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A characteristic study on the particles in a constructed stormwater wetland during dry days

Jianghua Yu, Kisoo Park, Youngchul Kim*

Department of Environment Engineering, Hanseo University, Seosan City, Chungnam, 356-706, Korea
Tel. +82 41 660 1432; Fax: +82 41 660 1440; email: ykim@hanseo.ac.kr

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ABSTRACT

A 0.78 ha stormwater wetland was monitored during dry days for the characteristic behavior of particles over a period of 4 mo (June 9–September 5, 2009). The results indicated that the particles in the outflow were finer than those in the inflow due to resuspension of the fine particles and algal growth in the wetland. Based on the particles number density, the particle removal efficiency varied over a wide range (–4000–100%). This variation was largely dependent on resuspension and antecedent dry days. In terms of particles removal, the wetland can be considered as a fiber-bed filter, which is facilitated by the mechanisms of interception, diffusion and sedimentation. Particles with different size ranges showed different removal behaviors due to the different controlling removal mechanisms. The curve for the removal of particles can be divided into three parts, with two turning points within the ranges of 0.51–1 μm and 2–5 μm. Particles less than 4 μm occupied a higher number fraction, with a lower volume fraction, and accounted for the relative high surface area fraction. Particles with different size ranges play different roles in their contributions to turbidity and total suspended solids (TSS). Turbidity was mainly related to particles less than 10 μm, and TSS were more affected by particles coarser than 4 μm. In summary, the success of a stormwater wetland depends on how the resuspension of highly polluting-related fine particles are controlled and particles with different size ranges are treated via appropriate design efforts.

Keywords: Particles removal; Particle size distribution; Resuspension; Stormwater wetland; Dry days; Algal growth

1. Introduction

Particles play important roles in many aquatic ecosystem processes. They can scatter light and give rise to turbidity in water, which are highly sensitive to habitat and spawning areas. Excess particles in a wetland lead to decreased photosynthetic activity and dissolved oxygen, and increased sludge production and treatment cost. Furthermore, the appearance of particles can significantly reduce the aesthetic quality of a water environment, and have harmful impacts on recreation and tourism [1,2]. The presence of particles also contributes to changes in the wetland geomorphology [3].

The transport of particulate matter is critical to the functioning of a wetland. Microscopic particles, such as colloid-sized mineral precipitates and colloidal organic matter, are capable of binding a variety of contaminants. They can serve as transport vectors and carriers of diverse contaminants in surface water due to their large surface to volume ratio, especially for particles finer

*Corresponding author.

than 2 μm, with specific surface areas typically ranging between 10 and 100 m^2/g [4,5]. As a result, the removal of suspended particles is the basic mechanism for the removal of particle-bound pollutants [6]. In this respect, information on the characteristics of the behavior of particles in a wetland is of fundamental importance in the understanding and modeling of the transport of particles and particulate-associated contaminants [7].

During wet days, stormwater wetland systems have short hydraulic retention times (HRT); thus, the major processes responsible for the removal of particles are sedimentation and filtration, which are facilitated by macrophytes via the adhesion of fine particles to plant stems and settling of coarse particles. The performance of a stormwater wetland is mostly influenced by the rainfall conditions, including rainfall depth and intensity [8,9].

On dry days, the HRT will be longer than on wet days. Therefore, many physical and biochemical mechanisms can occur in wetland, such as resuspension, flocculation and algal growth, etc. (Fig. 1), but not sedimentation and filtration. Resuspension contributes greatly to the particles number, and continued resuspension may affect the dissolution and decomposition of particulate matter.

A stormwater wetland environment provides the opportunity for several resuspension mechanisms, with hydrodynamic shear forces as a dominant mechanism, where rainfall activities potentially tear particles loose from the sediment bed. The effects of vegetation due to adsorption and filtration can also play important roles in determining the particles number; however, there are also other mechanisms, such as wind-driven turbulence, biological activity and gas lift. These processes are affected by the fluid properties (temperature, viscosity and density), particle properties (size, density and concentration), wetland morphometry and hydraulic resistance caused by vegetation. Conversely, these factors are also uncertain and random; thus, the behavior of particles in a wetland is complicated and not clearly defined. For this reason, it is desirable to have specific information on the characteristics of particles in a wetland.

Studies on particle characteristics in a wetland have been scare; therefore, this research focused on the behavior characteristics of particles less than 30 μm, which have significant effects on the water quality as a result of their large surface area. Our goal was accomplished by: (1) determining the particle size distribution and analyzing its characteristics; (2) revealing the functions of different sized particles in the mechanisms for the formation of turbidity and total suspended solids (TSS); and (3) examining the particles removal efficiency and summarizing their characteristics.

2. Material and methods

2.1. Description of sampling site

The studied wetland is located in Janghwa-do, Gimje city, on the west coast of Korea, which is a demonstration facility for the treatment of non-point source pollution. The surface area of the wetland was approximately 7,800 m^2, with a maximum water quality volume of around 2275 m^3 and watershed area of approximately 75 ha, which was mostly rural, primarily rice paddy, with some isolated single-family housing and forest. The wetland consisted of a forebay, shallow marsh and deep marsh and; finally, a settling pond (Fig. 2).

