Investigation of correlation between surface runoff rate and stream water quality

Sunsook Jang, Hyunseo Ji, Jiyong Choi, Kyo Suh and Hakkwan Kim

ABSTRACT

The purpose of this study was to investigate the relationship between stream water quality and the surface runoff rate defined as the ratio of annual surface runoff to annual average precipitation. The surface runoff rate was first estimated in the Han River basin located in South Korea using the calibrated and validated HSPF model. Then a linear regression analysis was performed to investigate the correlation between the computed surface runoff rate and the observed water quality. It was found that there were statistically significant relationships between the surface runoff rate and concentrations of BOD, COD, and T-P and higher surface runoff rate led to the deterioration of water quality in streams. Finally, the applicability of the surface runoff rate as an indicator to measure the impact of land development on stream water quality was evaluated using a receiver operating characteristic (ROC) curve analysis. The ROC curve analysis indicated that the surface runoff rate could be utilized as a useful indicator to illustrate the degradation of stream water quality at the watershed scale. The results from this study also suggest that the surface runoff rate needs to be managed and controlled within about 15% to prevent the degradation of stream water quality.

Key words | HSPF model, imperviousness, non-point source pollution, receiver operating characteristic curve analysis, surface runoff, urbanization

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HIGHLIGHTS

- The HSPF model was applied for simulating hydrological components.
- The linear regression analysis and receiver operating characteristic (ROC) curve analysis were utilized to analyze the impact of surface runoff rate on water quality.
- There were significant relationships between the surface runoff rate and water quality.
- Controlling the surface runoff rate within 15% is suggested to prevent the degradation of water quality.

INTRODUCTION

Non-point source (NPS) pollution, which is the polluted runoff from the land, is an important factor affecting the water quality of rivers (Li et al. 2011). NPS pollution occurs as water moves across the land or underground. Thus, the

factors that affect accumulation of pollutants on the lands surface or the mechanisms that transport pollutants from the land surface have a direct impact on NPS pollution (Donigian & Crawford 1976). In particular, the quantity of surface runoff, which occurs when the rainfall amount exceeds the infiltration capacity of the soil, substantially influences NPS pollution because a significant quantity of non-point pollutants such as sediment, nutrients and

pesticides are transported to nearby streams via surface runoff (Novotny & Olem 1994; Ritter & Shirmohammadi 2001). The expansion of urban areas has also created more impervious surfaces that prevent rainfall from infiltrating the soil, resulting in an increase in surface runoff (Shuster *et al.* 2005). These impervious surfaces and surface runoff directly affect the transport of NPS pollutants (Chithra *et al.* 2015). During the storm events, the surface runoff from urban areas is drained into urban drainage systems such as separate or combined sewer systems. In separate sewer systems, the increase in surface runoff may degrade the stream water quality because pollutants that accumulate on the surface from traffic, litter, street dust and other sources are washed off by the surface runoff into and run into the sewer system (Novotny & Olem 1994). In combined sewer systems, during rainfall events when the transport capacity of the sewer system is insufficient, the combined sewer overflows (CSOs) occur, resulting in the discharge with a mixture of untreated wastewater and urban runoff into the nearest watercourse (Even *et al.* 2007; Passerat *et al.* 2011). Since CSOs can contain high concentrations of various pollutants, CSOs may cause severe water pollution problems (Novotny & Olem 1994; Abdellatif *et al.* 2014; Liu *et al.* 2015). Therefore, the increase in surface runoff caused by increasing impervious area in the watershed may lead to an increase in the volume and frequency of CSOs and consequently result in a degradation of stream water quality (Novotny & Olem 1994). Thus, it is necessary and important to quantify the surface runoff in the watershed and manage it to improve stream water quality. However, a reliable measurement and prediction of the quantity and rate of surface runoff in the watershed is an inherently difficulty and time-consuming task for a large ungauged watershed (Li *et al.* 2018). Due to these difficulties, hydrologic models are frequently used to analyze and quantify the surface runoff in the watershed. Recently, the Hydrological Simulation Program-Fortran (HSPF) model has been used extensively to simulate hydrological components including surface runoff in the urban-dominated or mixed watersheds (Borah & Bera 2004, Bicknell *et al.* 2005; Duda *et al.* 2012; Rantunga *et al.* 2017).

