Desalination and Water Treatment
www.deswater.com

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doi: 10/5004/dwt.2012.3594

38 (2012) 389–394
January

Taylor & Francis
Taylor & Francis Group

Investigation of stormwater runoff strength in an agricultural area, Korea

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Received 14 October 2011; Accepted 24 December 2011

ABSTRACT

To manage and control the nonpoint source (NPS) pollution and to improve the water quality of impaired streams, rivers and lakes, practices including constructed wetlands, permeable pavement, swales and others are being attempted in the world. Before applying these techniques, an analysis of stormwater runoff characteristics should be understood due to the complexity in estimating system design factors for best management practices (BMPs). This study investigates the stormwater discharge from an agricultural area in Korea. Based on this investigation, pollutant and flow coefficient of variation (PFCoV) values were developed in an attempt to explain the stormwater runoff in the agricultural area. Four field studies categorized by rainfall type were then employed to assess the PFCoV values. The results show that the physical meaning of PFCoV values indicates the variation of NPS pollutants during a storm event. As such, this simple and meaningful result can be applied to a wide range of stormwater management designs or water quality controls in agricultural areas.

Keywords: Water quality management; Stormwater runoff; Agricultural area; Runoff strength; Coefficient of variation; Nonpoint source pollution

1. Introduction

Nonpoint source (NPS) pollutants are generally delivered from land to water bodies during rainfall events. Specifically, in agricultural areas, excessive nutrients and particulates are intensively released by phenomena such as rainfall, snow-melting and human activity. These activities can directly or indirectly cause eutrophication in rivers, lakes, estuaries and coastal oceans [1–4]. The factors affecting NPS release into water bodies can be summarized as rainfall intensity, rainfall duration, rainfall depth, antecedent dry days (ADDs), soil moisture conditions and human activities; the runoff in agricultural areas is a function of these various factors. Therefore, it is essential to understand and analyze these factors as they are potential design factors for determining best management practice (BMP) facilities, such as constructed wetlands, infiltration trenches and others.

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To date, there has been a considerable amount of research conducted in attempts to characterize the stormwater runoff in urban and agricultural areas. Rossi [5] assessed the first-flush strength (referred to as the β coefficient) using a power function. Kato [6] used the β coefficient as the strength of the first-flush and applied the ratio of direct runoff (DR) to examine the DR effect and base-flow on the nutrient discharge from an agricultural watershed having intensive livestock operations. Grant [7] attempted to characterize the relationship between stream flow and pollutant concentration based on fecal indicator bacteria and F$^+$ coliphages (viruses infecting *E. coli*) using statistical approaches. The results of these studies provided a reasonable scientific explanation of stormwater runoff characteristics and for developing a runoff coefficient based on many field experiments. However, these studies have shown limitations in their ability to predict the end of the runoff period and the decay strength of stormwater runoff, with further limitations in employing existing data and basic statistical information such as mean and standard deviation to runoff analyses.

Therefore, the objectives of this study are 1) to develop pollutant and flow coefficient of variation (PFCoV) values to explain the strength of stormwater runoff and 2) to interpret the physical meaning of PFCoV for application to stormwater runoff in an agricultural area.

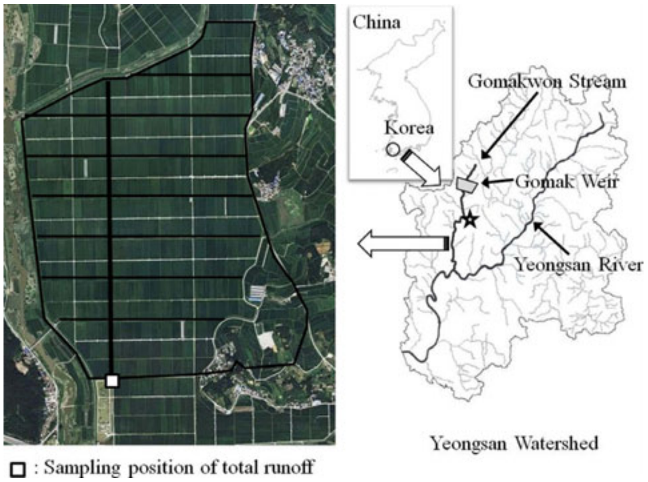


Fig. 1. Location of the field study site in the Yeongsan Watershed, Korea. Open red circles are sampling position of the soil collected to determine soil moisture condition. Open red rectangle is sampling position of total runoff in this drain area. Blue lines are irrigation canals and orange line is drainage canal.

