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Characterizing particle size distribution of nonpoint source pollutants in an agricultural area

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ABSTRACT

Nonpoint source (NPS) pollution is widely recognized as a major source affecting the water quality deterioration in rivers, lakes, and marine environments. Many studies about the relations between NPS pollutants and solid matters from drainage area have been carried out in the area of stormwater management. This study collected stormwater and soil samples from a drainage area in Korea; the particle size distributions (PSDs) were then analyzed during four storm events. The results indicate that the PSDs of fine and medium silt in the stormwater are related to the soil component of the drainage area. In addition, solid matter was strongly related to NPS pollutant discharges such as total nitrogen and total phosphorus during stormwater runoff. Therefore, to design an NPS management facility, the PSD from the drainage area should be considered. It is expected that this study can be applied to the designs of settling ponds used to remove particles from stormwater runoff.

Keywords: Stormwater runoff; Agricultural area; Particle size distribution; Nonpoint source pollution; Water quality management

1. Introduction

Nonpoint source (NPS) pollutants including nutrients and particulate matter are transported from the ground to water bodies during excessive rainfall or by human activities such as irrigation [1–3]. In agricultural areas, there are many nutrients and particulate in the soil that are affected by human activities and weathering. For example, nutrients including phosphorus or nitrogen are well-known major sources of eutrophication in rivers, lakes, estuaries, and coastal oceans; the discharge characteristics of particulate matter can reflect the water quality during storm events and can be affected by land use and land cover [4]. Specifically, particulate matter has been recognized as a potential source of the deterioration of water quality [5], and the inflow of NPS pollutants into a

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water body can be affected by vegetation along the riverbank.

As one of the four major rivers in Korea, the Yeongsan River is now facing critical environmental problems due to the “Four Major River Restoration Project” conducted by the Korean government [6]. Many wetlands, as a buffer for NPS discharges, and wildlife habitats have been damaged or destroyed during the completion of this project. Indeed, since the project was initiated, soil erosion with NPS pollutant discharges from the riverbank has occurred over almost the entire area of the Yeongsan River. Based on the results of prior studies, algae problems are seen to be the most immediate environmental issue to overcome in the management of water quality during the spring (March–May) and autumn (September–November). To reduce the algae problems, NPS control is considerably recognized as a practical solution in watershed management; however, the starting point of NPS management is to understand runoff characteristics and relationships.

Studies exploring the relationship between particulate matter and NPS pollutants have identified specific associations in runoff events. For example, Vaze and Chiew [7] found that the total nitrogen (TN) and total phosphorus (TP) can be related to specific particle sizes in urban stormwater. They also suggested that treatment facilities should be fitted with 11 μm filters, implying that the particle management can be a key process for removing NPS pollutants in a treatment facility. For example, one function of the sediment basin in a constructed wetland is to remove particles from then stormwater, which can considerably affect the removal efficiency of NPS pollutants, based on the optimal design of a constructed wetland (e.g. aspect ratio, shape, hydraulic structures, and volume).

Therefore, the objectives of this study are: (1) to characterize the surface runoff with respect to the soil and stormwater particles in an agricultural area, and (2) to elucidate the relationship between specific particle sizes and NPS pollutants.

2. Materials and methods

2.1. Site description

The research area is located in the southwestern region of Korea and directly connected to Gomakwon Stream, one of the Yeongsan River tributaries. The drainage area is 2.53 km^2 and land uses are composed of paddy fields, upland, forests, irrigation ditches, and stream banks; almost 95% comprise paddy fields, and the soil is mainly silt and clay. For this study, soil samples from the paddy field were collected at 10 sites in the drainage area. Water samples for the stormwater analysis and particle size distribution (PSD) were collected from the bottom end of the drainage area (Fig. 1). During the growing season from May to October, about 1.2 Cubic Meter per Second of irrigation water flows through this drainage area and is finally

