The mPELQ is a method for determining the extent to which heavy metals in sediments impact living organisms. The CCME SeQI is a method of assessing sediment contamination graded using the Canadian PEL criteria. In summary, these four pollution assessment methods consist in the evaluation of heavy metal concentrations, the evaluation of toxic reactions, the assessment of risks affecting organisms, and a graded evaluation using sediment environmental standards.

Pollution load index (PLI)

The pollution load index (PLI) is used to comprehensively evaluate the pollution load of heavy metals. This study used eight heavy metals (mentioned above) for this calculation. The PLI is calculated by obtaining the n-root from the n-CFs for all metals (Soares et al. 1999). The CF is the quotient obtained by dividing the concentration of each metal. PLI > 1 shows that the sediment is polluted, whereas PLI < 1 indicates no pollution (Harikumar et al. 2009). The PLI was developed by Tomlinson et al. (1980) and is calculated using Eq. (2).

$$\text{PLI} = n\sqrt{\text{CF}_1 \times \text{CF}_2 \times \cdots \times \text{CF}_n} \tag{2}$$

where CF is the contamination factor and n is the number of metals.

Potential ecological risk index method (RI)

Hakanson (1980) proposed a potential ecological risk index method (RI) to assess the effect of multiple-metal pollution in sediments found upstream of the water sources. RI can be calculated using Eq. (3).

$$\text{RI} = \sum_{i=1}^{n} \left(T_i \times \frac{C_i}{C_o} \right) \tag{3}$$

where T_i is the toxic-response factor for a given substance (Pb = 5, Zn = 1, Cu = 5, Cr = 2, Ni = 5, As = 10, Cd = 30, Hg = 40), C_i represents the metal content in the sediments; and C_o is the regional background value of heavy metals in the sediments. Based on the RI values, water quality is classified into four levels: low ecological risk (RI < 150), moderate ecological risk (150 < RI < 300), considerable ecological risk (300 < RI < 600), and very high ecological risk (RI > 600).

Mean PEL quotient

Igeo and PLI can evaluate the pollution levels of individual and all heavy metals, but they cannot identify the impact of heavy metals in sediments on freshwater organisms. The mean PEL quotient (mPELQ) is used to comprehensively evaluate the toxic effects and risks of heavy metals in sediments. mPELQ is calculated using Eq. (4) (Fairy et al. 2001; Hwang et al. 2008). The values of Smith et al. (1996) were used as the PEL values of heavy metals in river sediments.

$$\text{Mean PEL Quotient} = \left(\sum \frac{C_i}{\text{PEL}_i} \right) \Big/ n \tag{4}$$

where C_i and PEL_i are the concentration of each heavy metal and the PEL value proposed by Smith et al. (1996), respectively, and n is the number of trace metal elements. This study used eight elements, for which there are standard PEL values. mPELQ < 0.1 indicate that there is no toxic effect, mPELQ between 0.1 and 1.0 indicate a slight toxic effect, and mPELQ > 1.0 indicate a significant toxic effect (Fairy et al. 2001).

CCME SeQI

PLI, RI, and mPELQ can produce a comprehensive assessment of pollution levels in sediments for diverse pollutants. However, these methods evaluate the pollution in the sediments and determine their toxic effects. Accordingly, the water quality index proposed by the Canada Council of Ministers of the Environment (CCME 2002) was used for the qualitative assessment of sediments, because the index can identify the concentrations of different pollutants and compare them with a sediment management standard. The sediment quality index (SeQI)

calculator was developed for the CCME by the Western Newfoundland Model Forest with support from Environment Canada and was finalized by the CCME Water Quality Task Group. The interim sediment quality guideline (ISQG) value (Pb 50,000, Zn 200,000, Cu 65,000, Cr 80,000, Ni 21,000, As 20,000, Cd 1500, Hg 150 µg/kg), proposed by the Australian and New Zealand Environment and Conservation Council (2000), was used to calculate the sediment quality index (SeQI). Equations (4)–(9) show the steps involved in the calculation of SeQI (CCME 2007), based on equations from the original water quality index (WQI) (CCME 2002). The F1 (scope) factor can quickly overpower the index. When 10–30% of the variables consistently exceed the guidelines, the SeQI may misrepresent the quality of the lake or area. The SeQI yields a lower score for the area when many variables fail at one site than when one or a few variables fail at every site. Other factors (F2 frequency; F3 amplitude) may also skew the results. Users should, therefore, use their knowledge and good judgment in the application of the results.