2. Materials and methods

2.1. Site description

The agricultural watershed area for this study is 2.53 km^2 near Naju, in the southwestern region of Korea. Land use in this area includes paddy fields, upland, forests, irrigation ditches and stream banks. The maximum length of the main drainage canal is 1.49 km and is linked with a number of irrigation canals. The irrigation season of this area is from May to October, which includes the annual growing season. The water source for irrigation is from Gomak Weir located in the upstream of Gomakwon Stream, which is one of the tributaries of the Yeongsan River (*see* Fig. 1); return flows are discharged into the same stream. The irrigation requirement is about 1.0–1.2 CMS during the rice-transplanting season, which lasts for about 50 d starting at around May 1st (Table 1).

In general, most rivers in Korea are faced with relatively strong hydrological variation due to active meteorological conditions such as showers, a rainy season and typhoons [8,9]. In addition, this area is surrounded by paddy fields, making the hydrological variation more complex to predict because of human activities such as the use of irrigation water. The annual precipitation in this area was 1482 mm for a 10-y period from 2001 to 2010 (www.kma.go.kr). The rainy season from July to August accounted for 863 mm (about 60%) of the total precipitation; this season overlaps with the growing season of rice in Korea [10].

2.2. Data collection

The flow rate was measured by using an electronic vortex flow meter installed in the end of drainage area and all flow data were automatically transmitted to a storage device using a transmitter (4411e, Woojin Electro-Nite Inc., Republic of Korea). The vortex flow meter is a product of Woojin Inc., Korea and the basic principle of the vortex flow meter is based on von Karman Vortex shedding street theory [11]. This theory makes it possible to measure the turbulent flow with a Reynolds number of Re >3000 and the linear flow with Re >20,000. Flow meter calibration was conducted monthly as per the maintenance manual and all water samples were collected and concurrently measured in terms of conductivity, pH, turbidity and temperature using a YSI 63 pH meter (Yellow Springs, OH, USA) and TN-100 turbidimeter (Eutech Instruments, Singapore). All collected samples were then transported to the laboratory within 6 h at 4°C. For this study, biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and total suspended solid (TSS) were measured using standard methods [12]. For this study, precipitation data were measured using a rain gage that was installed at the end of the drainage area.

Table 1
Features of monitoring sites and storm samples

A. Surrounding land use

	Forest	Paddy	Field	Ground	Total
Area (ha)	3.1	215.6	24.5	9.8	253.0
Ratio (%)	1.2	85.2	9.8	3.8	100

B. Monitoring information

	Date	ADD	Rainfall (mm)	Duration (h)	Total 5-d ADD rainfall (mm)	Rainfall intensity (mm/h)
1	Jan. 20, 2010	7	10.0	4.0	0.0	3.0
2	May. 17, 2010	10	70	18.0	0.0	14.5
3	Jul. 25, 2010	1	12.5	0.2	78.0	69.4
4	Oct. 02, 2010	10	20.5	7.8	0.0	5.0