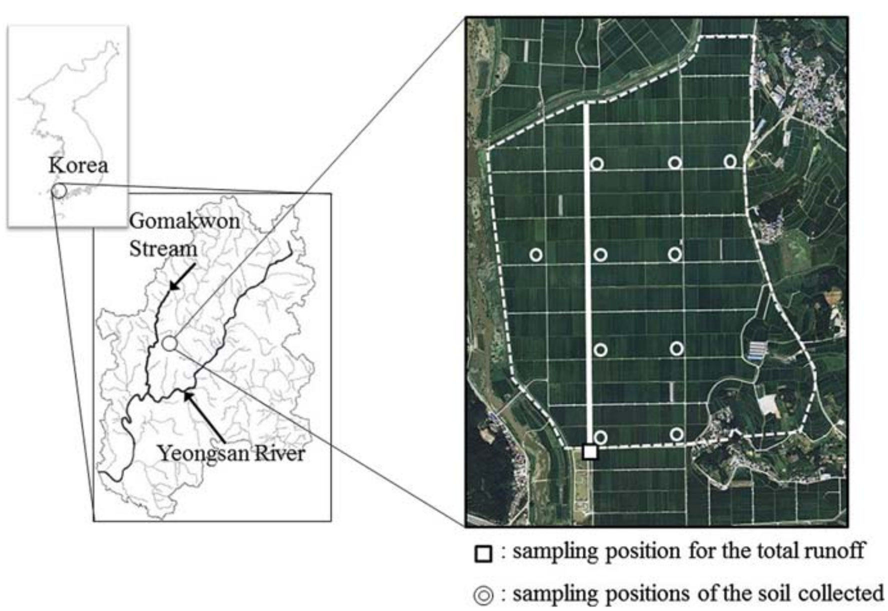

Fig. 1. Simplified map for this study. Open circles are the sampling position of the soil collected. Open rectangle is sampling position for the total runoff in this drain area. A thick straight line above the open rectangle indicates canals. Dotted polygon represents drainage area.

Table 1
Basic information about the four field experiments

	Date (mm/dd/yyyy)	ADD (day)	Rainfall depth (mm)	Duration (h)	Rainfall intensity (mm/h)
R1	07/16/2010	3	19.0	1.5	12.7
R2	07/25/2010	1	12.5	0.2	62.5
R3	07/28/2010	1	15.5	3.0	5.2
R4	08/15/2010	2	33.0	2.0	16.5

Table 2
PSD of paddy field soil in drainage area

Site	Clay (%) <0.002 mm	Fine silt (%) 0.002–0.006 mm	Medium silt (%) 0.006–0.02 mm	Coarse silt & fine sand (%) 0.02–0.1 mm
#1	19.08	30.54	40.38	10.01
#2	14.23	25.98	45.00	14.78
#3	12.93	18.14	37.47	31.48
#4	12.60	19.94	41.85	25.61
#5	14.66	19.90	39.86	25.56
#6	12.80	21.74	42.31	23.17
#7	12.52	19.86	40.31	27.29
#8	14.49	23.00	42.33	20.20
#9	13.33	21.12	39.68	25.90
#10	17.51	25.48	40.51	16.50
Mean	14.42	22.57	40.97	22.05
SD	2.22	3.76	2.02	6.58

discharged into the Gomakwon Stream [8]. Over the past 10 years, the annual rainfall in this area is 1510.5 mm, with about 70% coming during the four-month period from June to September (i.e. monsoon season).

2.2. Data collection

2.2.1. Field experiment

Four field experiments were carried out during the monsoon season (Table 1). The monsoon season can remove the effects of soil moisture conditions, among the many factors affecting the stormwater runoff in and agricultural area, including antecedent dry days (ADDs), rainfall intensity, and rainfall depth. Each field experiment was conducted until the water flow was similar to the base flow. For this study, the rainfall intensity strengths were R2 > R4 > R1 > R3.

2.2.2. Water flow measurement

Water flow was measured at the bottom end of the drainage area (Fig. 1) using an electronic vortex flow meter (Woojin Inc., Korea). The stormwater runoff discharge was recorded at 15 min intervals and all data were transmitted to a storage device (4411e, Woojin Electro-Nite Inc., Korea). The underlying theory for the vortex flow meter is the Karman vortex shedding street theory.