$$F_1 = \left(\frac{\text{Number of failed contaminants}}{\text{Total number of contaminants}}\right) \times 100 = \text{Scope} \tag{5}$$

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right) \times 100 = \text{Frequency} \tag{6}$$

$$F_3 = \left(\frac{\text{ase}}{0.01\text{ase} + 0.01}\right) = \text{Amplitude} \tag{7}$$

$$\text{ase} = \frac{\sum_{i=1}^{p} \text{excursion}_i}{\# \text{ of failed tests}} \tag{8}$$

$$\text{Excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Guideline}_i}\right) - 1 \quad \text{or} \quad \left(\frac{\text{Guideline}_i}{\text{Failed test value}_i}\right) - 1 \tag{9}$$

$$\text{CCME SeQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \tag{10}$$

where ase is the mean degree of noncompliance, I is the individual guideline, and P is the total number of guidelines used. Based on the CCME SeQI values, water quality is categorized into five levels: very poor (0–44), poor (45–59), fair (60–79), good (80–94), and excellent (95–100) (Garpentine et al. 2002; Marvin et al. 2004).

Sediment ecotoxicology assessment

The PLI, RI, and CCME SeQI assess the individual and overall degree of heavy metal pollution, but are limited, as they are unable to determine if heavy metals in sediments affect living organisms. Hence, a sediment ecotoxicology assessment is required to determine the comprehensive toxic influence (or risk) of heavy metals in sediments. The method proposed by the American Society for Testing and Materials (ASTM 2005) was used for the *H. azteca* sediment toxicity test to assess the ecotoxicological influence of stream sediments on *H. azteca*. The test involved exposing the amphipod larvae to sediments for 10 days, then determining the number of surviving species. This was then compared to the survival rate of the control group to determine toxicity. The sensitivity test involved introducing cadmium at different concentrations to culture water, exposing the amphipod larvae to this mixture for 4 days, then calculating the 50% lethal concentration. Cadmium chloride ($CdCl_2$, Sigma, USA) was used for the toxicity test and the test method was conducted according to ASTM (2010). Quality control included changes in water quality during exposure time (QA), suitability of the test water and test chamber (QA), and the health of organisms and sensitivity changes (QC). The Probit method (ToxCalc®) was used for the statistics program, the 50% lethal concentration (LC50) was 18.0 µg/L, and the 95% confidence interval was 14.7–21.5 µg/L.

The *H. azteca* toxicity test conditions were as follows: the test period, temperature lighting type, photoperiod, and illumination were the same as the sensitivity test conditions. The test chamber was a 300-mL plastic container, sediment volume was 100 mL, and the culture water volume was 175 mL. Culture water was changed daily to twice the culture water volume, and the population for each beaker was 10. The test was repeated four times for each test group. Test specimen was 7–14 days old, 1-mL of YCT was fed to the *H. azteca* specimens daily, in the absence of aeration. Water quality was evaluated by measuring the hardness, pH, and ammonia concentration once before and once after the test, and temperature and dissolved oxygen were measured daily. The

final measurement value was survival rate, and observation of the dead specimen was performed after the end of exposure. Test suitability was when the control group survival rate was 80% or higher, and when water quality, sensitivity, and other suitability conditions were met.

Results and discussion

Distribution of heavy metal concentrations in the Nakdong River

Figure 2 shows the distribution of concentrations of the eight heavy metals studied in this paper. Samples were collected from surface sediments at 38 points in the streams of the Nakdong River system in 2015. The kriging method, one of the integral spatial interpolation methods in the Arc-GIS program, was used to determine the distribution. This method calculates a "minimum variance best linear unbiased estimator" for a nearby area based on the following statistical concept: The expectation for the difference between the estimated and actual values should be zero and, at the same time, the variance for the difference should be the smallest.