3. Results and discussions

3.1. Water quality analysis in agricultural runoff

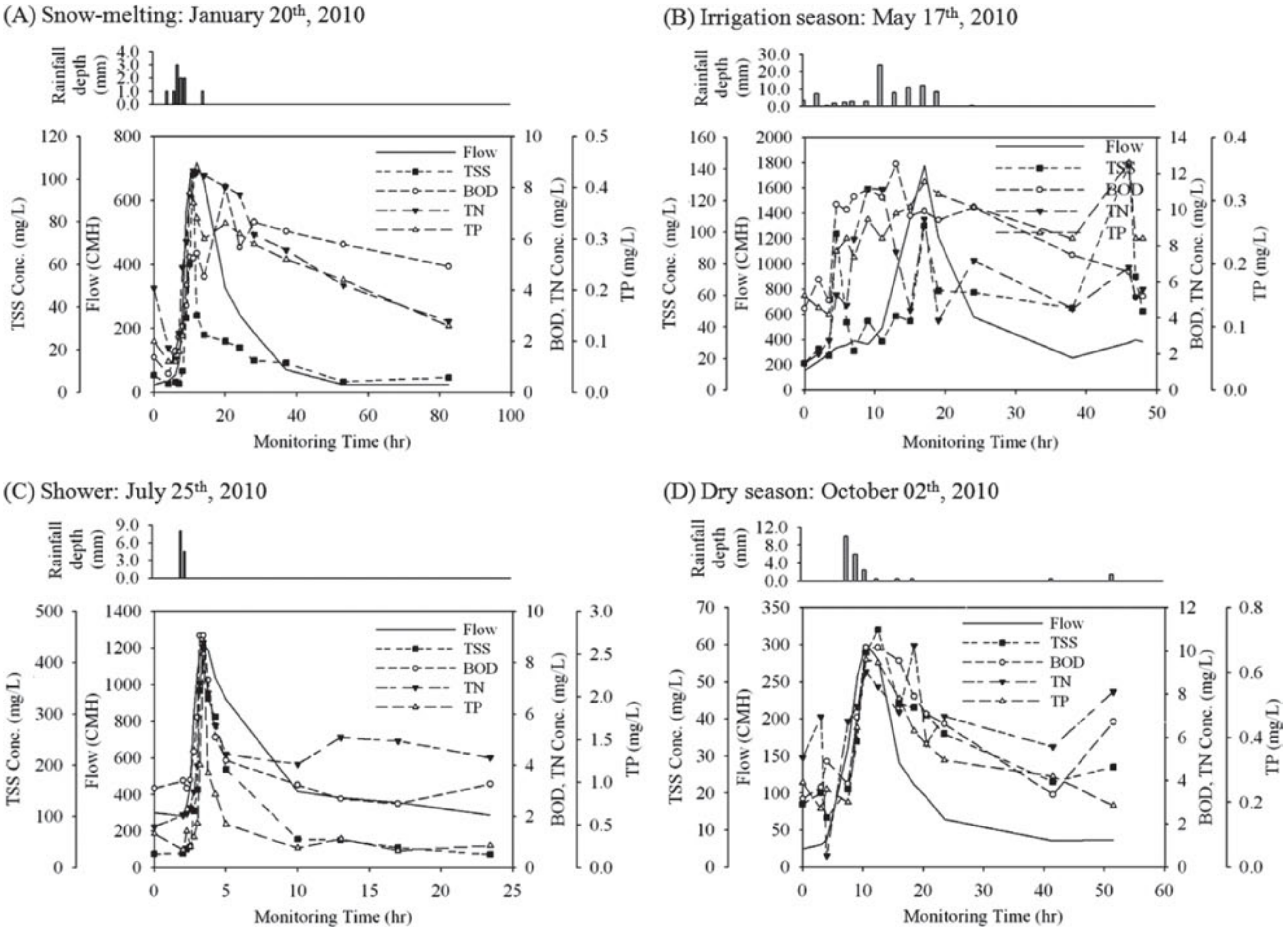
Runoff patterns can be categorized based on varying stormwater events by considering human activity, as well as rainfall characteristics such as snow-melting and showers. This study categorizes events as snow-melting, irrigation season, shower and dry season in accordance with the runoff and rainfall types in an agricultural area. Fig. 2 presents the categorized runoff hydrographs and pollutographs at the end of the drainage area for different rainfall events. In the figure, the horizontal axis indicates the monitoring time and the vertical axis indicates the concentration of each parameter and rainfall depth for each rainfall event. The runoff characteristics pertaining to the background, including meteorological information, flow variation and pollutant concentration variation are as follows.