To analyze the impact of urbanization on the stream water quality and determine the health of watershed environments, researchers have commonly used the percentage of total impervious areas as well as effective impervious areas in the watershed as a useful indicator (Ebrahimian *et al.* 2016, Kim *et al.* 2016). In particular, previous studies have focused on verifying the correlation between impervious surface and stream water quality and indicated that the increase in impervious areas are positively correlated with a decrease in stream water quality (Klein 1979; Schueler 1994; Holland *et al.* 2004, Kim *et al.* 2016). However, researchers frequently debate whether this approach is rather inefficient and whether the percentage of total impervious areas or effective impervious areas can be applied to all watershed environments as local factors such as terrain, soils, geology, and rainfall patterns (Pettigrove 2007). Pettigrove (2007) suggested that a more effective approach is to develop an understanding of the impact of urban runoff on all receiving waters because the impact of flows is likely to be strongest at the sub-watershed level. However, previous research has not adequately investigated the relationship between hydrological components such as total runoff and surface runoff and water quality in different geographical areas under different scales.

Understanding this correlation is necessary to identify the primary threats to water quality and to provide theoretical support for improving water quality. Thus, the purposes of this study are (1) to estimate the surface runoff rate, which is defined as a proportion of annual surface runoff to annual average precipitation using the HSPF model, (2) to investigate the correlation between the computed surface runoff rate and observed water quality, and (3) to evaluate the applicability of the surface runoff rate as an indicator to measure the impacts of land development on stream water quality.

MATERIAL AND METHODS

Study area

This study was conducted in the Han River Basin (HRB), which is located in the central part of South Korea (Figure 1). The HRB is the largest river basin in South Korea, covering approximately 34,428 km². The HRB has a typical semi-humid continental monsoon climate with an average annual precipitation of 1,300 mm. About 70% of the annual precipitation occurs during the summer season (June–September)
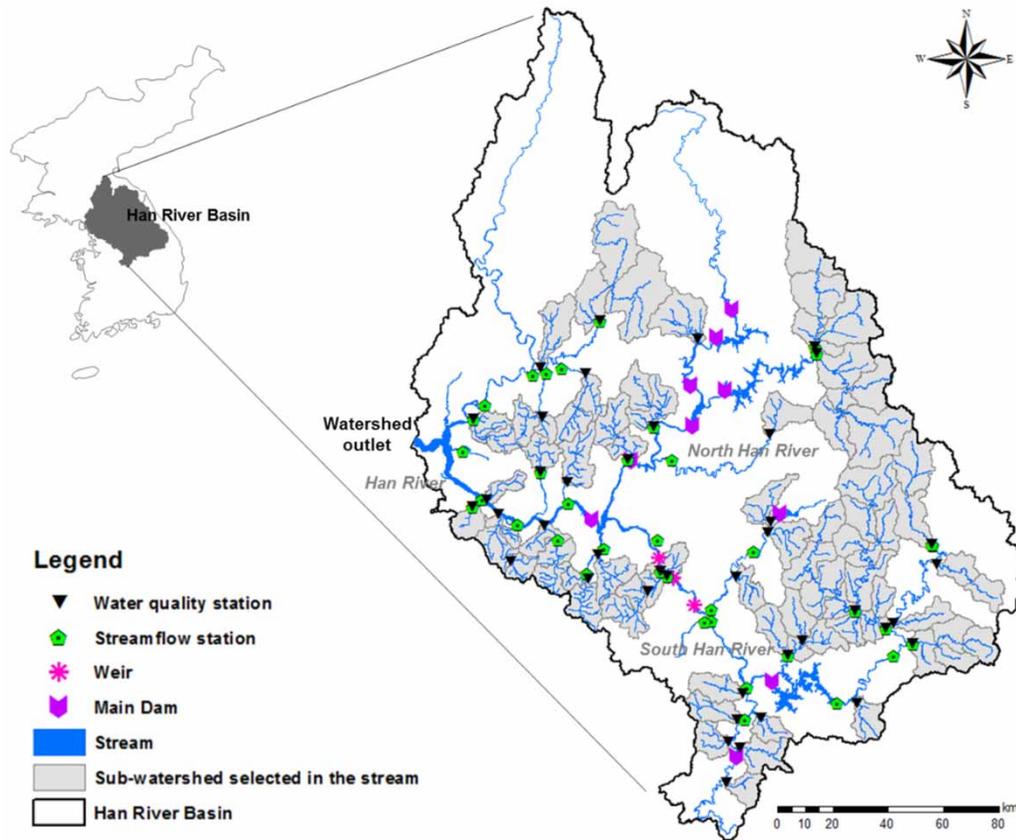
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Figure 1 | Location of the Han River Basin showing sub-watershed, affluent rivers, and monitoring stations.

(Kim *et al.* 2016). As a result, the maximum discharge occurs during the rainy summer season. The North and South Han Rivers in the HRB are the major sources of drinking water for more than 24 million people including the residents of the densely populated Seoul metropolitan area. As land development pressure continues in the suburban areas in Seoul, the urban area is expected to gradually expand. The HRB includes the 14 multipurpose dams and three multifunction weirs to ensure a stable water supply and mitigate floods.