2.2.3. Particle size analysis

Water samples were collected at the end of drainage area and transported within 6 h to a laboratory at the Gwangju Institute of Science and Technology, Korea. To prevent particle aggregation, the particle sizes of all samples were immediately measured using a particle size analyzer (LS230, Beckman Coulter, Germany). The

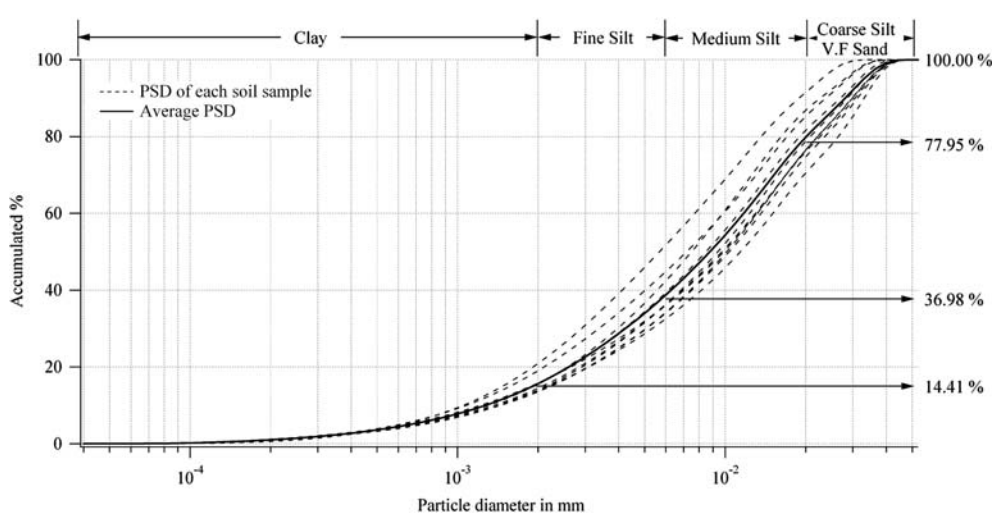

Fig. 2. PSD curves for soil samples collected from drainage area. In the graph, the vertical axis indicates the particle diameter in mm and vertical axis indicates the accumulated volume.