1) Snow-melting by rainfall (January 20, 2010): Variation of the hydrograph for flow rate was considerably similar with pollutographs for all parameters including TSS, BOD, TN and TP. In the case of TSS, after approaching the peak point, the concentration dramatically decreased. The reason for this decrease is assumed to be either: 1) the dilution effect by the water melted the snow and/or 2) there was a discharge of relatively huge particles due to frozen soil. The different peak point times of the hydrographs and pollutographs were then compared.
2) Irrigation season (May 17, 2010): Variation of the hydrograph for flow rate was considerably different from the pollutographs for all parameters in Fig. 2(B). The reasons for these differences are the relatively long rainfall duration (24 h), high rainfall depth (70 mm), high maximum rainfall intensity (22 mm/h) and increased base flow from irrigation water (10 × increase from 20 CMH to 200 CMH). The long duration and high rainfall intensity caused a lasting discharge of particulate from soil erosion and seasonal characteristics from agricultural activities such as fertilization and spraying pesticide affected the concentration level for each parameter.
3) Shower (July 25, 2010): Variation of the hydrograph for the flow rate and pollutographs for all parameters were similar to that of snow-melting by rainfall (*see* Fig. 2(A) and 2(C)). The reasons are: 1) there was a relatively short rainfall duration and 2) only a single rainfall period during the storm event. However, in the case of showers, the rainfall intensity was the highest (69.4 mm/h) among all monitored data.
4) Dry season during fallow period (October 2, 2010): Initial variation of the hydrograph and pollutographs was considerably analogous between snow-melting and showers. The reason for this similarity is strongly assumed to be due to the similar antecedent soil moisture conditions (38.7%) compared to snow-melting (38.5%) and shower (39.6%). Generally, the paddy field conditions during the fallow period from October are dry and exposed to litterfall after harvesting. Runoff from the drainage hole in the paddy field during this period is more predominant than the surface runoff unless the rainfall type is shower or heavy rainfall; drainage holes continuously discharge NPS pollutants from the paddy field during storm events.

3.2. Analysis of coefficient of variance

Table 2 shows the mean, standard variation and coefficient of variation (CoV) in each storm event and each parameter. The CoV can be calculated as:

$$\mathrm{CoV} = \frac{\sigma}{\mu} \qquad (1)$$



(A) Snow-melting: January 20th, 2010

(B) Irrigation season: May 17th, 2010

(C) Shower: July 25th, 2010

(D) Dry season: October 02th, 2010

Fig. 2. Hydrographs and pollutographs for each storm event in a paddy field.

Table 2
Mean, standard deviation and coefficient of variation of flows and pollutants

	TSS			BOD_5			Flow		
	Ari. Mean	S.D.	CoV	Ari. Mean	S.D.	CoV	Ari. Mean	S.D.	CoV
Snow-melting	23.56	25.93	1.10	4.36	2.13	0.49	290.55	272.62	0.94
Irrigation	55.53	33.37	0.60	8.51	2.57	0.30	582.84	458.67	0.79
Shower	144.07	139.63	0.97	4.66	2.21	0.47	683.21	379.79	0.56
Dry season	33.95	15.70	0.46	6.47	2.53	0.39	121.12	100.32	0.83
	TN			TP					
	Ari. Mean	S.D.	CoV	Ari. Mean	S.D.	CoV			
Snow-melting	13.77	6.42	0.47	0.22	0.12	0.52			
Irrigation	4.56	1.24	0.27	0.24	0.07	0.27			
Shower	4.09	1.45	0.35	0.63	0.61	0.97			
Dry season	4.94	1.37	0.28	0.36	0.16	0.44			

where μ is the mean and σ is the standard deviation for each storm event.

Across the data from the storm hydrograph and pollutographs, the mean and standard deviation were found to be dependent on the rainfall type. In terms of flow, TSS and TP, the rainfall intensity mainly affected their discharge characteristics. However, in the case of TN and BOD, there was no discharge characteristic determined based on rainfall intensity, depth and ADD; Rossi and Kato reported similar phenomena during storm events [5,6]. The CoV values for four storm events were less than 1.0, except for the TSS during the snow-melting event, which implies that the distributions of each storm event were statistically considered low-variance—except for one case. To more fully understand the storm water discharge, this study subsequently separated the hydrograph based on the peak flow and conducted a variance analysis of all parameters. Table 3 shows the PFCoV values of the separated stormwater runoff data, where the PFCoV value is a relation between the CoV of flow rate and CoV of pollutant during a storm event (Fig. 3). The PFCoV values can be calculate as:

$$\text{PFCoV} = \frac{\text{Coefficient of variance of flow}}{\text{Coefficient of variance for pollutant}} \quad (2)$$