HSPF model description

The HSPF model developed by the United States Environmental Protection Agency (US EPA) is a comprehensive river basin model that provides an integrated framework for modeling various hydrological and quality processes (Bicknell *et al.* 2005). The HSPF model is a semi-distributed conceptual model that combines spatially distributed physical attributes into hydrologic response units (HRUs), each

of which is considered to behave in a uniform manner in response to meteorological inputs and storage capacity factors. On a continuous basis, the HSPF model can simulate the hydrological, hydraulic, and water quality processes on pervious and impervious land surfaces. The HSPF model consists of three basic application modules (PERLAND, IMPLND, and RCHRES). The PERLND and IMPLND modules simulate hydrologic and water quality processes on pervious land and impervious land segments, respectively. The RCHRES module simulates the physical and chemical processes occurring in the reach of an open channel or a completely mixed lake. Regarding hydrological components, the HSPF model can compute interception, evapotranspiration (ET), surface detention, surface outflow, infiltration, shallow subsurface flow (interflow), base flow, and deep percolation. In this study, the surface runoff is computed by subtracting the infiltration and interception from the precipitation. A detailed description of the HSPF model can be found in the user's manual (Bicknell *et al.* 2005).

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Model setup

The HSPF model needs various input data including digital elevation model (DEM) as well as land use and meteorological data. In this study, the model was established by using the Better Assessment Science Integrating Point and Non-point Sources (BASINS). The DEM for the study area, which has a 30 m resolution, was obtained from the National Geographic Information Institute of the Ministry of Land, Infrastructure and Transport in Korea. Land use map (as of the year 2013) provided by Korea Ministry of Environment was utilized to characterize the land use in the watershed. In this study, land use data were classified into eight different types including forest, agricultural land, grassland, bare field, residential land, commercial land, wetland, and water. In this study, the values of impervious percent for residential land and commercial land were set at 50 and 70%, respectively (Neitsch *et al.* 2005). Meteorological data such as precipitation, evapotranspiration, air temperature, wind speed, solar radiation, dew-point temperature, and cloud cover for each weather station were collected from the Korea Meteorological Administration (KMA). Data for dams and weirs such as outflow and storage capacity were obtained from the Korea Water Resources Corporation (K-Water) and the Water Resources Management Information System (WAMIS).

For the point source discharge data, the daily water discharge data for the wastewater treatment facilities of which daily average discharge is more than 200 m^3 were collected from the Korea Environment Corporation and the National Institute of Environmental Research (NIER) in Korea.

Model calibration and validation

The calibration of the model was performed manually by adjusting the major parameters related to hydrology. Thirteen parameters were selected and adjusted within the range based on previous studies (USEPA 2000; Kim *et al.* 2007; Diaz-Ramirez *et al.* 2011; Luo *et al.* 2017). For calibration and validation of the HSPF model, 8-day interval flow data monitored by the NIER were collected from 36 streamflow monitoring stations within the HRB. The data from 2010 to 2012 were used for calibration, while the data from 2013 to 2015 were utilized as the validation set. The recommended ranges and calibrated values for the parameters calibrated in this study are given in Table 1. The coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NSE) were used to evaluate the HSPF model performance. A detailed explanation of these four statistical evaluation methods can be found in Legates & McCabe (1999) and Moriasi *et al.* (2007).

Table 1 | Calibrated values of parameters used during the SWAT model calibration

Parameter	Definition	Units	Range[a]	Calibrated value
FOREST	Pervious land fraction covered by forest	–	0–1	0–1
LZSN	Lower zone nominal storage	Mm	50.8–381	25.4–381
UZSN	Upper zone nominal storage	mm	0.25–50.8	1.27–50.8
INFILT	Index to infiltration capacity	mm/h	0.25–25.0	0.5–25.0
BASETP	Fraction of potential evapotranspiration from base flow	–	0.0–0.2	0.01–0.05
AGWETP	Fraction of remaining evapotranspiration from active groundwater	–	0.0–0.2	0.0–0.1
INTFW	Interflow inflow parameter	–	1.0–10.0	3.0
IRC	Interflow recession parameter	–	0.3–0.85	0.3–0.7
AGWRC	Groundwater recession parameter,	–	0.920–0.999	0.920–0.999
DEEPFR	Fraction of groundwater inflow that goes to inactive groundwater	–	0.0–0.5	0.0–0.5
CEPSC	Interception storage capacity	mm	0.0–10.2	0.1
KVARY	Variable groundwater recession	1/mm	0.0–127.0	0.0–80.3
LSUR	Length of overland flow	m	30.5–213.4	45.7–106.7

[a]Range of possible values for each model parameter (USEPA 2000; Kim *et al.* 2007; Diaz-Ramirez *et al.* 2011; Luo *et al.* 2017).

