Journal of Korean Society on Water Environment, Vol. 32, No. 2, pp. 142-148 (March, 2016)
pISSN 2289-0971 eISSN 2289-098X http://dx.doi.org/10.15681/KSWE.2016.32.2.142

Characterization of Stormwater Runoff according to Sewer System in Paldang Watershed

Dong-Han Kang[*] · Raja Umer Sajjad[**] · Keuktae Kim[*] · Chang-Hee Lee[**,†]

[*]*Department of Water Research, The Gyeonggi-do Health and Environment Institute*
[**]*Department of Environmental Engineering and Energy, Myongji University*

하수도 시스템 유무에 따른 강우유출특성 분석 - 팔당호 유역을 대상으로

강동한[*] · 라자 우말 사자드[**] · 김극태[*] · 이창희[**,†]

[*]경기도보건환경연구원 수질연구부
[**]명지대학교 환경에너지공학과

(Received 3 November 2015, Revised 5 January 2016, Accepted 20 January 2016)

Abstract

The characterization of stormwater runoff from mix land-use catchments with an inadequate sewer network is a challenge. This study focused on characterizing stormwater runoff from the Paldang watershed area based on land-use type and sewer system coverage. A total of 76 sites were monitored during wet weather from seven different counties within Paldang watershed. Public sewer system (*PSS*) was installed at 48 sites, while 28 sites had no or individual sewer system (*ISS*) coverage. The results indicated that the sites included in the ISS group with higher forest and paddy land-use percentage exhibit higher values of average event mean concentrations (*EMCs*) and first flush intensity for suspended solids (*SS*), total nitrogen (*TN*), and total phosphorous (*TP*). In addition, upgrading runoff interception system can capture 59 % of the TP load in the first 43% of runoff within these sites. Similarly, rainfall depth and storm duration showed a positive correlation ($R > 0.6$) with nutrient loads within *ISS* group sites, as compared to *PSS* group. Therefore, these sites are likely to contribute higher *TP* and *TN* loads during heavier storm events and should be selected as priority management areas to combat the problem of eutrophication in Paldang reservoir.

Key words : Eutrophication, Land-use, Sewer system, Stormwater runoff

1. Introduction

Non-point source (*NPS*) pollution not only occurs at various development sites, but also in everyday surroundings, including urban and industrialized areas, agricultural regions, forests, roads, rivers and streams. Changes in rivers, lakes and aquifer water quality are strongly related to surrounding land-use and land cover (*LULC*) (Bolstad and Swank, 1997) and the type of land-use usually determines the kinds and amounts of contaminants that flow into receiving water bodies (Moss, 1998). The type of water contamination is directly related to anthropogenic activities and non-point or point source, which can be quantified in terms of the population density and land-use type in the watershed (Elliott and Sorrell, 2002). The fact that non-point source pollution fluctuates according to precipitation causes difficulty in setting up management measures. It has long been recognized that the pollutant build-up and wash-off processes are influenced by rainfall and catchment characteristics (Kim et al., 2007; Liu et al., 2013). However, it is difficult to identify the characteristics of stormwater runoff, especially from mix land-use catchments with inadequate sewer system coverage.

In Korea, more than 70% of annual rainfall occur during the summer monsoon period. Consequently, reservoirs have been created for water management and > 90% of Korean water supplies use surface water from rivers and reservoirs (Park et al., 2009). The Paldang reservoir plays an important role in supplying drinking water to Seoul (the capital of South Korea) and the surrounding regions. It includes several multi-purpose dams which control the hydrological and water quality characteristics of the river system. High intensity rainfalls have been occurring frequently causing high fluctuations in total effluent load in Paldang reservoir. Water quality degradation, particularly eutrophication issues in the

† To whom correspondence should be addressed.
changhee@mju.ac.kr

Paldang reservoir over the last few decades has been continually reported (Kim et al., 1995; Shin et al., 2000; Youn et al., 2010) and stormwater runoff from various areas such as urban, agricultural, and industrial regions is considered to be a major source of water quality degradation.

