KSCE Journal of Civil Engineering (2020) 24(4):1060-1069
DOI 10.1007/s12205-020-2059-x

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Environmental Engineering

Selection of Priority Tributaries for Point and Non-Point Source Pollution Management

Jung Min Ahn [a] **and Siwan Lyu** [b]

[a]Member, Water Quality Assessment Research Division, Water Environment Research Department, National Institute of Environmental Research, Incheon 22689, Korea
[b]Member, Dept. of Civil Engineering, Changwon National University, Changwon 51140, Korea

ARTICLE HISTORY

Received 14 November 2019
Revised 2 February 2020
Accepted 5 February 2020
Published Online 11 March 2020

KEYWORDS

Tributaries
River management
Watershed
Water quality index
Principal component analysis
Non-point source pollution model

ABSTRACT

The Korean Ministry of Environment has established management policies for four major rivers; these policies include plans to restore ecosystems and manage hazardous materials and non-point source pollution in the watersheds. The purpose of this study was to select priority tributaries in the Nakdong River basin for immediate management under these plans by using water quality index (WQI), principal component analysis (PCA), and non-point source pollution modeling data. First, comprehensive water pollution was assessed for 22 sub-basins in the Nakdong River basin by using a WQI. Seasonal pollution was then categorized as either point or non-point source by using the PCA results based on observed water quality data, and lastly, a distributed model was developed to analyze non-point source pollutant loads. This allowed for an assessment of the degree of potential non-point source pollution from several land cover types and the selection of basins where such pollution should be managed on a priority basis. Four sub-basins (Nos. 12, 13, 19, and 21) were found to have high pollution levels, and sub-basin No. 12 had the highest non-point loading. As a result of this comprehensive basin assessment, the Geumho River was selected as the first priority tributary for management. The approach applied in this study should be useful for future efforts to develop effective strategies to improve water resources in river basins.

1. Introduction

As part of a comprehensive long-term plan for water resource management and aquatic ecosystem conservation, Korea mandated 10-year official plans for the management of four major rivers during the period 2006 – 2015, and comprehensive measures were established for the implementation of these plans. Under the plans, new concepts and directions for basin management involving strategies such as total pollution load management, water usage fees, and water-pollutant buffering zones were promoted. Over the past 20 years, a variety of policies have been implemented to manage aquatic environments for long-term water quality enhancements and aquatic ecosystem conservation. In 2006, the Ministry of Environment established the Water Environment Management Basic Plan ('06 – '15), which reinforced the existing basin management policies for the four major river basins and established planning measures to guide the restoration of the ecosystems and manage hazardous materials and non-point pollution sources.

Improvements in the water quality of the mainstream of a river require that the water quality of its tributaries be improved first. There are 785 known tributary streams in the Nakdong River basin, which account for approximately 82% of the total basin area. These are managed through total pollution load management techniques that establish legal biochemical oxygen demand (BOD) and total phosphorus (TP) targets that are used to maintain the overall target water quality level at the end of the 41 sub-basins; such an approach also stimulates regional environmental developments. However, it is difficult to accurately assess the water quality of rivers by using only two indicators; importantly, comprehensive assessments of various water quality features of the tributaries, rather than assessments based on only a few features in and near the mainstream, can lead to a more accurate understanding of the river water quality. This can be done by

CORRESPONDENCE Jung Min Ahn ahnjm80@gmail.com Water Quality Assessment Research Division, Water Environment Research Department, National Institute of Environmental Research, Incheon 22689, Korea

using water quality indexes (WQIs), which are actively being introduced in several countries. A WQI can be used to comprehensively assess water quality without distinguishing between point and non-point sources of pollution by taking into account several water quality indicators.

Point and non-point sources of pollution account for 67.8% and 32.2%, respectively, of all water pollution in Korea (Ministry of Environment, 2006). As point sources occur at specific points, the pollutant discharge points, pollution paths, and pollutant loads can be measured easily. The term non-point sources refers to pollutants that are largely discharged through precipitation induced surface runoff and atmospheric deposition directly into the river system, and these represent irregular sources of pollution in urban, farmland, and mountainous areas. The proper management of these sources can improve aquatic environments dramatically and is necessary for achieving water quality standards. The Water Environment Management Basic Plan ('06 – '15) reported that point sources of pollution are decreasing largely because of the expansion of measures to manage them, but it is expected that the proportion of non-point sources of pollution will increase relatively significantly if proper measures are not taken to manage these sources as well. Non-point sources of pollution accounted for approximately 68% of the river discharge load in 2010 and are expected to continue to increase. In 2012, the occurrence of algal blooms was mainly attributed to pollutants from non-point sources.

To properly manage non-point sources of pollution, it is necessary to characterize the runoff in a systematic manner, first by selecting survey targets in each basin or region and then by conducting long-term field surveys. Uncertainty should be reduced by identifying the status of non-point sources of pollution over a long period and monitoring runoff from different land uses. To meet the quantification and reproducibility requirements, the loads must be simulated by using a numerical model. Ahn et al. (2017) evaluated the changes in water quality in lower reaches due to the co-management of a dam and a multifunctional weir on the Geum River, and they found that the quality of the water in the mainstream was relatively poor due to the influx of pollution, including that from non-point sources from the tributaries. The water quality did not improve, and in fact worsened, when the flow produced by the co-management of the dam and weir was discharged downstream. Therefore, it is necessary to manage the water quality in the tributaries to improve the water quality of the mainstream. The limitations on costs and labor for this task require the selection of tributaries that should be managed on a priority basis.

In this study, we attempted to identify priority tributaries that should be managed first through the use of WQI, principal component analysis (PCA), and non-point load evaluation data. In order to evaluate the non-point loads, we developed a distributed model that considers both rainfall-runoff and event mean concentrations (EMCs). The total water pollution for 22 sub-basins was assessed by using the WQI established according to total pollution loads. The WQI was derived as a single value, with no distinction between point and non-point pollution sources. However, it is necessary to analyze whether a pollution source is a point or non-point source to manage the pollution appropriately. Hence, PCA was used to assess the observed data and determine whether pollution came from a point or non-point source. The order of water pollution was evaluated by the WQI and the order of occurrence of non-point loads was evaluated by the developed distribution model. This allowed for an assessment of the runoff characteristics and pollutant loads and the selection of basins in which point and non-point pollution sources should be managed preferentially.