Selection of sub-watershed

The evaluation of the correlation between surface runoff rate and water quality was not conducted for all sub-watersheds in HRB (Figure 1). The sub-watersheds where there were extensive impoundments or dams within the stream network were excluded. In addition, the sub-watersheds including the water quality monitoring stations within 1 km from major point sources of pollutant discharge such as a wastewater treatment plant were excluded. This approach has often been used to minimize the effect of major point sources or dam discharge on water quality observed from monitoring stations (Kim *et al.* 2016). In this study, 42 sub-watersheds among the sub-watersheds were finally selected for analysis (Figure 1).

Water quality data

Three water quality parameters including biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total phosphorus (T-P) were used in the analysis because these parameters have been regulated by water quality standards for managing stream quality in Korea. The water quality parameters have been monitored and analyzed on a monthly basis at the watershed outlet by the NIER. The water quality data from 2009 to 2013 were collected and analyzed, and the five-year (2009–2013) average values for each water quality parameter were used as a representative value for each water quality station.

Linear regression analysis

To evaluate the relationship between the surface runoff rate and stream water quality in the study area, the five-year (2009–2013) average values for the surface runoff rate were calculated based on the model simulation results. The values of the average water quality were retrieved from the 42 water quality monitoring stations. A simple linear regression analysis was performed to investigate the relationship between the surface runoff rate and water quality. All statistical analyses were performed using the computer package Sigmaplot 10.0 (Systat Software Inc, Chicago, IL, USA). A *p*-value <0.001 was considered statistically significant.

Table 2 │ Results of calibration and validation for stream flow at 36 monitoring stations in the HRB

Station code	Calibration (2010–2012)		Validation (2013–2014)	
	R^2	NSE	R^2	NSE
1002A20	0.70	0.63	0.77	0.72
1002A55	0.85	0.82	0.67	0.65
1001A30	0.88	0.86	0.75	0.57
1001A40	0.79	0.71	0.80	0.60
1003A17	0.80	0.71	0.82	0.77
1003A15	0.79	0.57	0.86	0.77
1003A47	0.84	0.77	0.82	0.76
1003A71	0.78	0.65	0.88	0.84
1004A45	0.94	0.91	0.95	0.90
1004A70	0.87	0.81	0.96	0.92
1005A60	0.84	0.64	0.96	0.94
1006A45	0.90	0.76	0.88	0.86
1006A80	0.82	0.54	0.94	0.84
1007A15	0.92	0.64	0.88	0.79
1007A44	0.73	0.55	0.82	0.62
1007A57	0.72	0.67	0.92	0.86
1011A20	0.84	0.55	0.68	0.62
1012A20	0.75	0.60	0.72	0.59
1013A90	0.69	0.53	0.75	0.65
1014A70	0.89	0.71	0.67	0.65
1007A70	0.87	0.58	0.83	0.78
1015A30	0.64	0.60	0.77	0.55
1016A45	0.80	0.59	0.76	0.58
1016A75	0.89	0.74	0.72	0.55
1025A51	0.72	0.67	0.64	0.52
1018A16	0.74	0.71	0.73	0.62
1018A52	0.98	0.97	0.98	0.97
1022A07	0.79	0.72	0.75	0.63
1022A35	0.88	0.72	0.85	0.72
1022A55	0.76	0.66	0.96	0.84
1022A80	0.87	0.76	0.87	0.76
1023A50	0.70	0.47	0.73	0.64
1023A22	0.83	0.74	0.61	0.38
1019A25	0.97	0.97	0.98	0.98
1019A40	0.69	0.62	0.53	0.46
1019A60	0.60	0.47	0.50	0.40

Receiver operating characteristic curve analysis

In this study, the threshold of the surface runoff rate was used to represent the point at which the water quality abruptly degrades with respect to the surface runoff rate. Receiver operating characteristic (ROC) curve analysis was utilized to evaluate the accuracy of the surface runoff rate index and to determine its threshold. ROC curve analysis has often been used to evaluate diagnostic index-based tests and to determine the decision threshold or cut-off value (Greiner *et al.* 2000; Dos Santos *et al.* 2008). The ROC curve shows how the true-positive proportion (sensitivity) on the Y-axis changes in relation to the false-positive proportion (1-specificity) on the X-axis as the decision criterion (or cut point)

varies (Storey *et al.* 2001). The area under the curve (AUC) estimates the proportion of correct predictions. The AUC value ranges from 0 to 1 because its value is a portion of the area of the unit square. Higher AUC values indicate better test performance. In general, AUC values between 0.50 and 0.70 represent low accuracy, whereas higher values (between 0.70 and 0.90) represent high accuracy (Greiner *et al.* 2000). In this study, the ROC curve analysis was conducted using SigmaPlot 10.0.