As shown in Fig. 2, Pb has a concentration range of 17.73–52.23 mg/kg, and its concentration is particularly high in the upper region of the Andong Dam. Zn has a range of 88.40–266.20 mg/kg, with the highest concentration found in the joint area between the upper region of the Andong Dam and the Geumho River. Cu has a range of 7.57–92.09 mg/kg, with the highest concentration found in the joint area of the Geumho River. Cr concentrations ranged between 44.90 to140.54 mg/kg, with the highest concentration recorded at the T18 site. Ni concentrations ranged from 6.64 to 63.59 mg/kg, with the largest concentration recorded at the joint area of the Geumho River. As and Cd concentrations ranged from 3.08 to 44.40 mg/kg and 0.15 to 2.41 mg/kg, respectively, and the highest concentrations of both elements were found in the upper region of the Andong Dam. The concentration range of Hg was 0.01–0.66 mg/kg, with the highest concentrations found in the T28 and T29 sites. The concentrations of heavy metals at each sampling point can be used to determine the target elements for priority management in the area.

The concentrations of Pb, Zn, As, and Cd were high at points N1 and T27 in the study area. These results are thought to be the influence of metals leaking from abandoned mines located in the upper part of the Nakdong River. The concentration of heavy metals in the mid-Nakdong River, where Zn, Cu, and Ni concentrations are high, is believed to be due to the influx of the Geumho River, the largest tributary of the Nakdong River. The Geumho River flows through Daegu Metropolitan City, the third largest city in Korea, with a large population and several factories.