The before and after values were determined based on the peak flow rate obtained during each storm event. As shown in Table 3, most cases show that the before value is greater than the after value, indicating that the pollutant variation before peak flow is greater than after peak flow. Then, in terms of physical meaning 1) if the PFCoV value is greater than 1.0, the pollutant concentration increases and decreases in parallel with the stream flow; and 2) if the PFCoV value is less than 1.0, the pollutant concentration is slightly decreases, such that it is not parallel with the stream flow. Based on these physical meanings and Fig. 2, the runoff characteristics can be explained as follows:

Table 3
PFCoV values for TSS, BOD_5, TN and TP

		TSS	BOD_5	TN	TP
Snow-melting	before	1.29	0.67	0.65	0.82
	after	1.09	0.19	0.35	0.26
Growing season	before	0.75	0.34	0.38	0.35
	after	0.55	0.35	0.22	0.21
Shower	before	1.87	0.86	0.88	1.85
	after	1.59	0.92	0.41	1.87
Dry season	before	0.67	0.54	0.42	0.60
	after	0.43	0.38	0.22	0.49

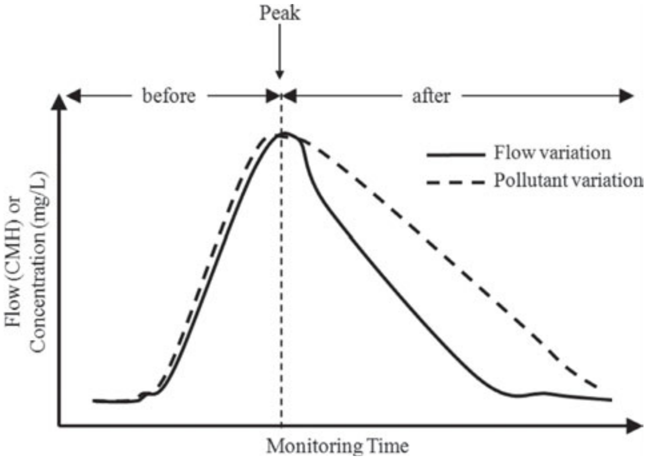


Fig. 3. Conceptual summary of the relation between pollutant and flow coefficient of variations (PFCoV).

1) Snow-melting by rainfall (January 20, 2010): Variation of the TSS concentration sharply increased and decreased according to the flow rate. PFCoV values indicate that the TSS concentration change was faster than the flow rate variation. The PFCoV values of BOD_5, TN and TP after peak flow were less than 1.0, indicating that the pollutants were lastingly discharged during the storm events (*see* Fig. 2).
2) Irrigation season (May 17, 2010): In the rainfall event for an irrigation season, the PFCoV values were relatively low compared to the other storm events because, as mentioned earlier, there were critical factors affecting the stormwater discharge in agricultural areas, including rainfall duration, rainfall depth and pond effect from irrigation water.
3) Shower (July 25, 2010): Variation of the TSS and TP concentration considerably increased and decreased according to the flow rate. The CoV values indicate that TSS and TP concentration changed faster than the flow rate variation (*see* Fig. 2). The PFCoV values of BOD_5 and TN after peak flow were less than 1.0, indicating that the pollutants were lastingly discharged during the storm events.
4) Dry season during fallow period (October 2, 2010): The PFCoV values for the dry season were less than 1.0 for all parameters, suggesting that the pollutants were lastingly discharged during the storm events.

4. Conclusions

Based on these results, the conclusions can be summarized as follows:

1) The stormwater runoff can be explained by the CoV values. In basic terms, our findings note that every research pertaining to stormwater runoff has mean and standard deviation results that can be used to determine stormwater runoff characteristics.
2) The relationship between the flow rate and pollutant concentration can relatively indicate which pollutant is more lastingly discharged during a storm event.
3) The physical meanings of PFCoV value are:
   - PFCoV > 1.0: pollutant runoff is dramatically increased or decreased compared to the flow rate during a storm event
   - PFCoV < 1.0: pollutant runoff is lastingly discharged compared to the flow rate during a storm event
   - PFCoV = 1.0: pollutant runoff is proportionally discharged compared to the flow rate during a storm event

Acknowledgements

This research was supported by the Korea Ministry of Environment as “The Eco-innovation Project: Nonpoint source pollution control research group”.

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