The classification scheme for stream water quality in Korea includes seven status classes for stream water quality management. Level II indicates that the water quality is appropriate for swimming and drinking after general treatment including filtration, deposition, and sterilization.
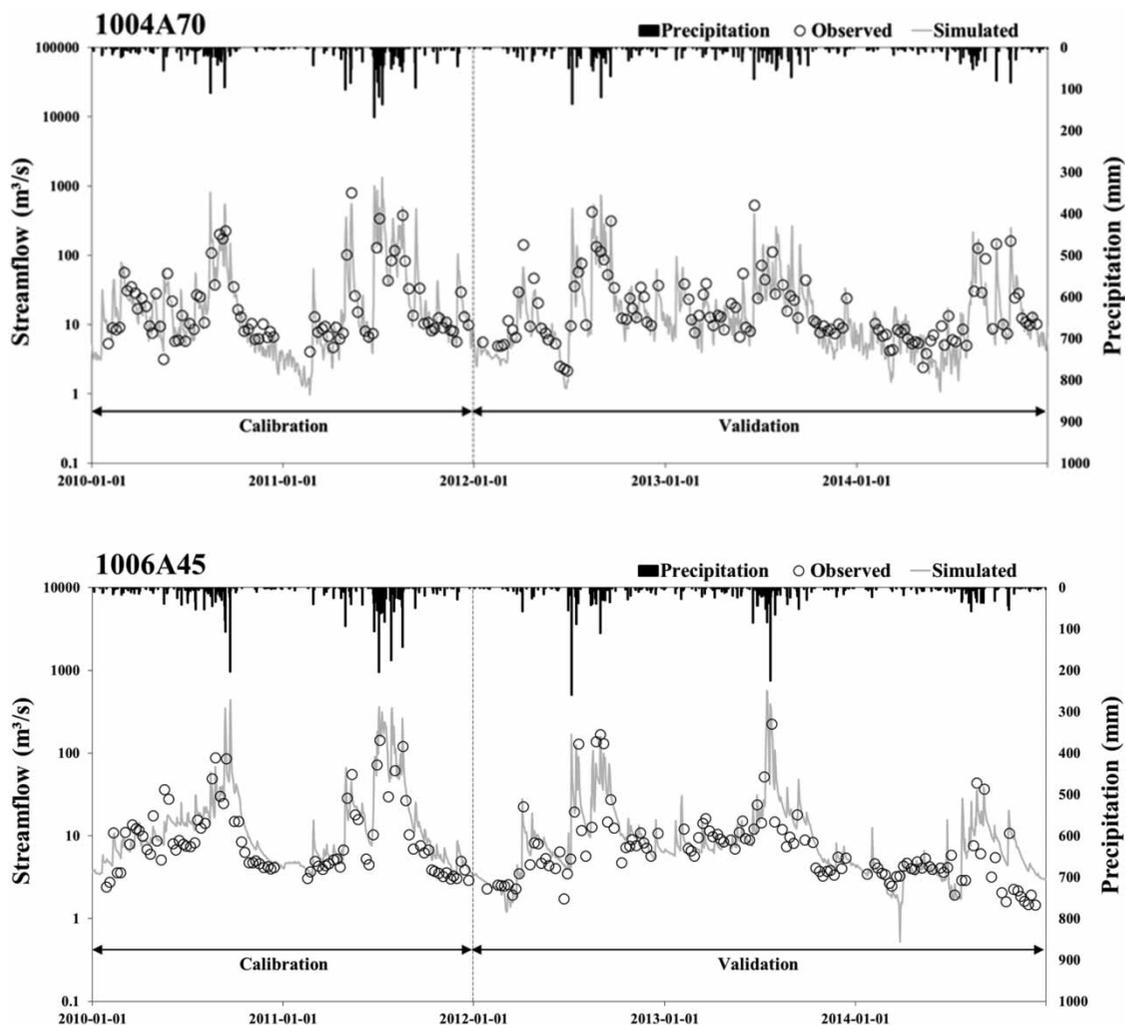

Figure 2 │ Observed versus simulated streamflow (Station code: 1004A70, 1006A45) during the calibration and validation periods.

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Class II is considered to be not polluted: the regulation levels of BOD, COD, and T-P are 3.0, 5.0, and 0.10 mg/L, respectively. Therefore, the water quality levels for Class II were used to determine the threshold value of the surface runoff rate for stream water quality management. This threshold value indicates that the water quality drops below Class II, caused by a change in the surface runoff rate of the sub-watershed.