Sediment pollution assessment

Figure 3 illustrates the evaluation of sediment pollution using PLI. PLI values over 1.0 occurred at N1, T8, N8, T21, and T29. N1 is located in the upper region of the Andong Dam. The tailing of 50 abandoned metal mines in the upper region of the Andong Dam has been washed out by heavy rains and typhoons, and mine water subsequently flowed into the river. T8 and N8 are on the Geumho River, which flows through Daegu and passes through many industrial complexes. The river at site N8 receives a continuous inflow of sediments from the Geumho River. The river at point T21 flows through Busan, the second largest city in South Korea, and also passes through many industrial complexes; T29 passes through Changwon-si, where many industrial complexes are also located. Except in N1, PLI values were high at the end of the streams flowing through big cities with industrial complexes. This result was also obtained from the RI values indicating ecological risk (Fig. 4). N1 and T21 showed "moderate ecological risk" and T28 and T29 showed "considerable ecological risk." At every point, mPELQ, which evaluates the toxic characteristics, suggested a "slight toxic effect" (Fig. 5). Figure 6 shows the result of the CCHE_ SeQI analysis. At N1, T8, N8, T19, and T21, the CCHE_SeQI value was below 70 (poor and fair).
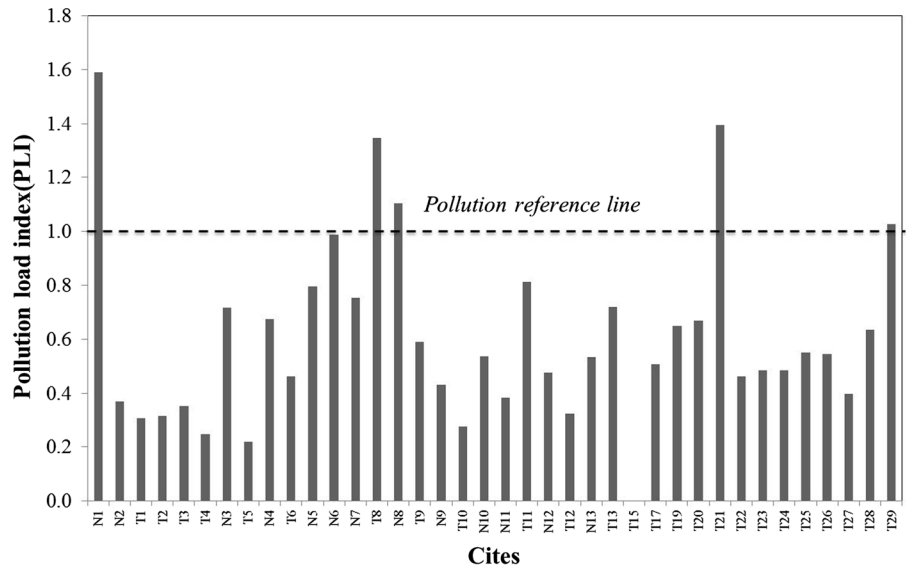
In this study, sediment pollution assessment using the PLI, the five points of the 29 points was found to be contaminated. According to a study by Ghosh et al. (2019), a study in the Hooghly-Matla estuarine region of India showed a PLI ranging from 1.5 to 2.5. All the sites that performed the study were found to be contaminated. It is concluded that the contamination by heavy metals is higher than the Nakdong River watershed in this study area.
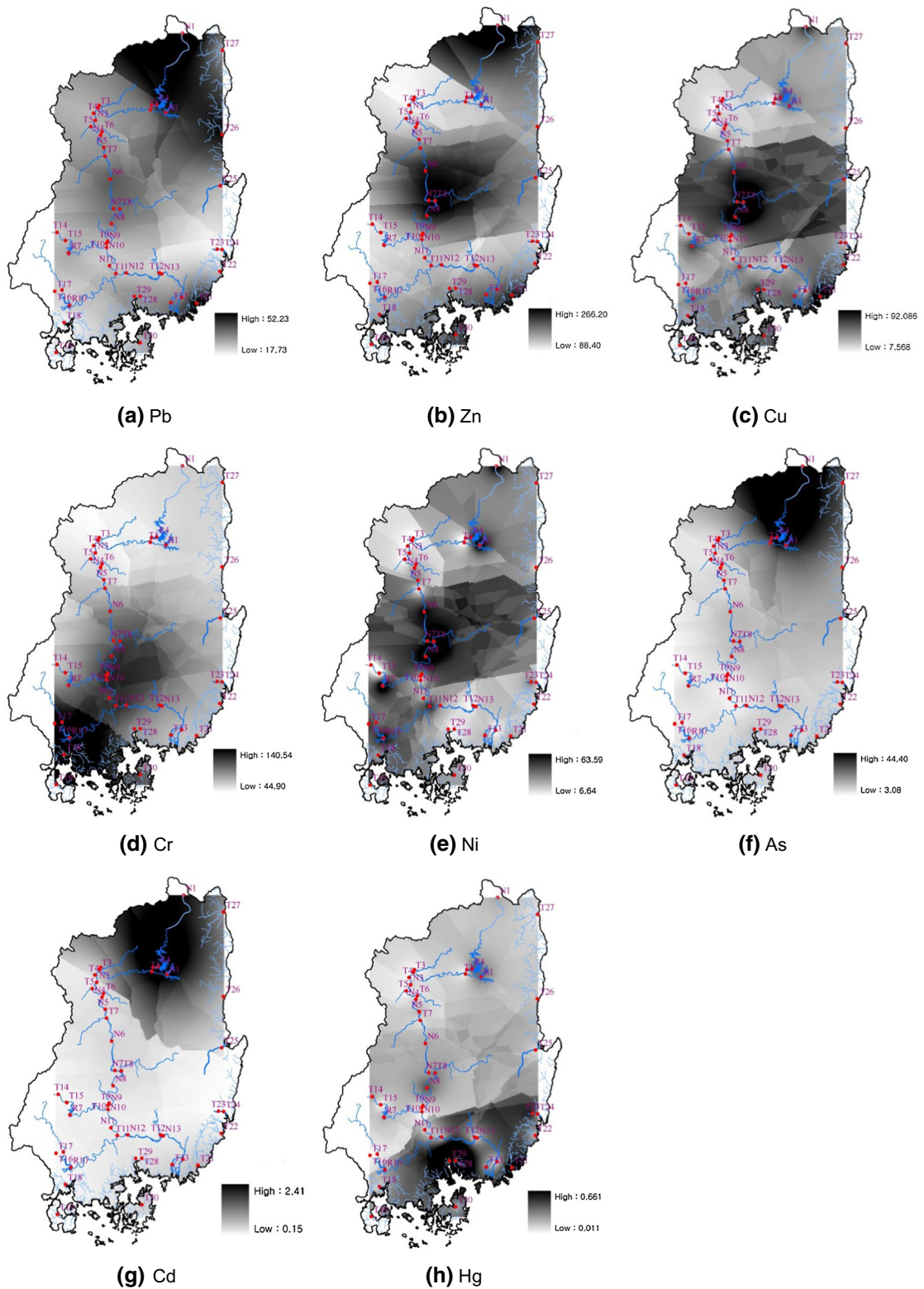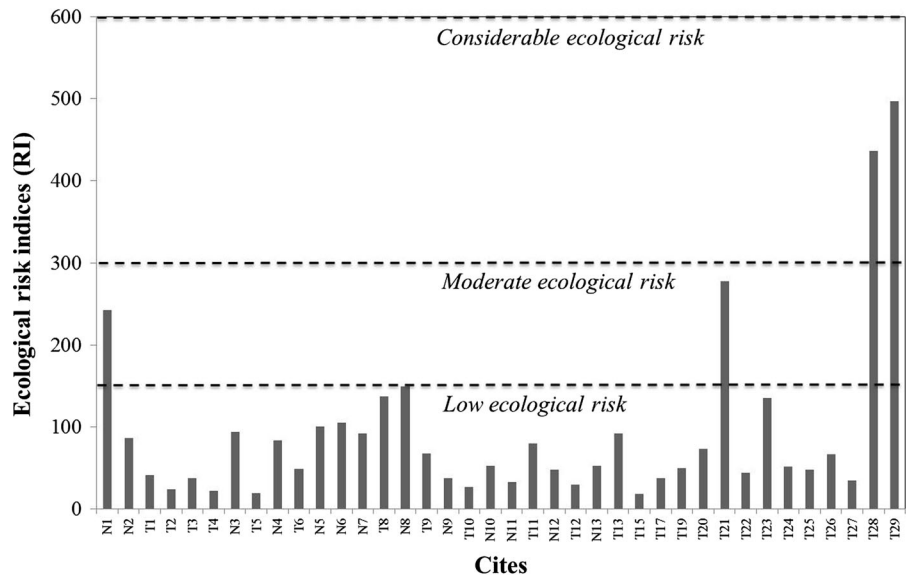
Fig. 2 Distribution of heavy metals in sediments of the Nakdong River

