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Determination of best management timing of nonpoint source pollutants using particle bins and dimensionless time in a single stormwater runoff event

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ABSTRACT

Efforts to alleviate nonpoint source (NPS) pollution contributing to the degradation of water quality in aquatic environments have increased over the last several decades. In this research, dimensionless time (τ_{DL}) and particle size bins were applied as indicators to optimize the management timing for NPS pollutants. Field experiments that included four single storm events and two multiple storm events were conducted in order to measure the flow and to collect water samples for the analysis of particle size bins at each monitoring site. Particle bins for all samples were measured using an LS230 laser diffraction particle size analyzer. An analysis of variance (ANOVA) test was carried out to statistically identify the importance of τ_{DL}. By considering the particle size bins of NPS pollutants during a single stormwater runoff event, these results showed that τ_{DL3} which is triple time of τ_{DL1} after τ_{DL0} optimized the flow management timing. ANOVA and *post hoc* tests further confirmed that τ_{DL3} can be viewed as an equivalent time for the end of particle discharge during a single storm event. In practical terms, this study thus suggests that the volume of first-flushed stormwater captured prior to τ_{DL3} is an important criterion for best management practices. It is also expected that the methodology proposed in this research using particle bins and τ_{DL3} can be further extended to different drainage areas and land uses.

1. Introduction

The quantitative management of nonpoint source (NPS) pollution is a function of hydrological parameters, such as runoff depth, the time for stormwater runoff, and other properties, including the discharge concentrations of NPS pollutants (Stephenson et al., 1998). Over the last several decades, methods attempting to quantify NPS pollution, such as pollutant loading, event mean concentrations (EMCs), and dynamic EMCs, have been developed using hydrological flows and pollutant concentrations (Kim et al., 2007). These methods were typically applied to assess the characteristics of NPS discharges and loadings into streams or lakes and to determine the relationships among runoff volume, NPS pollutant concentrations, and meteorological conditions (Brezonik and Stadelmann, 2001). Results obtained using these methods revealed that NPS discharges are indeed related to meteorological conditions, including rainfall intensity, rainfall depth, and antecedent dry days (ADDs), and that they subsequently affect the efficiency of structural best management practices (BMPs) for constructed wetlands and infiltration systems (Carleton et al., 2001; Persson and Wittgren, 2003). Structural BMP devices have been generally designed and constructed in attempts to control NPS pollution because of the benefits, such as pollutants removal and flood control (Park and Roesner, 2012). According to the USEPA guidelines for structural BMP designs, there are four major concepts for designing structural BMP devices: (1) BMP performance goals and objectives, (2) hydrological design concepts, (3) flood and peak discharge control strategies, and (4) water quality management strategies. Most guidelines, such as the EPA guideline, mention the importance of stormwater volume and quality; however, some structural BMP devices—over the few decades that they have existed—have been used more to reflect the hydrological variables related to stormwater volume, such as runoff depth, soil permeability, and drainage area. These

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hydrological variables about stormwater runoff make it quite difficult to optimize the solutions for structural BMP designs.

To meet these challenges based on the hydrological characteristics of stormwater, this study employs *dimensionless time* as a flow management scheme based on the peak flow time and *particle size distributions* as controllable NPS pollutant matter. As mentioned above, one of the major objectives of structural BMPs is to control the peak flow of stormwater runoff. In single stormwater runoff events, the flow rate has one peak flow point and two dimensions, time and length. To compare the flow rate or runoff characteristics of single storms, a reference point in accordance with the peak flow can be a reasonable guide in a hydrograph. The purpose of using dimensionless time in this study is to set the time equivalent to a peak of 1.0. The definition of *time-to-peak* is the time interval from the start of direct runoff to the time needed to reach a peak runoff, as recorded in the hydrograph. For example, if the measured total runoff duration is 10 h and the peak time is 2.5 h after the direct runoff, then the total runoff dimensionless time is 4.0 (10 h divided by 2.5 h). This elimination of the time dimension can make it easier to generalize runoff patterns and to then compare runoff characteristics, such as pollutant loadings or particle size distributions.

Another objective of optimizing the structural BMP device design is to control the stormwater quality. Even though no clear relationship between pollutant wash-off and stormwater flow has been established, relationships between the discharge of NPS pollutants, such as nutrients and heavy metals, and soil particles discharged from stormwater has been reported (Vaze and Chiew, 2004; Yun et al., 2010; Zhao and Li, 2013). The relations can be summarized as follows:

- Particulate matter less than 50 μm in size is related to total suspended solids (TSS) loads of about 70–80% (Andral et al., 1999).
- Total nitrogen (TN) loads of 30–60% and total phosphorus (TP) loads of 30–50% in stormwater are related to particles less than 20 μm in size (Tomanovic and Maksimovic, 1996; Roger et al., 1998; Andral et al., 1999; Furumai et al., 2002; Brenner et al., 2002).
- In TSS concentrations of less than 100 mg/L, particulate matter less than 20 μm in size comprised over 50% of TSS loadings (Furumai et al., 2002).