RESULTS AND DISCUSSION

Model calibration and validation

During the calibration period (2010–2012), R^2 ranges from 0.60 to 0.98 and NSE from 0.47 to 0.97 (Table 2). Parajuli (2010) suggested that the model performance for monthly streamflow can be categorized into six classes based on the threshold R^2 or NSE value: excellent (≥ 0.90), very good (0.75–0.89), good (0.50–0.74), fair (0.25–0.49), poor (0–0.24),

and unsatisfactory (<0). For a daily time step, Nejadhashemi *et al.* (2012) reported that the criteria of $R^2 \geq 0.3$ and NSE $\geq$ 0.3 are recommended to assess if the model results are satisfactory. Thus, the performance of the HSPF model using 8-day interval flow data for calibration was considered acceptable. For the validation period (2013–2014), R^2 and NSE varied from 0.50 to 0.98 and from 0.38 to 0.98, respectively. Overall, the HSPF model results showed a good agreement between the simulated and observed streamflow for the validation years (2013–2014) was as good as for the calibration period, as shown in Table 2 and Figure 2. These statistical results and graphical comparisons indicated that the HSPF model performed satisfactorily for streamflow monitoring stations during both calibration and validation periods.

Correlation between the surface runoff rate and water quality

Figure 3 shows the scatter plots of the surface runoff rate and water quality. The results of the linear regression
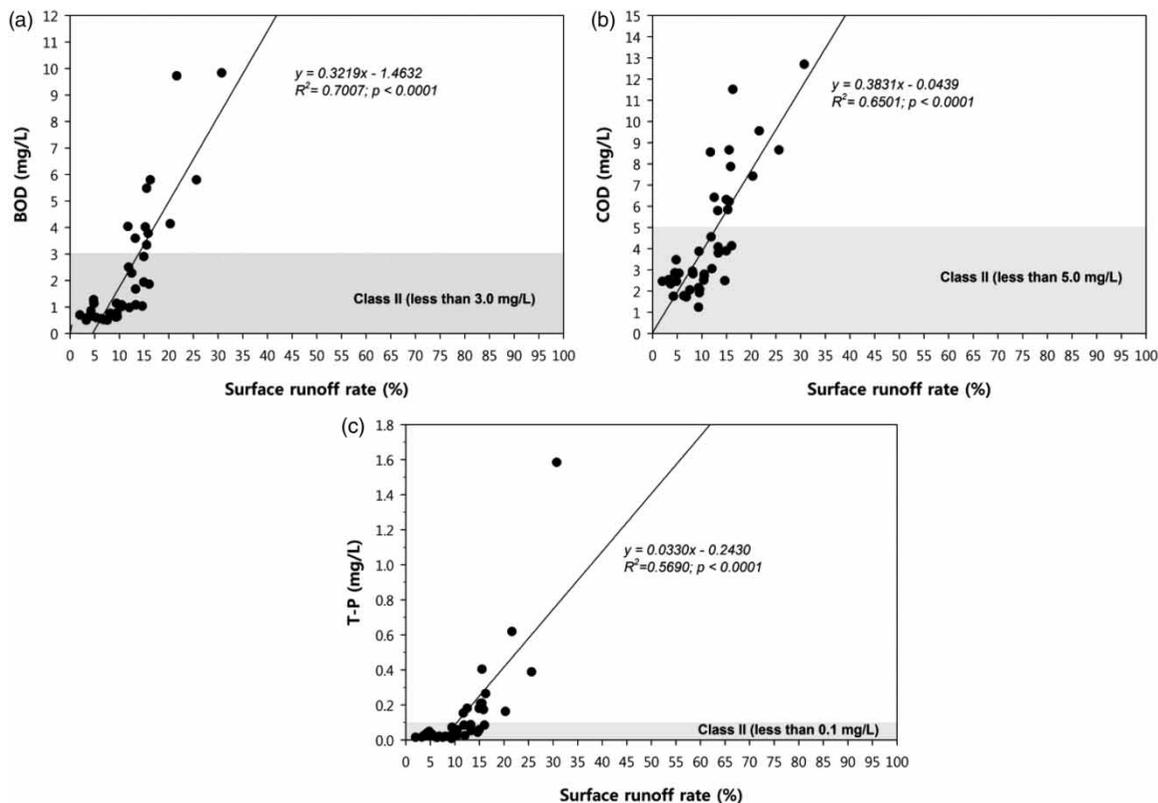

Figure 3 | Plots of linear regression correlation of (a) BOD, (b) COD, and (c) T-P in relation to the surface runoff rate.

analysis revealed significant linear relationships between the surface runoff rate and water quality because the scatter plots showed a linear trend and the coefficient of determination (R^2) was significantly different from zero (BOD = 0.7007, COD = 0.6501, and T-P = 0.5690) as shown in Figure 3. In addition, the linear regression analysis indicated that higher proportions of surface runoff could lead to higher concentrations of BOD, COD, and T-P in streams.