Fig. 3 Pollution load index (PLI) of heavy metals in surface sediments from the Nakdong River


Fig. 4 Ecological risk indices (RI) of heavy metals in surface sediments from the Nakdong River

According to a study by Looi et al. (2019), sediment pollution assessment using the RI showed that one of the 48 sites was "moderate ecological risk" and the rest was "low ecological risk." In the Nakdong River watershed, two points are considered as "moderate ecological risk" and two points are considered as "considerable ecological risk," which means that the RI value of surface sediments in the Nakdong River watershed is higher than the west coast of Peninsular Malaysia.

PLI, RI, mPELQ, and CCHE_SeQI were used to evaluate the comprehensive pollution levels of eight heavy metals at each site. When the results for these indices were compared, there was a difference in the pollution levels at each site; the same sites were identified as requiring priority management. This method of analysis and evaluation of heavy metals is useful for policymakers in determining priority management areas. Therefore, the ecotoxicology assessment for N1, T8, N8, T19, T21, T28, and T29, which

Fig. 5 Mean PEL quotient (mPELQ) of heavy metals in surface sediments from the Nakdong River
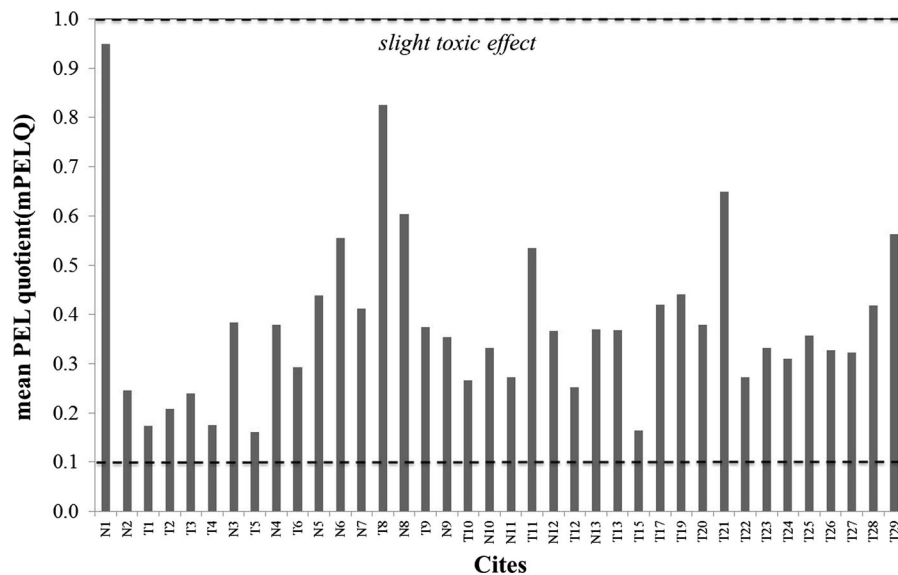
were sites characterized as considerably contaminated by the comprehensive sediment pollution assessment (using PLI, RI, mPELQ, and CCHE SeQI), was performed.