While managing stormwater runoff, the land use of a catchment area plays an important role in the runoff process. Land use types can dictate or correlate with many other factors such as ground cover, soil type, topography and even rainfall patterns when looking at a much larger scale. Several researchers have shown that there are strong relationships between the land use of a particular site and the runoff volume and characteristics (Ying et al., 2009). In this study stormwater runoff was monitored and characterized from seven different counties within Paldang watershed, according to land use and population density. Several monitoring sites were selected within each county based on sewer system as some areas within each county is connected to the public sewer system while others have individual or no sewer system.

The primary purpose of this study was to characterize the stormwater runoff according to land use type and sewer system facility in Paldang watershed. All sites were grouped into two groups; those connected to the public sewer system (referred as *PSS* group) and others with individual or no sewer system (referred as *ISS* group). The comparison of both groups was made in terms of event mean concentrations (*EMCs*), unit effluent load, first flush intensity and correlation with hydrological parameters and land use percentage. This study provides baseline information to identify priority management areas and role of a sewer system in order to combat non-point source pollution in Paldang reservoir.

2. Materials and Methods

2.1. Study Area

The Paldang reservoir is one of Korea's major reservoirs, and one from which most people in Seoul and the surrounding areas receive drinking water. The watershed of Paldang reservoir covers 20,459 km^2 comprising the portion of 3 provinces, 11 cities and 18 counties. Monitoring sites were selected evenly at 7 special countermeasure counties, according to land-use and population density. A total of 76 monitoring sites were selected within 7 counties in Paldang watershed (Figure 1). Geographic information system (*GIS*) was used to determine the land-use characteristics within each county (Gyeonggi-do Provincial Government, 2010). The average land-use percentage of the study area and the hydrological characteristics of monitored events is presented in Table 1.

Fig. 1. Sampling locations in the Paldang reservoir watershed

2.2. Sampling Strategy and Water Quality Parameters Analysis

Pollutant concentrations, rainfall, and flow were measured for the entire storm duration. Among the 76 sites selected for storm water monitoring in Paldang watershed, 48 were connected to the public sewer system (*PSS* group) whereas 28 sites has no or individual sewer system (*ISS* group). Stormwater runoff monitoring was carried out from April 2009 to November 2011. A total of 26 storm events were monitored throughout the monitoring period with storm duration ranged between 2 to 29.9 hours. Similarly, rainfall intensity ranged between 0.4 to 11mm/hr and the rainfall depth ranged between 2 to 104 mm for all monitored events. The hydrological characteristics of monitored events do not show any considerable variation within both groups. The antecedent dry days (*ADD*) were determined as the number of days following the cessation of measurable rain. In this study, minimum *ADD* were selected to be $\geq$ 2 and ranged between 2 to 12 days in both *PSS* and *ISS* group sites. Each site was monitored 5-6 times during wet weather and 12-15 grab samples were acquired during each event based on optimal sampling frequencies described by Leecaster et al. (2001). Samples were taken at 5 to 15 min intervals in the initial hour of the storm event, and then at 60 min interval during receding flow. The shortest acceptable sampling duration for each event was based on the principle of sampling from the beginning of the runoff until it recovered to its