These studies indicate that the analyses of stormwater particulate matter can be used to more effectively manage NPS pollutants and the design of structural BMPs, such as to determine the optimal size of drainage capture reservoirs. The optimal design of BMPs can potentially include cost savings for construction and maintenance. As such, this study intensively analyze the particle size distributions (PSDs), pollutant loads, and flow variations based on dimensionless time. Based on these considerations, the objectives of this study are (1) to identify the best flow management timing of single stormwater runoff events using PSDs and dimensionless time and (2) to suggest procedures for determining the optimal volume design of BMPs.

2. Materials and methods

2.1. Description of study area

The study area is in the southwestern part of Korea (see Fig. 1(A)). The drainage area is about 2.54 km^2 and is composed of paddy fields, upland, irrigation and drainage canals, and stream banks; of these, paddy fields comprise the largest portion (85.2%) (see Table 1(A)). Each paddy has numerous drainage holes that are used to drain excessive irrigation water into irrigation canals, which then merge into one drainage canal (see Fig. 1(B)). Drainage holes, irrigation canals, and the drainage canal are the major pathways for carrying NPS pollutants into the paddy field during a storm event. The drainage canal is designed as a concrete-lined trapezoidal canal, and the irrigation canal is a concrete-lined rectangular canal. Stream baseflow at the end of the drainage canal is 10 m^3/h during non-irrigation periods, including the dry season, which runs from November to April, and 300 m^3/h during the irrigation period, which includes the rainy season from July to August. The overall irrigation season in this area is from May to October, and during this period, many farmers intensively use fertilizers, pesticides, and herbicides in efforts to improve the rice productivity. These activities can potentially play a role in the discharge of NPS pollutants into the paddy field.

2.2. Dimensionless time

The concept of *dimensionless time* (τ_{DL}) for this study is defined as the time based on the time-to-peak (τ_{DL1}) in the field monitoring data during a single storm event. τ_{DL1} can be identified by *in situ* flow monitoring and is expressed as $dF/dt = 0$ of the observed flow data in the field. Similarly, τ_{DL0} is the time at which excessive rainfall ($dF/dt > 0$) is present after a rainfall event and can also be observed *in situ*. This study uses the time-to-peak as τ_{DL1} based on the real-time data collected in field experiments. τ_{DL} can only be applied for a single storm event, which is defined as a storm event in which there is only one $dF/dt = 0$ and there is no rebound in the hydrograph by the end of stormwater runoff after τ_{DL1}. Note that the τ_{DL} concept cannot be applied to a multiple storm event, defined as a storm event in which there is an additional $dF/dt = 0$ by the end of stormwater runoff after τ_{DL1}. Additionally, τ_{DL2} and τ_{DL3} can be defined as double and triple time of τ_{DL1} after τ_{DL0}.

- Postulation for τ_{DL} implementation
  - Before rainfall, $dF/dt = 0$, which means that the flow variation measured in the field should be almost 0.
  - Rainfall type should be a single rainfall event.

2.3. Stormwater and soil sampling and analysis

Six intensive field experiments, including four single storm events and two multiple storm events, were conducted during the rainy season from July to August in 2010 in Korea (see Table 1(B)). To eliminate factors affecting the stormwater runoff from the ADDs, all field experiments were conducted within three ADDs. All stormwater runoff samples were collected at the end of a drainage area (see Fig. 1(A), black circle). All stormwater runoff samples collected were immediately stored in a container at 4 °C and transported to the laboratory at the Gwangju Institute of Science and Technology within 6 h to prevent particle coagulation in the water samples. The first sample was collected at the start of the rainfall event, and subsequent samples were collected to allow for variations of the flow and turbidity during the event.

Flow, as an indicator of stormwater variation, was measured using an electronic vortex flow meter (Woojin Inc., Korea) that was installed in the end of the drainage area. The flow meter was periodically calibrated to ensure data accuracy, as per the maintenance manual. Turbidity, as a real-time indicator of particulate in stormwater runoff, was measured *in situ* using a TN-100 turbidimeter (Eutech Instruments, Singapore). Total suspended solids (TSSs) were measured using Standard Method 2540 D, in triplicate. Total nitrogen (TN) and total phosphorus (TP) for stormwater samples were collected from the end point of the drainage area (see Fig. 1(A)). Concentrations of TN and TP were measured by the standard method (APHA, 1995)