2. Materials and Methods

2.1 Study Area

The Nakdong River, which is 511.01 km long, has a basin area of 23,702.02 km^2; it is the longest mainstream in Korea and the one with the largest basin area (Water Resources Management Information, 2018). There are agricultural activities in its upper reaches, industrial activities including the presence of metropolises in the middle river, and complex human activities including agriculture and industry in the lower river region (Park et al.,

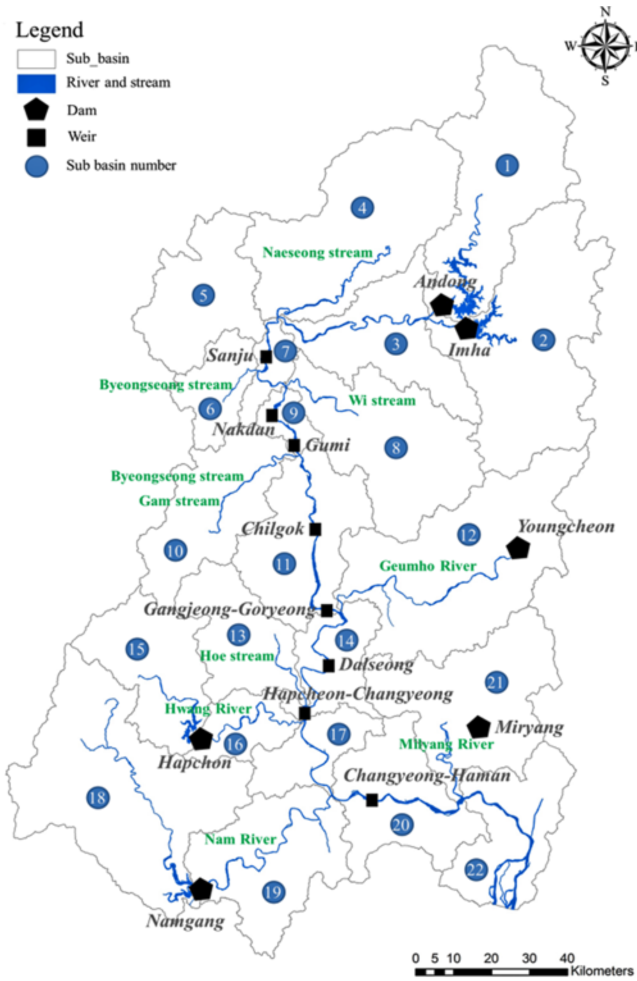

Fig. 1. The Study Area

2001). In Korea, water quality management is carried out by the establishment of target BOD and TP criteria for the estuaries of sub-basins within the total maximum daily load management program. Target water quality criteria in this area have been established based on TP since 2011, and from 2004 – 2011, the criteria were based on the BOD. Total pollution load management is based on both of these indicators. Fig. 1 shows the 22 sub-basins that were used to assess the water quality, in which the Nakdong River Environment Research Center has monitored the water quality every eight days since 2004.

2.2 Evaluation of River Pollution

2.2.1 Water Quality Index

A WQI presents the water quality data as an index number that represents the overall quality of water for any intended use and is defined as a rating that reflects the composite influence of different water quality parameters. These have been formulated by researchers from all over the world, for example, the U.S. National Sanitation Foundation Water Quality Index, Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), British Columbia Water Quality Index (BCWQI), and Oregon Water Quality Index (Sharifi, 1990; Abbasi, 2002; Lumb et al., 2006; Kannel et al., 2007); such data can be used to easily assess the overall water quality in a particular area in a prompt and efficient manner. Tirkey et al. (2015) investigated studies that used a WQI and compared the advantages and disadvantages of each formula; the work showed that these WQIs are frequently used for water quality assessments. Recall that WQI data represent both point and non-point sources of pollution. Research has shown that the CCME and BCWQI can be efficiently used even if the number of water quality indicators is small; therefore, in this study, we used a similar WQI method.

The WQI in this study was calculated by using the seven water quality parameters shown in Table 1. The range was set according to the current situation in Korea by referring to the values in the existing CCME documents (CCME, 2001).

The WQI was calculated by using factors F_1, F_2, and F_3, as shown in Eq. (1) below. F_1 is the result of dividing the number of water quality parameters that violated the reference value by the total number of water quality parameters measured; F_2 is the result of dividing the total number of parameters that violated the reference value by the total number of measurements of each water quality parameter taken during the measurement period; and F_3 is the sum of the factors that fractionalized the degree of the reference value for each water quality parameter.

$$WQI = 100 - \sqrt{\frac{F_1^2 + F_2^2 + F_3^2}{3}} \quad (1)$$

Table 1. Appropriate Criteria for Water Quality Factors

Water quality parameters	Range
Dissolved oxygen (DO)	$8 \le DO$
Biological oxygen demand (BOD)	$BOD \le 3$
pH	$6.5 \le pH \le 9.0$
EC (Electrical conductivity)	$EC \le 200$ µS/cm
Total organic carbon (TOC)	$TOC \le 3.0$ mg/L
Total nitrogen	$T-N \le 3.0$ mg/L
Total phosphorus	$T-P \le 0.1$ mg/L

2.2.2 Principal Component Analysis

The basic idea of PCA is to reduce the dimensionality of a data set containing a large number of correlated variables. The analysis is performed by transforming the variables into a new set of variables, which are known as the principal components (or simply, the PCs), and these PCs are orthogonal and ordered such that the retention of variation present in the original variables is decreased.

Because certain correlations exist among multiple indicators, a PCA attempts to transform a large set of inter-correlated indicators into a smaller set of composite indicators, i.e., the uncorrelated (orthogonal) variables called PCs, and this simplifies the structure of the statistical analysis system (Jianqin et al., 2010).