Sediment ecotoxicology assessment

In this study, ecotoxicology was assessed for sediments at N1, T8, N8, T19, T21, T28, and T29. The *H. azteca* sensitivity test conditions were identical to that of the culture water toxicity test, the test period was four days, the reference toxic substance was cadmium chloride (Sigma Aldrich), and the concentration grade was 0 (control group), 3.13, 6.25, 12.5, 25, and 50 μg/L. Temperature was 23 ± 1 °C, the lighting type was fluorescent light, the photoperiod was 16:8 (L/D), illumination was 100–1000 lx, the test chamber was a 250-mL beaker, the culture water volume was 100 mL, the culture water was not changed, and the population for each beaker was 10.

The test was repeated four times for each test group, the test specimen size was 7–14 days old, specimens were fed 0.5 mL of YCT 0 on day 0 and day 2, the substrate was a 0.7-mm screen, there was no aeration, water quality was verified by measuring the hardness, pH, dissolved oxygen, and ammonia concentration once before and once after the test, and temperature was measured daily. The final measurement value was survival rate, observation of the dead specimen was

performed 24, 48, 72, and 96 h after exposure, and test suitability was when the control group survival rate was > 90%.

Table 1 shows the results of the ecotoxicology test. The control group survival rate was 100% for the sediment test at the end of exposure; thus, it was over the suitability standard of 80%. Survival rate was 90-100% at N1, N8, T28, and T29, but was below 67.5% at T8, T19, and T21, and only 25% at T8. To determine toxicity, the significance probability was set to $p < 0.05$, with a survival rate of less than 80%. Results indicated that sediments at N1, N8, T28, and T29 were not toxic but those at T8, T19, and T21 were. According to the ecotoxicology assessment results for N1, N8, T28, and T29 (classed as considerably contaminated by the sediment pollution assessment), because sediments were not found to be toxic, an ecotoxicology analysis must be conducted in addition to the sediment pollution assessment. Because heavy metal concentrations were high at N1, the sediment pollution assessment also showed considerable pollution. However, this may be a result of exhausted mines upstream, as well as tailings around the sediment extraction point.