Evaluation of the applicability of surface runoff rate as an indicator

Figure 4 presents the ROC curves for BOD, COD, and T-P. The values of the AUC for BOD, COD, TOC, and T-P were 0.95, 0.97, 0.95, and 0.95, respectively. This result showed that the surface runoff rate is a suitable indicator to discriminate between the two opposite categories of 'good status (better than Class II of the water quality standard)' and
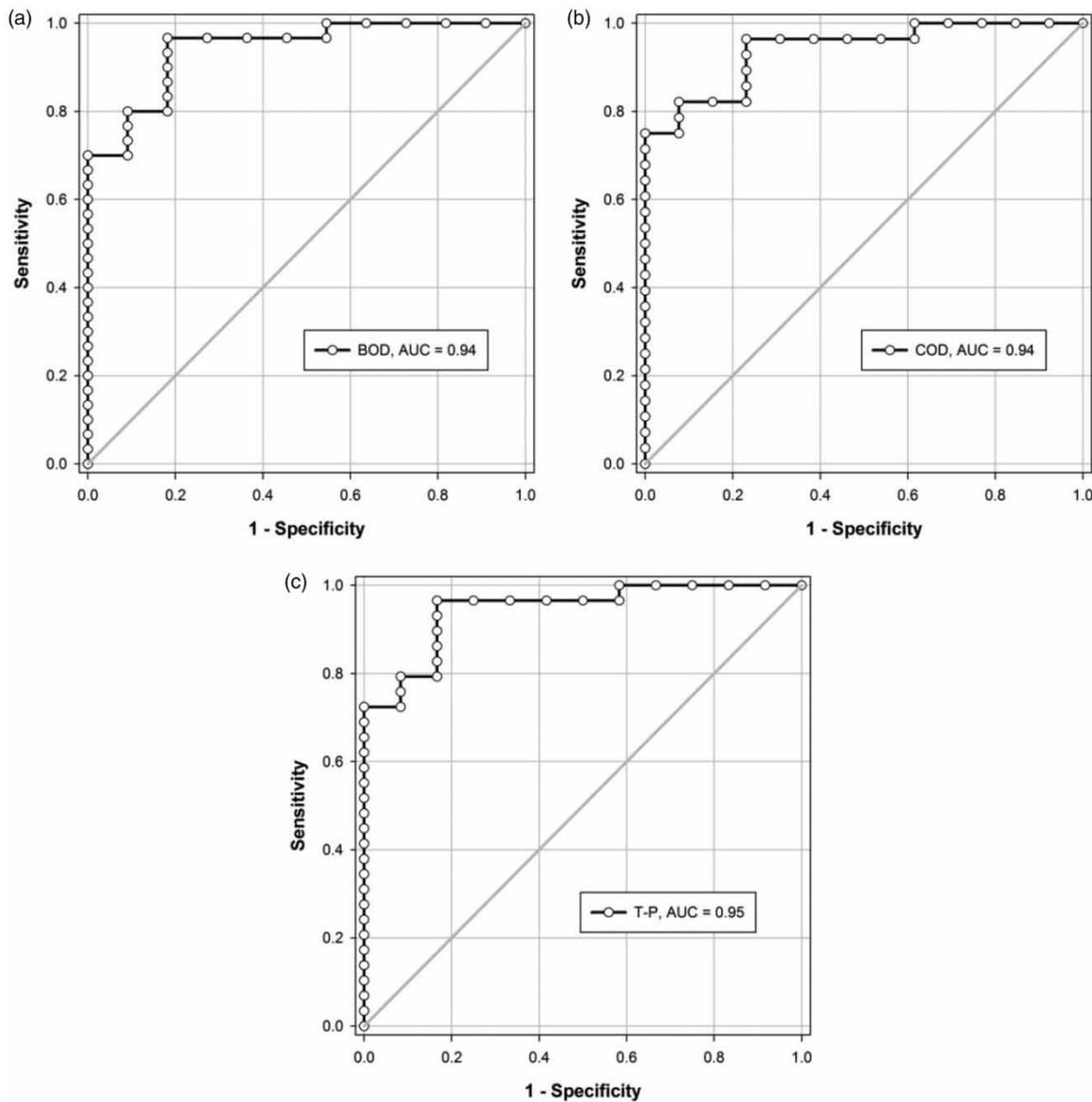

Figure 4 │ Receiver operating characteristic (ROC) curve for (a) BOD, (b) COD, and (c) T-P.