The direction of the arrows (water parameters) represents the largest direction in which the parameters changed, as shown in Fig. 8. The longer the arrow, the greater the effect on site characteristics; each arrow can be extended all the way through the origin. Therefore, a projected point or red circle at or beyond the end of the arrow has a strong positive correlation with the environmental variable that the arrow represents and is influenced by environmental variables. Sites with projections near the origin are less affected by the corresponding variable.

In the present study, PCA was applied to determine the extent to which the monthly observed water quality at each survey point was affected by point or non-point sources or pollution.

2.3 Evaluation of Non-Point Pollution

Techniques to research non-point sources of pollution include analyses of low impact development, load duration curves, application of treatment devices, estimations using a rainfall-runoff model, and EMCs; the present study used a combination method involving rainfall-runoff modeling and EMCs. Effective rainfall was calculated by using the runoff curve number (CN) method developed by the Natural Resources Conservation Service (NRCS). In order to calculate the non-point pollution load reflecting the characteristics of runoff, the EMC was applied, and the model was developed as a grid-based basin runoff analysis program (based on Fortran 90) to estimate the loads for different land cover types. The runoff and contributions to non-point pollution loads were calculated according to unit basins and land cover types. The results were used to select the basins to be managed on a priority basis for non-point sources of pollution.

2.3.1 Development of the Model

Hydrological models can be divided into centralized types such as the Hydrological Simulation Program: FORTRAN (HSPF) (Lumb et al., 1994), the Soil and Water Assessment Tool (SWAT) (U.S. EPA, 2001), and the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army Corps of Engineers, 1976), and distributed types such as the European Hydrological System Model (MIKE-SHE) (Abbott et al., 1986), CASC2D (Julien et al., 1995; Johnson et al., 2000), GSSHA (Gridded Surface/ Subsurface Hydrologic Analysis) (Downer and Ogden, 2003), and Vflo (Vieux and Vieux, 2002). Tegegne et al. (2017) reviewed the differences in watershed-scale models in terms of the spatial basis used such as lumped, semi-distributed, or distributed models, and they discussed the best hydrological modeling approaches among the lumped and physically-based semi-distributed hydrological models for the assessment of surface water resources in a data-limited environment by using a more comprehensive model comparison approach. Centralized models divide a basin by using hydrologic response units, grouped response units, and elevation bands. They also have fast stimulation times and have been applied in many cases worldwide by several users. However, these models require long-term observation data and empirical formulas. Because stimulations according to sub-basin units and runoff points are possible, these models can reflect the ratio of basin lag times for runoff through hydrologic channel routing at each runoff point. On the contrary, distributed models divide a basin based on a grid, and data are compared with an unmeasured basin region, thus enabling analyses of all the points within the basin, and this minimizes user interference; however, such an approach requires a significant amount of analysis time. One of its greatest advantages is that it can reflect changes in the arrival time as non-point pollutant loads generated from the basin slope move into the mainstream, which is an issue that has been consistent mentioned in the analyses of non-point sources of pollution. In addition, since movement between the grids can be identified, the movement path, quantity, and velocity of the pollutants can be derived and understood in a visual manner.

We have developed a program that can calculate the runoff and non-point pollutant loads by operating control, rainfall, and input files, and the result file was derived so that the contribution rate and the load result for each land cover type did not require additional processing. As a governing equation for the analysis of runoff, the CN developed by the NRCS was used to estimate infiltration and effective rainfall and to analyze the direct runoff. Based on the analyzed runoff, the pollutant load was estimated per land cover type by using EMCs, and the contribution rate per land cover type was also evaluated. Furthermore, when rainfall occurs the non-point pollutants on roads flow into rivers with the rainfall runoff. Therefore, because the total load generated during rainfall events is important, EMCs are very useful and have been used widely to analyze the characteristics of non-point pollutants from runoff (Choi et al., 2009; Moon et al., 2014).

The CN method has been widely used to estimate direct runoff based on the relationships among rainfall, land use, and hydrologic soil groups. The hypothesis of the CN method is that the ratio of actual retention in the watershed to the potential maximum retention is consistent with the ratio of actual direct runoff to the potential maximum runoff (USDA, 1985; Chow et al., 1988), and this is indicated by:

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{2}$$

where F_a is the actual retention in the watershed (excluding I_a), P is the precipitation, P_e is the actual direct runoff, S is the potential maximum retention determined by Eq. (2), and I_a is the initial abstraction before ponding. The total precipitation (P) equals the sum of the actual direct runoff (P_e), the initial abstraction before ponding (I_a), and the actual retention in the watershed (F_a). Thus, the runoff equations are:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{for} \quad P > I_a = 0.2S \tag{3}$$

$$P_e = 0 \quad \text{for} \quad P = I_a = 0.2S \tag{4}$$

$$S = \frac{25400}{CN} - 254 \tag{5}$$

Figure 2 shows the land use types and hydrologic soil group of each basin derived by using Arc-GIS (Geographic Information System), and these data were combined to obtain a grid-type NRCS-CN. The CN value was recognized by the dynamic array based on the number of grids in directions I and J, as defined by the user. Effective rainfall was calculated by using the I and J arrays, and the non-point pollutant load was calculated according to the EMCs. Based on the long-term hydrologic impact assessment (L-THIA) of estimated direct runoff, pollutant loadings for non-