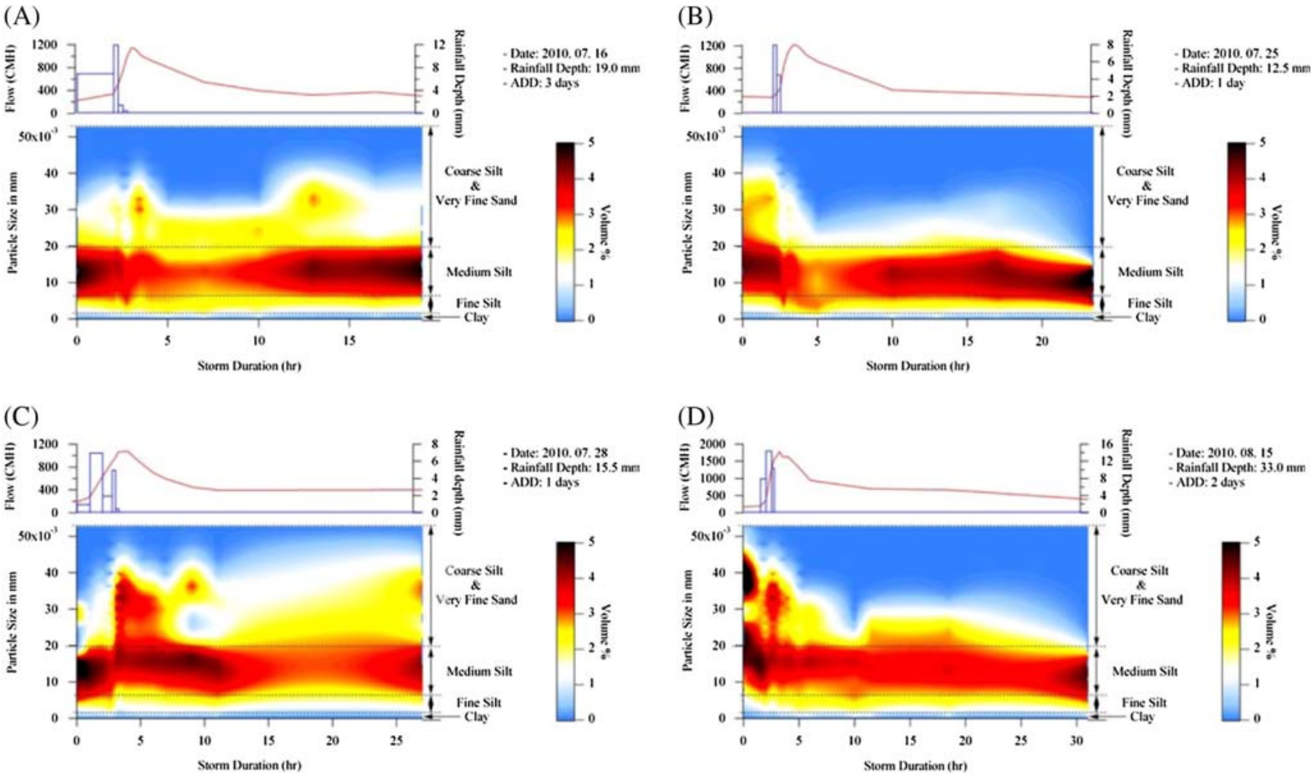

Fig. 3. Volume percentage of each particle size for four field experiments. Top panel indicates the flow and the rainfall depth and bottom panel indicates the contour plot for particle volume percentages with respect to storm duration.

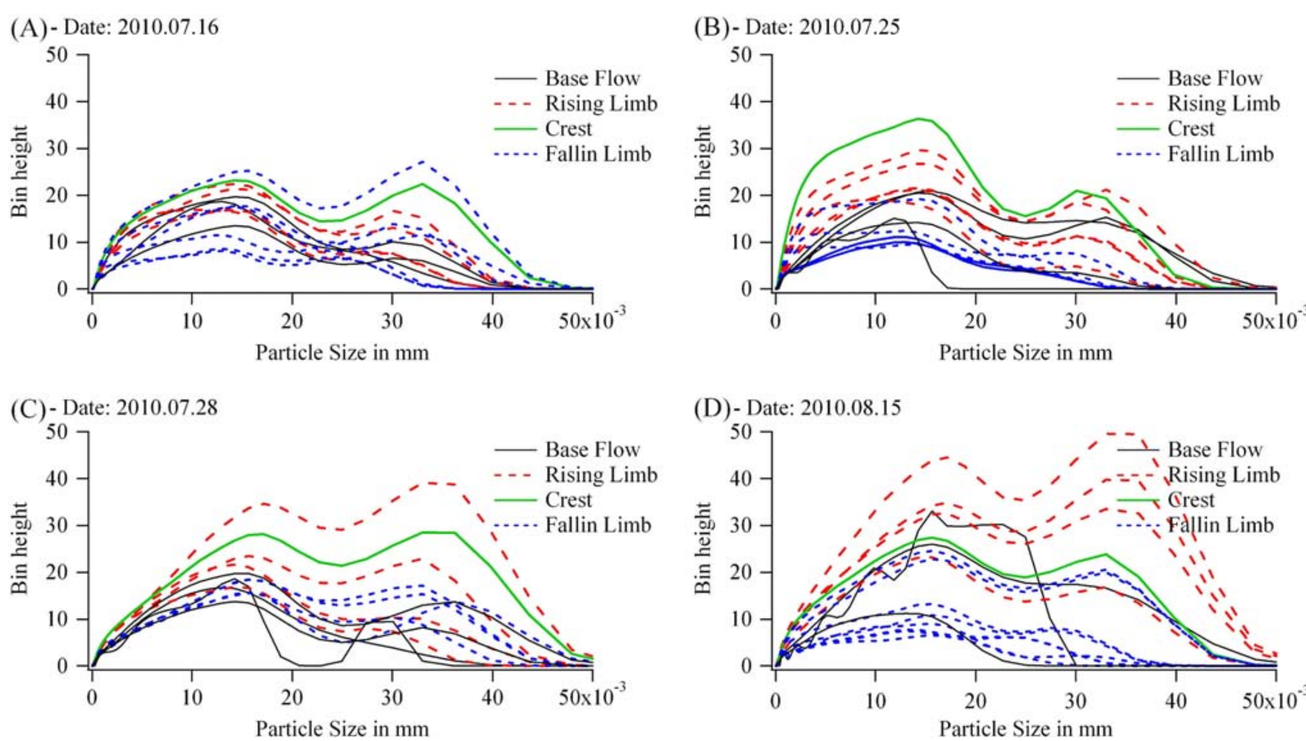

Fig. 4. Bin height of each particle size in accordance with hydrograph. Vertical axis indicates the bin height and horizontal axis indicates the particle size in mm.

detection methods used include polarization intensity differential scattering (PIDS), Fraunhofer diffraction theory, and Mie optical theory. Here, 450 nm, 600 nm, and 900 nm light wavelengths were used to detect the particle sizes, at a detection range of 0.04–2000 μm [9].