Table 1. Summary statistics of rainfall and land use type in study area

	Hydrological parameters				Area	Land use (%)				Other factors	
	Storm duration (hr)	Rainfall intensity (mm/hr)	Rainfall depth (mm)	ADD (days)	Area (ha)	Imper--vious cover	Farm land	Paddy field	Forest	Slope (%)	Population (capita/ha)
Average	10.7 (12.6)	4.7 (2.9)	39.1 (27.0)	8 (7)	18.2 (3.9)	19.2 (63.7)	15.3 (15.6)	9.0 (8.1)	52.7 (3.7)	13.8 (4.6)	8.6 (67.0)
Stdev	6.9 (7.3)	2.0 (2.5)	22.0 (16.4)	2 (2)	17.5 (3.8)	19.1 (21.3)	10.8 (12.4)	13.3 (11.6)	28.2 (6.5)	8.1 (4.9)	11.1 (132.2)
Min	4.0 (2.0)	2.5 (0.4)	18.5 (2.0)	2 (2)	0.5 (2.2)	0.5 (2.2)	- (-)	- (-)	- (-)	1.0 (0.1)	0.3 (0.2)
Max	28.5 (29.9)	8.9 (11.0)	104.3 (66.5)	12 (12)	73.1 (98.3)	- (-)	44.3 (48.0)	55.2 (44.4)	95.0 (26.7)	26.6 (18.0)	53.8 (606.0)

*Parenthesis data refers to PSS group; without parenthesis data refers to ISS group

original flow. Meteorological information for each rainfall event was obtained from the regional office of the National Weather Service in Korea. Rainfall data were also measured through an automated rainfall gauge. Automated flow meter was installed at the outlet of the catchment area, and discharge was calculated based on velocity, depth of water, and width of the channel. Two liters of each sample were collected in polyethylene bottles, and transported to the laboratory and refrigerated at 4°C until analysis. Water quality parameters including, chemical oxygen demand (*COD*), biological oxygen demand (*BOD*), suspended solids (*SS*), total nitrogen (*TN*), and total phosphorous (*TP*) were analyzed according to Korean standard methods.

2.3. Data Analysis

Some stormwater management strategies are based on the assumption that there is a first flush of pollutants at the start of each event. The first flush of pollutants can be visualized by a hydro-pollutograph, in which an X-Y plot of pollutant mass (M) against volume (V) is developed. On this plot a cumulative M-V line and a bisector line (45° line) are drawn and first flush occurred when M-V line lies above the bisector line. In this study first flush mass and volume is calculated by the difference of M-V line and bisector line. The highest difference point between M-V and bisector line means the first flush amount for *BMPs* (Best Management Practices). In this study first flush characteristics were compared between *PSS* and *ISS* group sites in order to quantify the effluent load percentage corresponds to initial runoff.

Similarly *EMCs* and pollutant loads were also estimated from different sites occupying variable land use type percentage to evaluate the stormwater runoff quantity and quality characteristics of the monitored events. *EMC* is appropriate for evaluating the effects of stormwater runoff on receiving waters and is often used as a single index to characterize concentrations. It can be expressed as:

$$EMC = \frac{M}{V} = \frac{\int_0^t Ct\,Qtdt}{\int_0^t Qtdt}$$

Where C_t is the pollutant concentration at time t and Q_t is the storm water discharge at time t. M is the pollutant mass and V is the runoff volume during the storm event. *EMC* can be used in water quality management and concentration control for a catchment as it reflects the water quality of the runoff.

The runoff coefficients could be calculated for the storm event measured by taking into account the total rainfall and total catchment area and is an important factor in calculating the pollutant load. The generated load mechanism of watershed development was estimated by using the *EMCs* criteria, which requires flow rate, pollutant concentration, and time data. Both *EMCs* and load values were then compared according to sites grouping. To analyze the impact of hydrological parameters and land use percentage on *EMCs* and pollutant loads, a Pearson's correlation coefficient matrix (MS Excel, 2010) was adopted to perform a bivariate analysis of storm water quality parameters. Pearson correlation coefficient is a measure of the correlation between two variables, giving a value between +1 and -1 inclusive. The two-sided test method was chosen for significance level at a ^{p} value < 0.05.