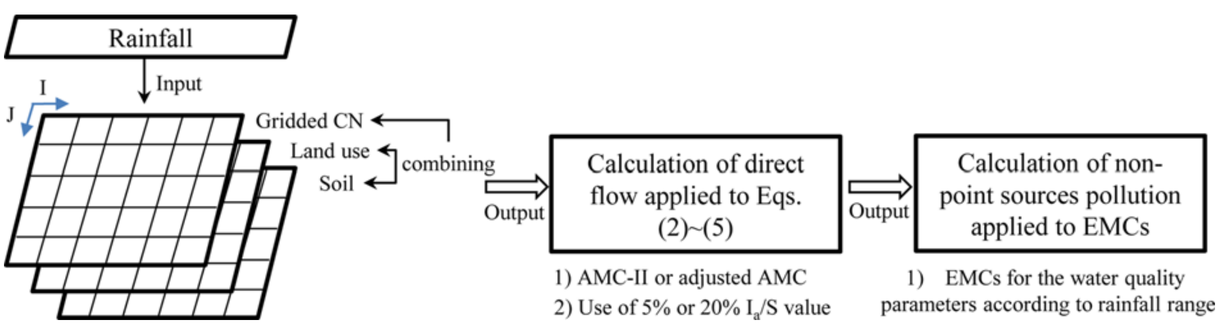

Fig. 2. Overview of the Method Used in This Study

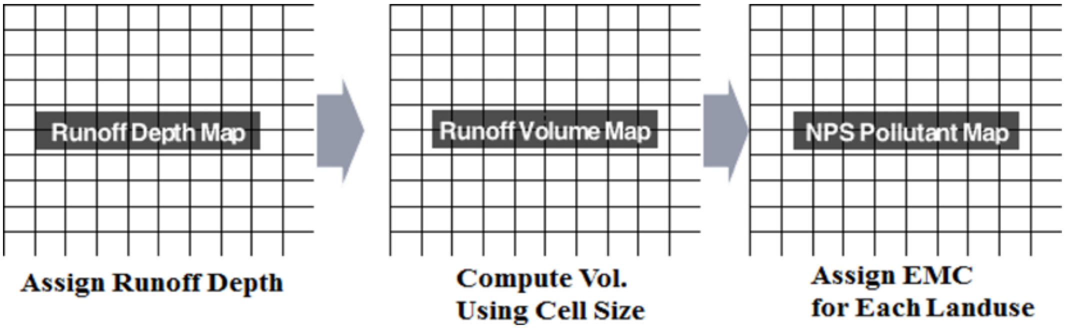

Fig. 3. Procedure Used to Calculate Event Mean Concentrations for Runoff

Table 2. Characterizations of Water Quality Index (WQI)

Rating	WQI	Characterization of water sample
Excellent	95.0 – 100	Water quality intact, conditions close to natural levels
Good	80.0 – 94.9	Water quality is protected, with only a minor degree of threat or impairment; conditions rarely depart from natural, desirable levels
Fair	65.0 – 79.9	Water quality usually intact, but occasionally endangered, conditions often deviate from natural levels
Marginal	45.0 – 64.9	Water quality frequently endangered, conditions very often deviate from natural levels
Poor	0 – 44.9	Water quality almost always endangered, conditions regularly deviate from normal levels

Table 3. EMC for BOD according To Rainfall Range

Level-2 classification	EMC of BOD according to rainfall range (mg/L)			
	10 mm or less	10 – 30 mm	30 – 50 mm	50 mm or more
Residential area	6.10	7.30	7.00	2.75
Industrial area	53.70	29.70	12.00	3.85
Commercial area	16.80	21.05	20.35	9.75
Amusement facility	24.15	64.75	19.85	16.05
Traffic area	12.28	6.75	5.53	2.30
Public facility area	7.93	9.00	4.75	4.73
Paddy	3.95	3.90	3.90	3.65
Farm	0.00	16.88	13.56	40.72
Greenhouse	7.80	11.77	10.97	12.37
Orchard	0.00	1.00	3.70	2.45
Other cultivation areas	0.00	0.00	4.40	2.00
Broadleaved forest	1.20	1.20	1.80	2.10
Coniferous forest	1.10	1.10	1.20	0.90
Mixed forest	1.20	1.80	1.80	0.90
Natural grassland	3.60	6.80	3.90	3.40
Golf course	4.60	6.10	6.20	3.90
Other grassland	3.60	6.75	3.85	3.35
Inland wetland	0.00	0.00	0.00	0.00
Coastal wetland	0.00	0.00	0.00	0.00
Mining area	15.63	12.40	19.80	13.27
Bare land	15.60	12.40	19.80	13.30
Inland water	0.00	0.00	0.00	0.00
Marine water	0.00	0.00	0.00	0.00

Table 4. EMC for TP according to Rainfall Range

Level-2 classification	EMC of TP according to rainfall range (mg/L)			
	10 mm or less	10 – 30 mm	30 – 50 mm	50 mm or more
Residential area	0.2	0.2	0.2	0.4
Industrial area	1.2	0.6	0.1	0.1
Commercial area	1.3	0.5	1.3	1.4
Amusement facility	1.8	0.7	0.5	0.7
Traffic area	1.3	0.2	0.2	0.1
Public facility area	0.3	0.3	0.1	0.7
Paddy	0.2	0.6	0.3	0.4
Farm	0.0	2.4	2.3	10.3
Greenhouse	0.6	1.7	3.2	2.1
Orchard	0.0	0.1	0.2	0.4
Other cultivation areas	0.0	0.0	1.3	1.4
Broadleaved forest	0.1	0.1	0.2	0.5
Coniferous forest	0.1	0.0	0.0	0.0
Mixed forest	0.1	0.0	0.1	0.0
Natural grassland	0.5	0.6	0.3	0.7
Golf course	1.5	1.3	1.9	1.5
Other grassland	0.5	0.6	0.3	0.7
Inland wetland	0.0	0.0	0.0	0.0
Coastal wetland	0.0	0.0	0.0	0.0
Mining area	0.2	0.9	0.7	0.7
Bare land	0.2	0.9	0.7	0.7
Inland water	0.0	0.0	0.0	0.0
Marine water	0.0	0.0	0.0	0.0

urban areas as well as urban areas were estimated by multiplying the estimated daily direct runoff by pollutant loading coefficients, called EMC values, associated with the land use (Lim et al., 2006). In the first stage of the study, the runoff and the non-point pollutant load calculated for each grid were not shifted based on the bed slope and flow direction. The total loads, pollutant loads for each land cover type, and contribution rates estimated for each grid were calculated as shown in Fig. 3. The antecedent moisture condition – II (AMC-II) values were 12.7 and 27.94, and the AMC-III values were 35.56 and 53.3. The EMC data on BOD and TP for each land use type as measured earlier (Nakdong River Environment Research Center, 2014) were applied to the model. We estimated the EMC directly, as shown in Tables 3 and 4.