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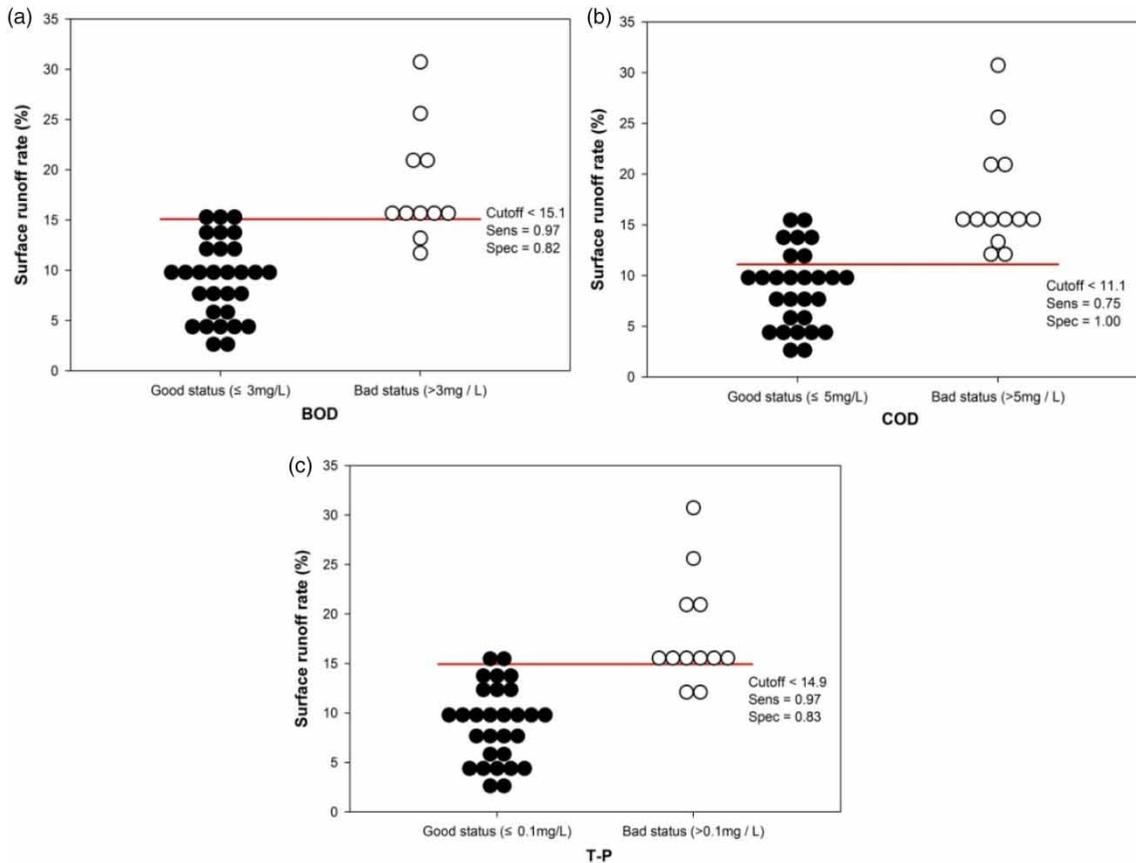
Figure 5 | The cut-off value for (a) BOD, (b) COD, and (c) T-P.

'bad status (worse than Class II of the water quality standard)' because all the AUC values were more than 0.94. The cutoff (or threshold) value of the surface runoff rate at which the degradation of stream water quality occurs ranged from 11.1% to 15.1% for BOD, COD, and T-P (Figure 5). This result indicates that managing the surface runoff rate to be approximately within 15% can strategically be required to prevent the degradation of stream water quality caused by a higher surface runoff rate in the watershed and to satisfy the stream water quality standards for Class II which is the target of stream water quality management in Korea.

CONCLUSIONS

In this study, the HSPF model and statistical analysis including the linear regression analysis and ROC curve analysis were applied to investigate the relationship between the surface runoff rate and stream water quality. The results derived

from this study reveal that the surface runoff rate significantly affects the stream water quality parameters including BOD, COD, and T-P. In addition, it was found that since higher proportions of surface runoff could lead to higher concentrations of BOD, COD, and T-P in streams, managing and controlling the surface runoff rate within approximately 15% could be a fundamental strategy to prevent the degradation of stream water quality.

The results from this study could be slightly different from those derived from other hydrologic models because the others models could employ different methods for simulating the hydrologic components including surface runoff. Thus, more research may be needed to compare the results simulated by various hydrologic models. In addition, various other ranges of possible surface rate in the watersheds were not sampled as this study was performed using observed water quality data in order to analyze the impact of the surface runoff rate on stream water quality. Therefore, further research based on simulated water quality data using the

calibrated and validated model for water quality is rec-ommended to analyze the relationship between the surface runoff rate and stream water quality.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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