3. Results and Discussion

3.1. Rainfall and Land Use Characteristics of Monitoring Sites

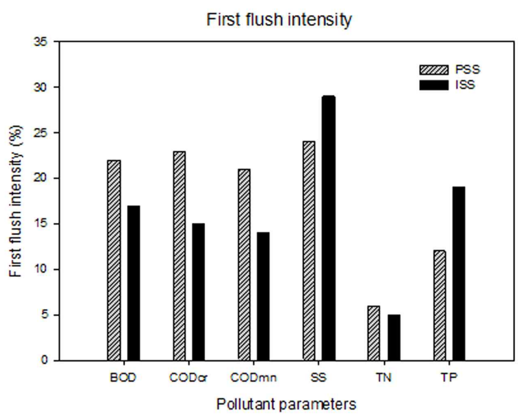
The statistical summary of monitored rainfall events and land use percentage is shown in table 1. The study area is classified into four different land use types including impervious cover, farm land, paddy field, and forest. The geomorphological factors like slope and population density were also quantified. At *PSS* group sites, the average impervious land use and population density are higher i.e.; 63.7 % and 67.0 capita/ha as compared to the *ISS* group which is 19.2 % and 8.6 capita/ha respectively. It shows that *PSS* group mostly represents the urban area within the watershed. On the other hand, average forest land-use percentage is considerably higher, i.e.; 52.7 % in the *ISS* group as compared to 3.7 % in *PSS* group. Overall, the average watershed area connected to the public sewer system is far less.

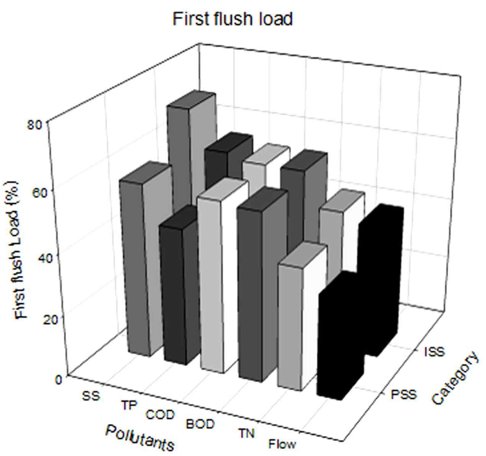
3.2. First Flush Analysis

Initial rainwater interception is one of the effective and popular measure to reduce runoff pollutant loads if the catchments have high first flush intensity. Generally, the first flush intensifies as the watershed area gets smaller, the impervious land area gets larger or the rainfall intensity increases (Lee and Bang, 2000). A Similar trend was observed in this study for most water quality parameters. The first flush intensity for BOD_5, TN, COD_{cr}, and COD_{mn} was observed higher at *PSS* group sites (Figure 2) with higher impervious cover and smaller watershed area. However, the first flush intensity for *SS* and *TP* was found higher at *ISS* group sites. This is perceived to be the function of rainfall characteristics and higher forest land-use percentage within *ISS* group sites (Table 1). In case of *ISS* group sites the average rainfall intensity and rainfall depth of monitored events were comparatively higher. This is particularly noticeable in the case of *SS* first flush intensity, where runoff flow (function of rainfall intensity) needs sufficient energy to scour and mobilize the pollutant as well as runoff volume (function of rainfall depth) to wash out the pollutant. The study carried out by Menacher and Augustin (1992) showed that first rainfall peak is not necessarily sufficient to flush out a sewer system and that the following flow peaks, when they exist, contribute greatly to the pollutant mass discharged. However, Bertrand-Krajewski et al. (1998) argued that these conclusions can be different for pollutants other than suspended solids because of their sources and their transfer conditions. In terms of pollutant loads, 33 % of the initial flow at *PSS* group sites contain 40 % to 57 % of all pollutant loads whereas, 43 % of the initial flow at *ISS* group sites contain 46 % to 71 % of all pollutant loads. The results imply that intercepting the first 33 % and 43 % of runoff volume can remove 40 % to 57 % and 46 % to 71 % of all pollutant loads respectively within *PSS* and *ISS* group sites. In case of *TP* load, which is considered major pollutant causing eutrophication within Paldang reservoir, 59 % of load can be captured during first 43 % of storm runoff by upgrading runoff interception system. As mentioned in earlier section, the average area connected to *PSS* within Paldang watershed is far less compared to *ISS* (table 1), lack of sewer system within these sites is supposed to accelerates the erosion of topsoil and the untreated stormwater runoff is constantly being discharged into the tributaries and subsequently entering the reservoir without any treatment. Therefore, first flush should be taken into account while selecting management measures such as a storm runoff interception system to reduce the pollution loads for Paldang reservoir. The effective rainfall range for designing runoff interception system as *BMPs* (Best management practices) was found to be 4.5 mm and 3.5mm for both *PSS* and *ISS* group sites respectively.