2.3.2 Model Building

Figure 4 shows that there were 24 meteorological stations in the target basin. To estimate the average rainfall in the basin area, a Thiessen network for sub-basins located in the Nakdong River watershed was constructed by using Arc-GIS, and Thiessen coefficients were calculated for each station and rainfall data were applied. Rainfall data were collected from 24 meteorological stations during the period 2013 – 2017.

The hydrologic characteristics of the basin are significantly influenced by the topography, land cover type, and soil type. In order to evaluate the effects of non-point source pollution from paddy fields, farmland, and other cultivated areas on the water quality monitoring points at the end of the unit basins, land cover

Fig. 4. Meteorological Stations and Thiessen Network

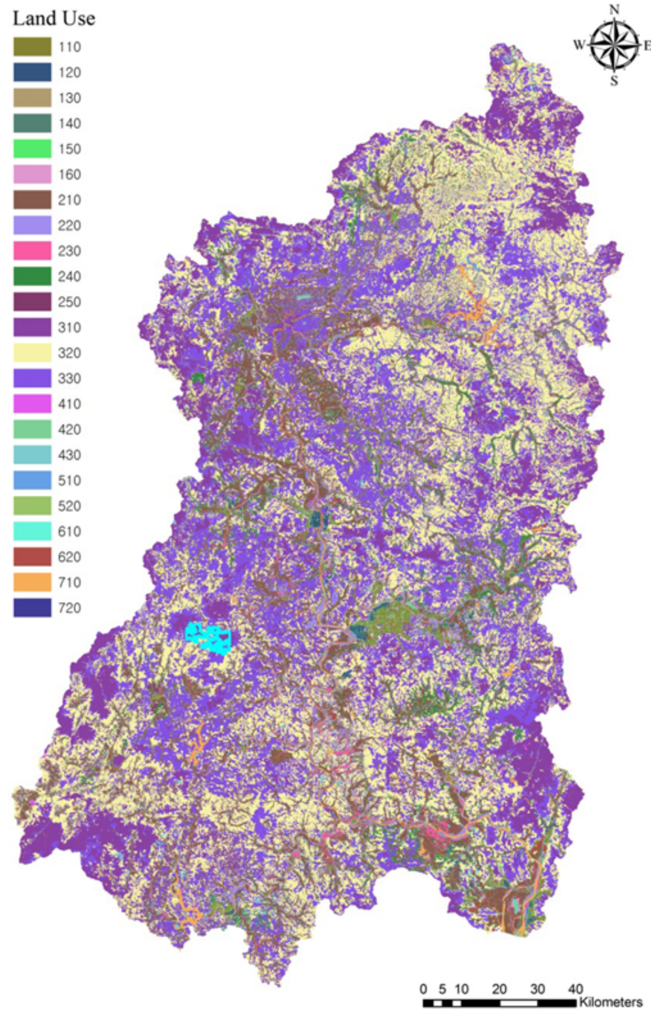

Fig. 5. Land Use Map of the Nakdong River Basin

and hydrological soil maps were constructed by using 10 m × 10 m grids, as shown in Figs. 5 and 6. The CN was calculated based on these data, and the CN based on the Korean land use classification criteria for the application of AMC-II conditions referred to the estimation method of design flood discharge (Ministry of Land, Infrastructure, and Transport, 2012).

3. Results and Discussion

3.1 Point Source Pollution in the Nakdong River Basin

The water pollution for each tributary was evaluated as shown in Fig. 7. Sub-basin Nos. 12 and 13 (the Hoecheon River) were evaluated as “poor,” followed by sub-basin No. 21 (the Milyang River) and 19 (the Nam River). Sub-basin Nos. 15, 16, and 18 were evaluated as “good,” while most others were deemed “marginal.” Tributary No. 12, the Geumho River, is the largest tributary that joins the Nakdong River. It is of particular interest because it passes through the metropolitan city of Daegu and provides drinking water to the citizens. Indiscriminate development in the past had led to this water body becoming known as “highly