3. Results and discussion

3.1. Particle distributions of soil in drainage area

This study determined the soil PSD of the drainage area in order to compare stormwater runoff samples having sizes less than 0.05 mm; particles less than 0.05 mm in diameter are about 80% of the total suspended solid (TSS) load during stormwater runoffs [9]. In addition, particles less than 0.02 mm in diameter have been related to TP and TN in soils [7,10]. Table 2 and Fig. 2 show the PSD percentages of 10 soil samples collected and the plot of a semi-log graph to create a grain-size distribution curve. The particle size ranges for clay, fine silt, medium silt, and coarse silt and very fine sand are < 0.002 mm, 0.002–0.006 mm, 0.006–0.02 mm, and 0.02–0.1 mm, respectively. Almost

Table 3
Skew and Kurtosis analysis for PSDs in four field experiments

No.	Skew	Kurtosis	Stage	No.	Skew	Kurtosis	Stage
2010.07.16				2010.07.25			
1	0.950	0.527	BF	1	0.910	0.108	BF
2	1.201	0.944	BF	2	1.027	0.287	BF
3	1.059	0.456	RL	3	1.094	0.673	RL
4	1.136	0.776	RL	4	1.170	0.857	RL
5	1.364	1.536	RL	5	1.419	2.112	RL
6	1.161	0.600	RL	6	1.172	0.587	RL
7	**1.060**	**0.182**	**Crest**	7	1.227	0.838	RL
8	0.967	−0.087	FL	8	**1.297**	**1.144**	**Crest**
9	1.172	0.579	FL	9	1.385	1.605	FL
10	1.119	0.381	FL	10	1.315	1.138	FL
11	1.203	0.596	FL	11	1.342	1.224	FL
12	1.005	0.114	FL	12	1.055	0.692	FL
13	1.064	0.449	FL	13	1.010	0.426	FL
14	1.120	0.788	FL	14	1.080	0.987	BF
15	1.064	0.449	BF	15	0.343	−0.996	BF
2010.07.28				2010.08.15			
1	1.213	1.408	BF	1	0.132	−1.036	BF
2	0.982	0.710	BF	2	0.875	0.114	BF
3	1.142	0.846	RL	3	0.958	0.140	RL
4	1.113	0.692	RL	4	0.668	−0.613	RL
5	0.790	−0.356	RL	5	0.675	−0.593	RL
6	0.583	−0.708	RL	6	0.778	−0.403	RL
7	**0.756**	**−0.435**	**Crest**	7	**0.912**	**−0.078**	**Crest**
8	0.772	−0.379	FL	8	0.949	0.015	FL
9	0.814	−0.244	FL	9	0.881	−0.147	FL
10	0.893	0.017	FL	10	1.046	0.333	FL
11	1.122	0.369	FL	11	0.828	−0.032	FL
12	1.219	0.933	BF	12	0.901	−0.122	FL
13	1.128	0.563	BF	13	0.920	−0.068	FL
				14	0.897	−0.120	FL
				15	1.080	1.069	FL
				16	0.622	−0.536	BF

Notes: BF: base flow. RL: Rising Limb. FL: Falling Limb.