3.3. Pollutant Loads and *EMCs* Comparison

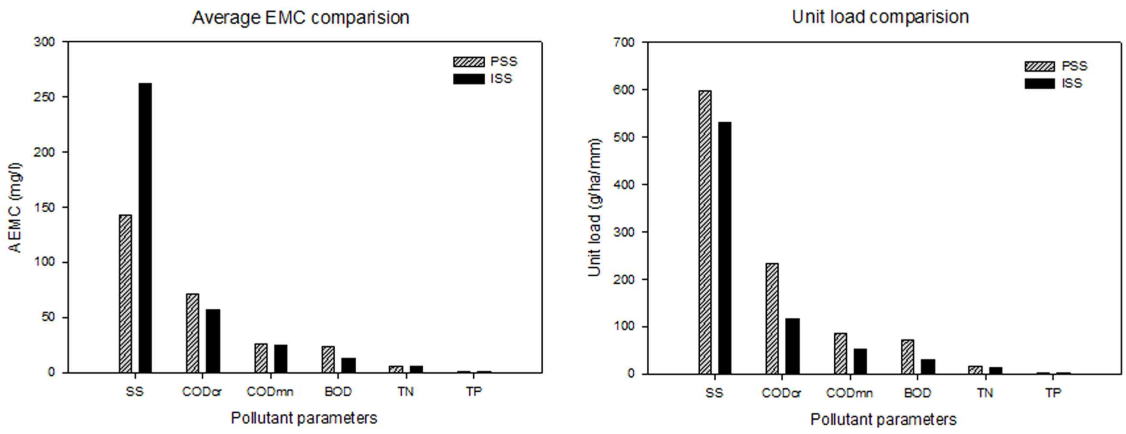
The runoff coefficient calculated for *PSS* group sites was found to be 0.40 as compared to 0.23 for *ISS* group sites. In case of *ISS* group, the EMC for *SS*, *TN*, and *TP* were 1.8, 1.2, and 1.4 times higher than *PSS* group sites (Figure 3). It is thought to be the function of watershed characteristics such as slope and the land-use impact within *ISS* group sites which has higher coverage of forest and paddy fields. The application of fertilizers and soil erosion in steeper areas is perceived to be greater within these sites which results in





PSS: Public sewer system; *ISS*: Individual sewer system

Fig. 2. First flush intensity and load comparison.



PSS: Public sewer system; *ISS*: Individual sewer system

Fig. 3. Pollutants average *EMC* and unit load comparison.

higher EMC values for solids and nutrients. The center for streamside studies (2001), found a strong correlation between *TSS* and *TP* under storm conditions, which indicates that the dominant fraction of *TP* moved through the stream systems in particulate form. Therefore, controlling sediment will aid in controlling particulate -bound phosphorous. Because of inadequate sewer network within these sites, the sediment-attached nitrogen and phosphorous could be dissolved and transported to receiving water body during heavy rainfall event. It has important implications as Paldang reservoir faces major problem of eutrophication in recent years (Kim et al. 2014). The higher nutrient concentrations contributed by *ISS* group sites can be selected as priority management area to combat eutrophication of Paldang reservoir. On the other hand, organic matter (*BOD* and *COD*) showed higher *EMC* values in *PSS* group. The *PSS* group sites are mainly associated with urban area with the higher percentage of impervious cover. The main sources of organic matter during storm events are restaurants and food stalls, especially in the commercial catchments. Therefore, higher *EMCs* regarding organic matter were observed within *PSS* group sites.