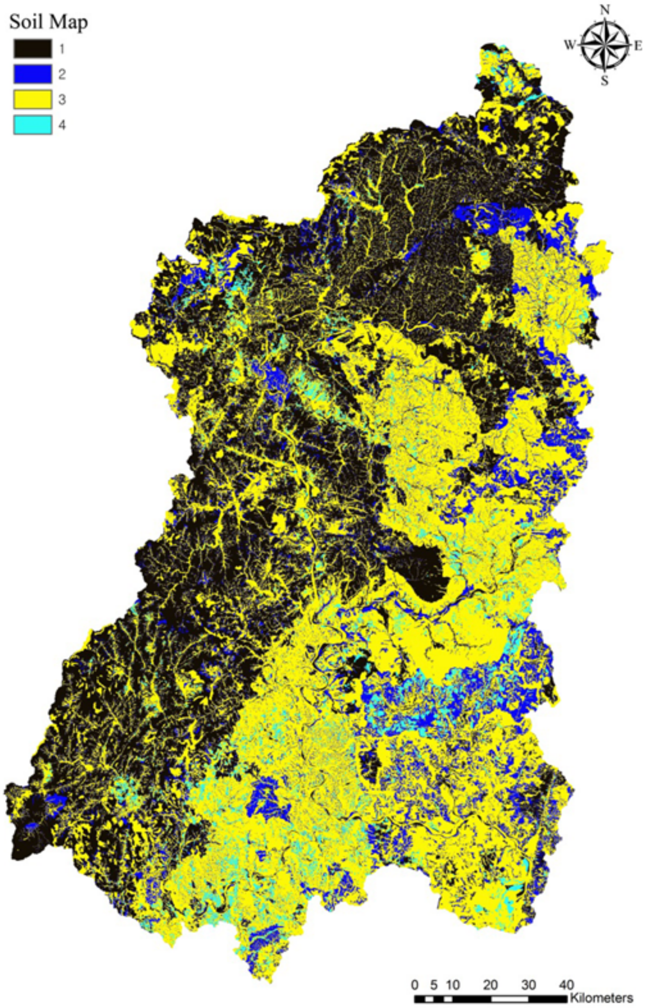

Fig. 6. Soil Group Map in the Nakdong River Basin

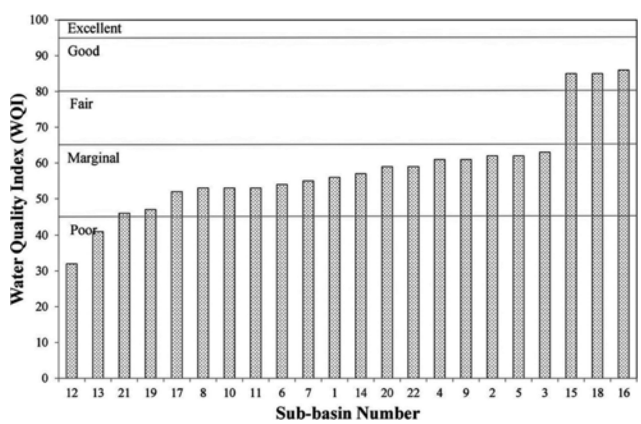

Fig. 7. The Water Quality Index (WQI), Arranged from Lowest to Highest, Calculated for the Nakdong River Basin

contaminated," and a BOD value of 111 mg/L was measured there in 1984. However, in 2010, the BOD levels were 3.0 mg/L or less thanks to efforts to improve the water quality that have received national attention.

Figure 8 shows the results of the PCA, in increasing order, for the BOD and TP observed from 2013 to 2017 for the four rivers evaluated as having high pollution levels. The numbers of dots represent the months January to December, "FR" denotes the "flow rate," and BOD-14 is the BOD in 2014. Fig. 8(a) shows that pollution was high in sub-basin No. 12 from April to August. April to June corresponds to the farming season in Korea, while July to August is the rainy season. The flow rate was highly correlated with rainfall, and the effect of non-point pollution was considered large when the flow rate, BOD, and TP were positive. In Fig. 8(b), most of the pollution was concentrated in May and July in sub-basin No. 13, but in 2017, the flow rate and TP were positive and BOD was negative; in other words, TP was considered highly correlated to the flow rate and therefore strongly related to non-point source pollution. However, Fig. 8(c) shows that TP was concentrated in the Nam River in February, which demonstrates that the TP in this tributary was caused by point source pollution rather than non-point source pollution; on the contrary, BOD was positively related to the flow rate. In Fig. 8(d), most of the arrows pointed in the positive direction in the Milyang River, thus indicating that the TP seemed to be affected more by point source pollution than non-point source pollution in 2014 and 2015, although the former was proportional to the flow rate. Thus, the effect of non-point pollution sources was greater in this tributary.

3.2 Non-Point Source Pollution in the Nakdong River Basin

The Fortran-based program developed in this study was also applied to estimate the non-point pollutant loads for BOD and TP in the 22 sub-basins of the Nakdong River basin. The results of non-point pollutant loads for each sub-basin, according to land cover type, are shown in Fig. 9. The highest non-point pollutant loads for BOD and TP were seen at sub-basin No. 12 (area: 2,059 km^2), and the lowest loads were recorded at sub-basin No. 3. This is consistent with the results of the WQI and PCA analyses; thus, the Geumho River was the tributary selected to be managed first. The sub-basins with the second highest potential for contamination by non-point source pollutants were sub-basin No. 18 (the Nam River, area: 2,255 km^2) and No. 19 (area: 1,158 km^2). Sub-basin No. 20 (area: 980 km^2) is in the lower section of the Nakdong River and includes the Changnyeong-Hamahn Weir, while sub-basin No. 4 (area: 1,797 km^2) is the Naeseongcheon, which is located in the upper Nakdong River. The upper stream affects the mainstream of the Nakdong River more than the lower stream does and thus requires more management. However, the possibility of non-point pollution occurring according to different land cover types was high in sub-basin No. 18, but the WQI based on the observed water quality data was "good." Therefore, it would be preferable to exclude sub-basin No. 18 from those which will be managed in terms of non-point source pollution. Based on the results of comprehensively analyzing the WQI and the possibility of non-point pollution, and by carrying out a PCA on these results, the Geumho River (sub-basin No. 12), Nam River (sub-basin No. 19), and Milyang River (sub-basin No. 21),