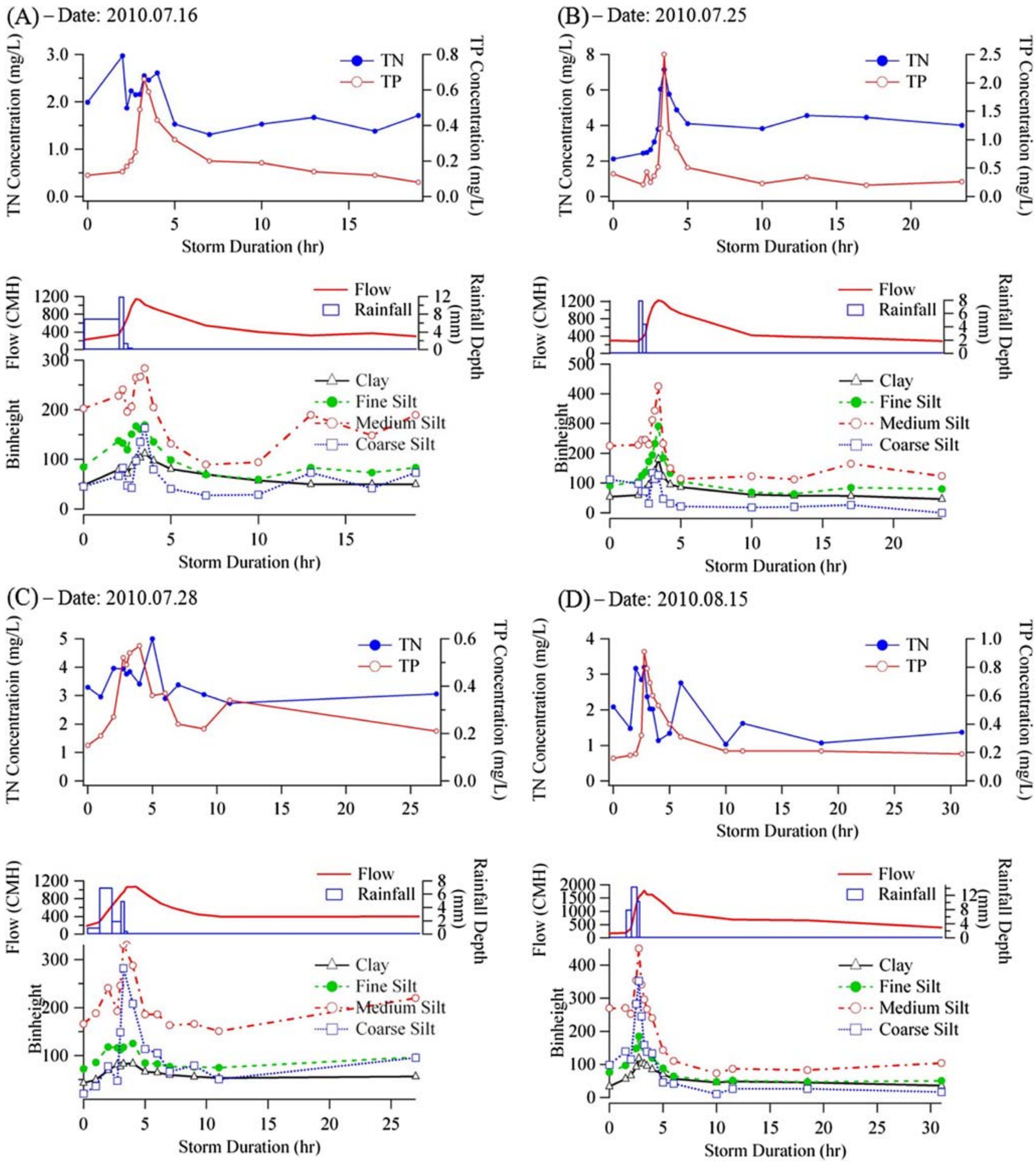

Fig. 5. Relationship between NPS pollutants (TN and TP) and soil groups (clay, fine silt, medium silt, and coarse silt) for four field experiments.

80% of soil particles were composed of clay, fine silt, and medium silt. The average percentage by volume were 14.42 ± 2.22 for clay, 22.57 ± 3.77 for fine silt, 40.97 ± 2.02 for medium silt, and 22.05 ± 6.58 for coarse silt and very fine sand (Table 1). This result implies that almost 78% of the particles affecting NPS pollution can be discharged during stormwater runoff in the agricultural area.

3.2. Particle distributions of the stormwater runoff

Fig. 3 shows the volume percentage of PSDs of stormwater runoff for four field studies (i.e. R1–R4). In each graph, the vertical axis of the top and bottom panels indicates the flow rate for the left side, rainfall depth for the right side, and particle size in mm, respectively. In the figure, blue indicates a relatively low percentage of each particle, with red and black denoting sequentially higher percentages of each particle in these plots. Overall, the PSDs of stormwater runoff in this agricultural area dramatically increased or decreased with storm duration, in terms of flow variation. In all cases, the percentages of medium silt were the highest compared to the other soil particles. Coarse silt and clay showed relatively low volume percentages during storm events.