Furthermore, because sediments were found to be toxic at T8, T19, and T21 (which all had lower pollution levels than N1 but were still polluted), the level of pollution must be verified by expanding the analysis range both upstream and downstream. Site T8
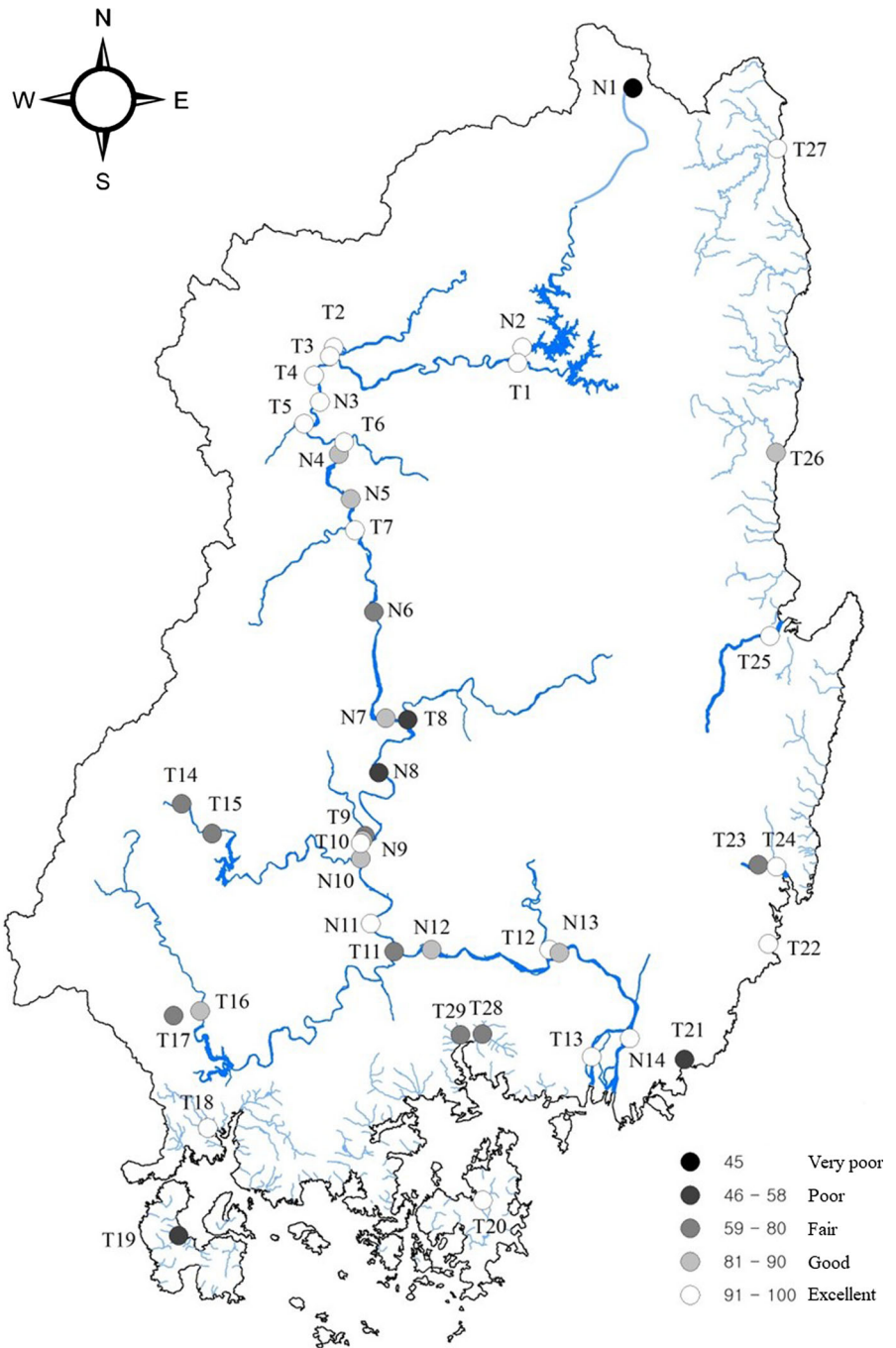
is located at the estuary of the Geumho River, the largest tributary of the Nakdong River, which is known as a major urban stream that was severely polluted in the 1980s–1990s. The 2014 water quality analysis results show that water quality improvement was extremely high (98.1%), reflecting continuous water quality improvement policies. This study highlights the need for additional improvement measures that specifically address sediments.

Table 1 *H. azteca* ecotoxicology test results

Location	Survival rate % (average ± standard deviation)	Significance probability	Toxicity
N1	100 ± 0	1.000	X
T8	25.0 ± 17.3	0.000*	O
N8	100.0 ± 0.0	–	X
T19	67.5 ± 12.5	0.000*	O
T21	12.5 ± 12.5	0.000*	O
T28	90.0 ± 8.1	0.968	X
T29	100 ± 0.0	1.000	X

*($p < 0.001$) Toxicity assessment was performed if significance probability was less than 0.05 and survival rate was less than 80%

Conclusions

In this study, we propose that priority management rivers should be selected using pollutant indicators and additional toxicity tests. We present a comprehensive evaluation of sediment pollution at 38 locations in the Nakdong River in South Korea and used toxicity tests to show that high heavy metal pollution does not necessarily lead to a toxic ecosystem environment.

1. The comprehensive assessment of heavy metal pollution levels by PLI, RI, mPELQ, and CCME SeQI showed that sites N1, T8, N8, T19, T21, T28, and T29 had relatively high sediment pollution levels and thus demanded preferential management.

2. Toxicity tests results found no toxicity that might influence the ecosystem at N1, N8, T28, and T29. However, the *H. azteca* survival rate was ≤ 67.5% at T8, T19, and T21, which implies that the sediments are toxic enough to impact the ecosystem. Therefore, sites T8, T19, and T21 require preferential management.

3. High contaminant concentrations do not necessarily lead to negative impacts on humans and the ecosystem. Contaminants that influence humans and the environment as the source of pollution and the flow path have organic correlations with humans, soil, water sources, the ecosystem, and other affected mediums. Hence, a comprehensive pollution assessment must be performed, based on various quantitative assessments such as ecotoxicology analysis, sediment leaching tests, or sequential extraction procedures, in addition to a sediment pollution assessment based on sediment analysis results.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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