However, the pollutant loads results were different compared to *EMCs* between two groups. The unit load for all pollutants were found higher is *PSS* group compared to *ISS* group (Figure 3). This was due to the difference in the drainage area sizes and runoff coefficient. The relative effluent loads of *SS*, *TN*, and *TP* are higher within the *ISS* group than that of organics.

3.4. Correlation of *EMCs* and Pollutant Loads with Different Parameters

The Pearson correlation analysis was carried out in order to determine the relationship of *EMCs* and pollutant loads with hydrological parameters as well as with land use percentages and geomorphological factors. The pollutant load showed relatively higher positive correlation with hydrological parameters in the *ISS* group as compared to *PSS* group. The nutrient load within *ISS* group sites showed a positive correlation ($R^2 > 0.6$) with rainfall depth and storm duration. It shows that these sites can contribute elevated nutrient load during heavier storm events and therefore can be targeted as priority management areas. Overall, rainfall depth and storm duration exhibit positive R^2 values (> 0.4) with almost all water quality parameters. Similarly, impervious land use percentage and population density also showed relatively higher R^2 values (> 0.6) with pollutant loads in *ISS* group. Generally, the correlation coefficient for pollutant loads was found very pronounced and higher in the *ISS* group as compared to *PSS* group. It implies that sites connected to the public sewer system are less susceptible to different hydrological and land use variables. The *EMCs* correlation with hydrological parameters and with land use percentage was not profound in both groups. Most constituents *EMCs* showed weak correlation with hydrological parameters as well as with land use percentage.

4. Conclusion

This study focused on characterizing stormwater runoff from the Paldang watershed area based on land-use type and sewer system coverage. In recent years the water quality degradation, especially eutrophication problem in Paldang reservoir is extensively reported. The major sources of excessive nutrients and eutrophication are fertilizers and animal manure, mostly received from agricultural non-point sources. It was found that monitoring sites with a higher percentage of forest land-use with no or individual sewer system coverage generates higher pollutant concentrations for particulate matter and nutrients. Lack of sewer system within these sites accelerates the erosion of topsoil and the untreated stormwater runoff is constantly being discharged into the