To clearly identify the increase or decrease of each particle during stormwater discharge, the bin heights for the four field experiments were analyzed (Fig. 4). In each graph, the vertical axis indicates the bin height and the horizontal axis indicates the particle size in mm. In terms of PSD variations, solid black lines denote the base flow stage, dotted red lines are the rising limb stage, sold green lines are for the crest stage, and dotted blue lines are the falling limb stage in a typical flood hydrograph. As mentioned above, it was assumed that ADDs and soil moisture conditions were fixed during the four field experiments. However, the rainfall intensity was found to be a significant factor affecting the stormwater runoff in these experiments. Even though the rainfall depth and ADDs are similar, the bin heights displayed different distributions and height. We posit here that the different rainfall intensity had different effects pertaining to soil erosion on the paddy field. To identify whether specific particle sizes were intensively discharged or not, a kurtosis analysis was conducted. As shown in Fig. 4 and Table 3, the kurtosis for PSD variations in the four field experiments was less than 3.0, implying that the stormwater PSD is not a normal distribution, but rather a platykurtic distribution; i.e. there is a less concentrated distribution about the mean than for a corresponding normal distribution [11]. This finding subsequently suggests that a dramatic increase of quick-flowing water, including runoff, interflow, and direct precipitation, can only affect the overall bin height of each particle size—not the specific particle sizes.

3.3. Relation between NPS pollutants and PSD of the stormwater

Fig. 5 presents the TN and TP concentration variations, hydrograph, and bin height of clay, fine silt, medium silt, and coarse silt for each stormwater runoff. In each graph, the left vertical axis on the left and right sides of the top panel indicate the TN and TP concentrations, respectively. The left and right vertical axes on the mid panel indicate the flow and rainfall depth, the left vertical axis on the bottom panel is the bin height of each particle. In the figure, variations of the TN and TP concentrations in the four field experiments were similar to the flow variation during stormwater runoff; i.e. the flow generally varies in conjunction with the PSD variations, as mentioned above.

Table 4
Correlation table for relationship between NPS pollutants and soil groups including clay, fine silt, medium silt, and coarse silt

Soil group	TN	TP	Soil group	TN	TP
R1: 2010.07.16			R2: 2010.07.25		
Clay	0.636*	0.885**	Clay	0.760**	0.913**
Fine silt	0.786**	0.734**	Fine silt	0.612*	0.845**
Medium silt	0.750**	0.553*	Medium silt	0.354	0.711**
Coarse silt	0.569*	0.761**	Coarse silt	0.057	0.461
R3: 2010.07.28			R4: 2010.08.15		
Clay	0.500	0.924**	Clay	0.497	0.909**
Fine silt	0.387	0.735**	Fine silt	0.612*	0.827**
Medium silt	0.293	0.654*	Medium silt	0.648**	0.669**
Coarse silt	0.284	0.717**	Coarse silt	0.655**	0.713**

**$p < 0.01$. *$p < 0.05$.

To determine which particle sizes have a relationship with the NPS pollutants, stormwater particles were classified using a geographical soil classification system. The top and bottom panels of Fig. 5 and Table 4 show the relationship between the NPS pollutants and soil groups. In the table, clay, fine silt, and medium silt are seen to have a relatively strong correlation with TN and TP, except for R3 of TN. This result suggests that the TN and TP concentration during stormwater runoff in an agricultural area can be managed by controlling the clay, fine silt, and medium silt during stormwater runoff periods.

4. Conclusions

Based on the results of this study, the conclusions can be summarized as follows:

(1) About 80% of soil PSDs were clay, fine silt, and medium silt; these soil types can be easily discharged into streams/rivers and affect the NPS pollution during stormwater runoff periods.
(2) Drastic changes of stormwater runoff significantly affected the relative ratio of stormwater PSD and bin height of soil groups, including those for clay, fine silt, medium silt, and coarse silt.
(3) To control NPS pollutants during storm events in an agricultural area, fine soils should be considered as factors in the design of constructed wetlands for use as sedimentation basins.

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