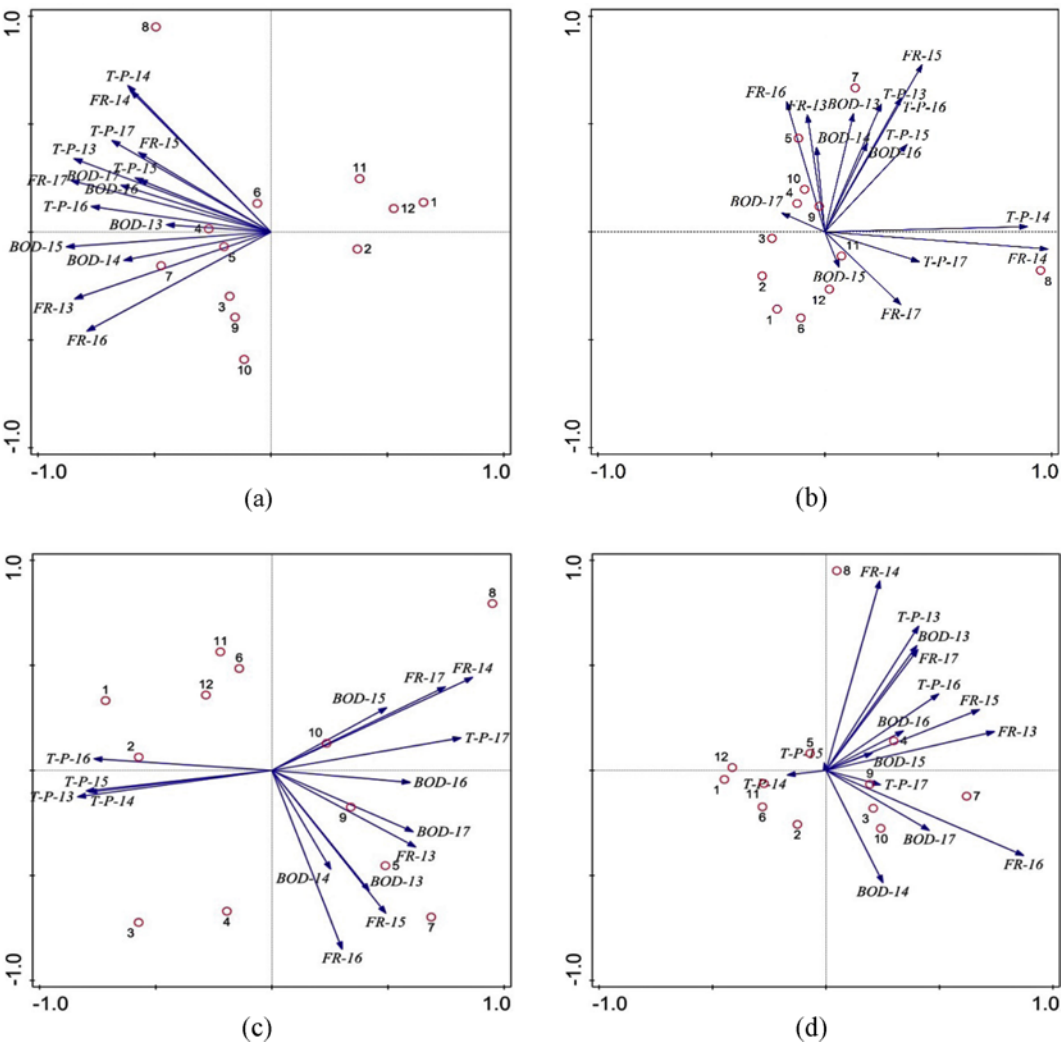

Fig. 8. Principal Component Analysis of Selected Sub-Basins of the Nakdong River Basin: (a) Sub Basin No. 12, (b) Sub Basin No. 13, (c) Sub Basin No. 19, (d) Sub Basin No. 21

were chosen for priority management. These rivers and the Hwang River (sub-basin No. 16) are the largest tributaries that join the mainstream of the Nakdong River.

4. Conclusions

In this study, tributaries that need to be managed first to improve the water quality of the mainstream of the Nakdong River basin were selected by using WQI, PCA, and distributed non-point source model data. The WQI was used to comprehensively evaluate the water quality resulting from both point and non-point sources of pollution. Then, the PCA was used to determine whether seasonal changes in water pollution came from point or non-point sources (e.g., non-point source pollutants tend to increase during times of higher flow rates). The results showed that sub-basin Nos. 12 and 13 had "poor" water quality, and thus, these basins require further water quality management. In addition, the degrees of non-point source pollution were evaluated by land cover types with the model developed in this study. The results of this analysis showed that sub-basin Nos. 12 and 18 need management for non-point sources of pollution. The comprehensive analysis showed that sub-basin No. 12 (the Geumho River) had a high-level pollution across all indices. Additionally, the PCA, BOD, and TP data were also used to evaluate the seasonal effects of pollution in sub-basin No. 12; all analyses showed positive results, thus revealing the great influence of non-point pollution sources in this water body. The method proposed in this study can be used to determine whether the pollution in a tributary is caused by a source or a non-point source, thereby enabling proper management measures to be enacted. The degree of non-point pollution based on the land cover type can be also evaluated to predict the levels of this type of pollution resulting from the development of sub-basins.

The model developed in this study is the first step in a distributed model that estimates non-point pollutant loads based on direct runoff and EMCs. In the second step, which uses grid-

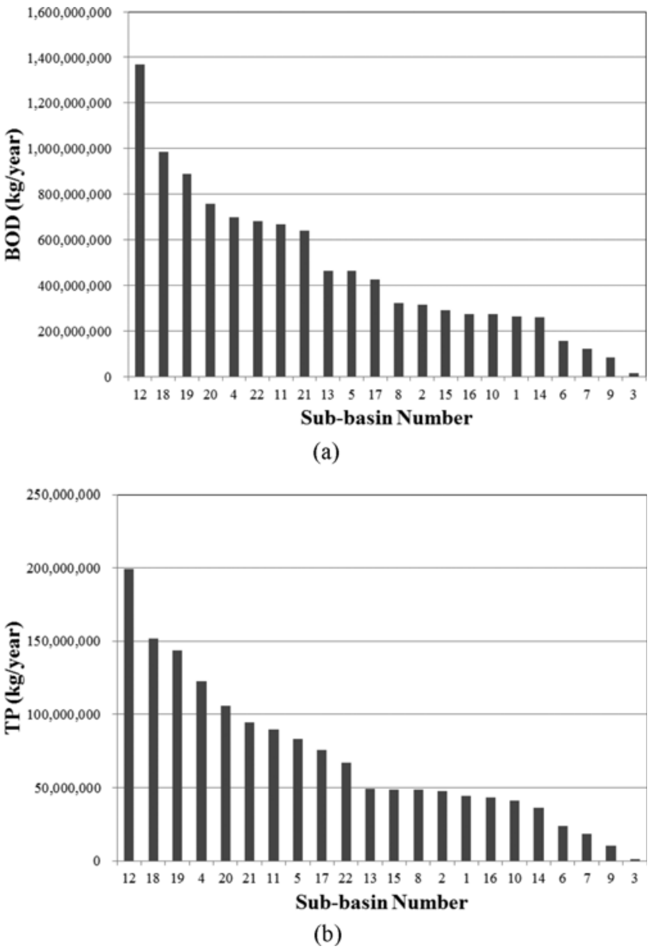

Fig. 9. Estimates of Non-Point Source Pollution in the Nakdong River Basin: (a) BOD, (b) T-P

based hydrological information, it is necessary to improve the model to consider the time taken by pollutants to move from the basin slope to the stream channel by adding a governing equation for basin runoff based on physical motion wave theory or diffusion wave theory. In the third step, a physical equation such as the Darcy equation should be applied to determine base flows, including those for water in the river bed, for soil, and for direct runoff. Finally, the accuracy of data collected on EMC conditions must be improved.