Table 2. Correlation of *EMCs* and pollutant loads with various parameters

	Pollutants	Hydrological parameters				Land use (%)				Other factors	
		Storm duration (hr)	Rainfall intensity (mm/hr)	Rainfall depth (mm)	ADD (days)	Impervi--ous cover	Farm land	Paddy fields	Forest	Slope (%)	Population (capita/ha)
Unit effluent load (kg/ha)	BOD	**0.37**	0.02	**0.47**	-0.17	**0.66**	0.17	0.23	**-0.66**	**-0.47**	**0.56**
		(0.12)	(0.01)	(0.04)	(0.07)	(0.05)	(0.10)	(-0.19)	(-0.08)	(0.17)	(-0.23)
	COD_{cr}	**0.64**	0.03	**0.73**	**-0.38**	**0.80**	0.12	0.09	**-0.66**	**-0.54**	**0.70**
		(0.26)	(0.08)	(0.20)	(0.01)	(0.12)	(0.07)	(-0.27)	(0.09)	(0.13)	(0.09)
	SS	**0.46**	0.15	**0.61**	**-0.48**	**0.50**	**0.30**	-0.03	**-0.43**	**-0.47**	**0.49**
		(0.25)	(0.20)	**(0.32)**	(0.05)	(0.14)	(0.06)	(-0.15)	(0.07)	(0.04)	(0.23)
	TN	**0.72**	-0.11	**0.72**	**-0.42**	**0.85**	0.11	-0.02	-0.02	**-0.54**	**0.79**
		(-0.17)	(0.17)	(-0.04)	(0.05)	(0.06)	(0.05)	(-0.17))	(-0.01)	(-0.01)	(-0.12)
	TP	**0.66**	-0.10	**0.75**	**-0.46**	**0.72**	0.25	-0.14	-0.14	**-0.42**	**0.65**
		(0.02)	**(0.34)**	(0.25)	(0.02)	(0.13)	(0.05)	(-0.16)	(-0.07)	(0.04)	(-0.17)
EMC (mg/l)	BOD	-0.14	-0.05	-0.14	0.23	0.22	-0.01	0.12	-0.22	0.19	-
		(-0.02)	(-0.08)	(-0.14)	(0.02)	(-0.07)	(0.24)	(-0.10)	(-)	(0.12)	(-0.14)
	COD_{cr}	-0.08	-0.18	-0.21	**0.32**	0.17	-0.04	0.01	-0.11	-0.15	-
		(0.11)	(-0.11)	(-0.01)	(0.07)	(-0.02)	**(0.36)**	(-0.22)	(-0.22)	(0.10)	(-0.01)
	SS	0.09	0.10	0.07	0.07	0.07	**0.30**	-0.06	-0.13	-0.19	-
		(0.26)	(0.18)	**(0.33)**	(-0.11)	(0.05)	(0.10)	(-0.20)	(-0.20)	(0.06)	(0.19)
	TN	0.13	-0.21	0.03	0.06	**0.54**	0.20	-0.02	**-0.37**	**-0.43**	**0.34**
		(-0.27)	(0.04)	(0.19)	(0.02)	(-0.03)	(0.23)	(-0.10)	(-)	(-0.05)	(-0.18)
	TP	0.20	-0.23	0.12	0.07	**0.30**	0.25	-0.22	-0.18	0.13	0.28
		(-0.06)	(0.28)	(0.20)	(-0.03)	(0.03)	(0.25)	(-0.10)	(-)	(-0.04)	(-0.22)

*Parenthesis data refers to *PSS* group; without parenthesis data refers to *ISS* group

tributaries and subsequently entering the reservoir without any treatment. Based on first flush analysis, it was proposed that installation of the runoff interception system for the first 43 % of storm runoff can capture up to 59 % of nutrient load within these sites and contribute meaningfully in combating eutrophication problem in Paldang reservoir. On the contrary, the sites connected to public sewer network with higher impervious land-use generates higher pollutant concentrations for organic matter. The results of this study will be helpful for *NPS* management policy in Paldang reservoir.

Acknowledgements

Preparation of this article was supported by the Korea Environmental Technology and Industrial Institute, Next Generation Eco Innovation Project (No.413-111-003).

국문초록

토지이용이 혼재되고 하수관거 시스템이 미흡한 유역의 강우유출 특성을 파악하는 것은 매우 어렵다. 본 연구에서는 팔당호 유역에서 토지 이용 및 하수관거 형태에 따른 강우 유출 특성을 파악하고자 하였다. 이를 위해 팔당호 유역 7개 시·군에서 공공 하수관거 시스템 지역 48개소, 개인하수처리시설 지역 28개소에 대한 강우 유출수 모니터링을 실시하였다. 개인하수처리시설 지역의 토지 이용은 산림과 논의 비율이 높았으며 SS, TN, TP EMCs와 초기세척 강도가 공공하수처리지역에 비해 높게 나타났다. 또한 초기강우 차집 시스템을 설치하여 초기강우 유출수 43%를 처리할 경우 59%의 TP 유출부하량을 저감할 수 있을 것으로 기대된다. 개인하수처리시설이 설치된 지역에서 강우량 및 강우지속시간과 영양염류 유출 부하량은 양의 상관관계(R>0.6)를 나타내어 팔당호의 부영양화 문제를 관리하기 위해 개인하수처리지역에 대한 우선적 정책이 필요함을 알 수 있다.

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