Acknowledgements

This research was funded by the National Institute of Environmental Research (NIER), which is financially supported by the Ministry of Environment (MOE) of the Republic of Korea.

ORCID

Jung Min Ahn https://orcid.org/0000-0001-7275-3763
Siwan Lyu https://orcid.org/0000-0003-1727-7172

References

Abbasi SA (2002) Water quality indices, state of the art report. National Institute of Hydrology, Scientific Contribution No. INCOH/SAR-25/2002, Roorkee: INCOH, Roorkee, India, 73

Abbott DH, Morton JL, Holmes ML (1986) Heat flow measurements on a hydrothermally-active, slow-spreading ridge: The Escanaba Trough. *Geophysical Research Letters* 13(7):678-680, DOI: 10.1029/GL013i007p00678

Ahn JM, Jung KY, Shin D (2017) Effects of coordinated operation of weirs and reservoirs on the water quality of the geum river. *Water* 9(423), DOI: 10.3390/w9060423

CCME (2001) Canadian water quality guidelines for the protection of aquatic life: CCME water quality index 1.0. user's manual. In: Canadian environmental quality guidelines. Canadian Council of Ministers of the Environment, Winnipeg, MB, Canada

Choi JY, Lee SY, Kim LH (2009) Wash-off characteristics of NPS pollutants from forest landuse. *Journal of Korean Society of Hazard Mitigation* 9(4):129-134

Chow VT, Maidment DR, Mays LW (1988) Applied hydrology. McGraw-Hill, New York, NY, USA

Downer CW, Ogden FL (2003) GSSHA user's manual: Gridded surface subsurface hydrologic analysis, version 1.43 for WMS 6.1. Technical report, U.S. Army Engineer Research and Development Center, Vicksburg, MS, USA

Jianqin M, Jingjing G, Xiaojie L (2010) Water quality evaluation model based on principal component analysis and information entropy: Application in Jinshui River. *Journal of Resouces and Ecology* 1(3):249-252, DOI: 10.3969/j.issn.1674-764x.2010.03.008

Johnson BE, Julien PY, Molnar DK, Watson CC (2000) The two-dimensional upland erosion model CASC2D-SED. *Journal of The American Water Resources Association* 36(1):31-42, DOI: 10.1111/j.1752-1688.2000.tb04246.x

Julien PY, Saghafian B, Ogden FL (1995) Raster-based hydrologic modeling of spatially-varied surface runoff. *Water Resource Bulletin* 31(3):523-536, DOI: 10.1111/j.1752-1688.1995.tb04039.x

Kannel PR, Lee S, Lee YS, Kanel SR, Khan SP (2007) Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment* 132:93-110, DOI: 10.1007/s10661-006-9505-1

Lim KJ, Engel BA, Tang Z, Muthukrishnan S, Choi J, Kim K (2006) Effects of calibration on L-THIA GIS runoff and pollutant estimation. *Journal of Environmental Management* 78:35-43, DOI: 10.1016/j.jenvman.2005.03.014

Lumb A, Halliwell D, Sharma T (2006) Application of CCME Water Quality Index to monitor water quality: A case of the Mackenzie River Basin, Canada. *Environmental Monitoring and Assessment* 113:411-429, DOI: 10.1007/s10661-005-9092-6

Lumb AM, McCammon RB, Kittle JL Jr (1994) User's manual for an expert system (HSPEXP) for calibration of the hydrological simulation program - Fortran. Water-Resources Investigations Report 94-4168, US Geological Survey, Reston, VA, USA

Ministry of Environment (2006) Water quality management master plan: 4 majors river water quality conservation master plan ('06 – '15). GPVP1200710956, Ministry of Environment, Sejong, Korea

Ministry of Land, Infrastructure, Transport (2012) Flood estimation method. Ministry of Land, Infrastructure, Transport, Sejong, Korea

Moon JH, Lee IK, Kim JT, Chang SW (2014) Assessment of efficiency for constructed wetlands to reduced non-point source pollution.

Journal of Korean Society of Hazard Mitigation 14(1):333-339, DOI: 10.9798/KOSHAM.2014.14.1.333

Nakdong River Environment Research Center (2014) Study on long-term runoff monitoring and reduction techniques for major nonpoint source pollution. Nakdong River Environment Research Center, Daegu, Korea

Park H, Park C, Song M, Baek K, Shin S (2001) Evaluation of water quality characteristic using factor analysis in the Nakdong river. *Journal of Water Environment Research* 17(6):693-701

Sharifi M (1990) Assessment of surface water quality by an index system in Anzali basin. In: The hydrological basis for water resources management, IAHS Publication, Wallingford, UK, 163-171

Tegegne G, Park DK, Kim Y (2017) Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin. *Journal of Hydrology: Regional Studies* 14:44-66, DOI: 10.1016/j.ejrh.2017.10.002

Tirkey P, Bhattacharya T, Chakraborty S (2015) Water quality indices-important tools for water quality assessment: A review. *International Journal of Advances in Chemistry* 1(1):15-29, DOI: 10.5121/ijac.2015.1102

U.S. Army Corps of Engineers (1976) Development and application of the SSARR model. Summaries of technical reports, North Pacific Division, Portland, OR, USA

U.S. EPA (2001) Better assessment science integrating point and nonpoint sources, BASINS version 3.0., user's manual. EPA-823-B-01-001, Office of Water, U.S. Environmental Protection Agency, Washington, DC, USA

USDA, Soil Conservation Service (1985) National engineering handbook, section 4 hydrology. USDA, Soil Conservation Service, Washington, DC, USA

Vieux BE, Vieux JE (2002) VfloTM: A real-time distributed hydrologic model. Proceedings of the 2nd federal interagency hydrologic modeling conference, July 28-August 1, Las Vegas, NV, USA

Water Resources Management Information System (2018) Water resources management information system. Retrieved November 30, 2018, http://www.wamis.go.kr/