The monitoring period was the first year after the wetland operation. The vegetation area was around 30% of the total area. The water depth was stable, and was no more than 80 cm during the monitoring period.

2.2. Sampling information

Samples (including inflow and outflow) to establish the base flow were collected during 6 events over a period of 4 mo (June 9–September 5, 2009). Most of the rainfall (around 50%) occurred during this period,

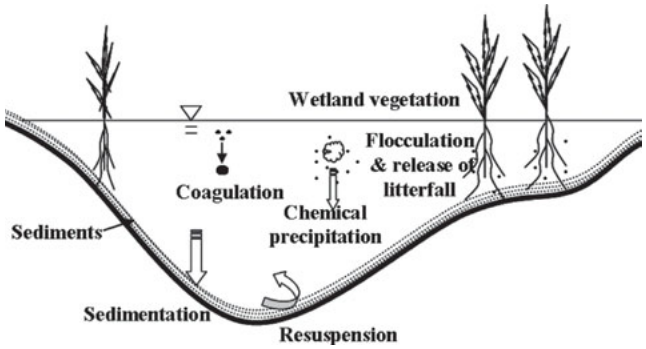

Fig. 1. Schematic diagram of the behavior of particles in a wetland.

Fig. 2. Schematic diagram of the stormwater wetland in this study.

Table 1
Summary of the information for dry day samples

Item	E1	E2	E3	E4	E5	E6
Date	06/09/09	07/01/09	07/21/09	08/11/09	08/26/09	09/05/09
ADD	5	2	2	3	6	6
Rainfall (mm)	6.5*	14.5*	3*	16*	23*	21*
Intensity (mm/h)	3.3*	3.0*	1.0*	2.3*	4.6*	2.6*

with higher temperatures in Korea. The sampling information is summarized in Table 1, which shows that the antecedent dry days ranged from 2 to 6 d; the previous rainfall depths ranged from 3 to 23 mm. All samples were measured for TSS and turbidity, and analyzed for their particle size distributions using an AccuSizerTM 780A particle analyzer. This instrument was equipped with an auto dilution system and a light scattering/ extinction sensor (Model: LE400-0.5 EXT). Between the analysis of each sample, the system was flushed via three cycles, which reduced the background particles concentration to less than 10/ml.

3. Results and discussion

3.1. Particle size distribution

The particle size distribution in the wetland is illustrated in Fig. 3, which shows the cumulative volume fraction of particles. Generally, the particles in the inflow were coarser than those in the outflow, which was thought to be caused by the resuspension of fine particles and algal growth through the wetland. The average D50 values were 13.7 and 10.7 µm for the inflow and outflow, respectively. In addition, the particles in the inflow were slightly more uniform than those in the outflow, with uniformity coefficients (U) of 3.7 and 3.9, respectively (Table 2).

As discussed previously, the mechanism affecting the behavior of particles in a wetland is complicated. Many factors can affect the particle size distribution; settling, resuspension and flocculation, as well as other mechanisms. Also, the particle size distribution will change under different hydraulic loads and surrounding conditions in a natural wetland [10].

Thus, there were some exceptions in terms of the particle size distribution, such as event E2 during this study, where the particles in the inflow were finer than those in the outflow. This can be explained by the special situation at that time, i.e. some coarse floatable organic matters was trapped around the corners close to the outlet due to wind and waves, where the adsorption of most fine particles to these organic matter resulted in the coarser particle size distribution in the outflow.

A previous study has also reported on the particle size distribution in a wetland. Li et al. measured the particle size distribution on a lab-scale constructed wetland. The results indicated that the particles became finer along the experiment channel, which was mainly due to the sedimentation of larger particles [6].

The particle size distribution has a significant effect on the removal of associated contaminants, because different pollutants are associated with different particles [11]. Therefore, information on the particle size distribution is important and valuable for the design and management of a wetland.

3.2. Particles resuspension

The resuspension phenomenon can be supported by the fact that the particles number density was higher in the outflow than the inflow (Fig. 4). For particles finer than 10 µm, the number density in the outflow was evidently higher than in the inflow. This difference was also closely related with ADD, the shorter the ADD, the bigger the difference. Jordan and Valiela also studied the particles behavior in a muddy creek, which indicated that resuspension significantly increased the concentration of fine particles, as found in this study [12].

In this study, one important parameter that significant affected resuspension was the water depth, which was less than 80 cm during the studied period. It is known that shallow water can be easily mixed by the current caused by rainfall runoff or wind-generated ripples. Algal growth is another factor resulting in an increased particle number density. In this study, the presence of algal growth was supported by the increased pH and dissolved oxygen concentration (DO) between the inflow and outflow (Table 3) because algal growth is known to result in increased pH and DO.

Moreover, the oxygen generated by submerged plants, as well as nitrogen oxides and nitrogen gas from denitrification, may enhance the resuspension of particulates [9].

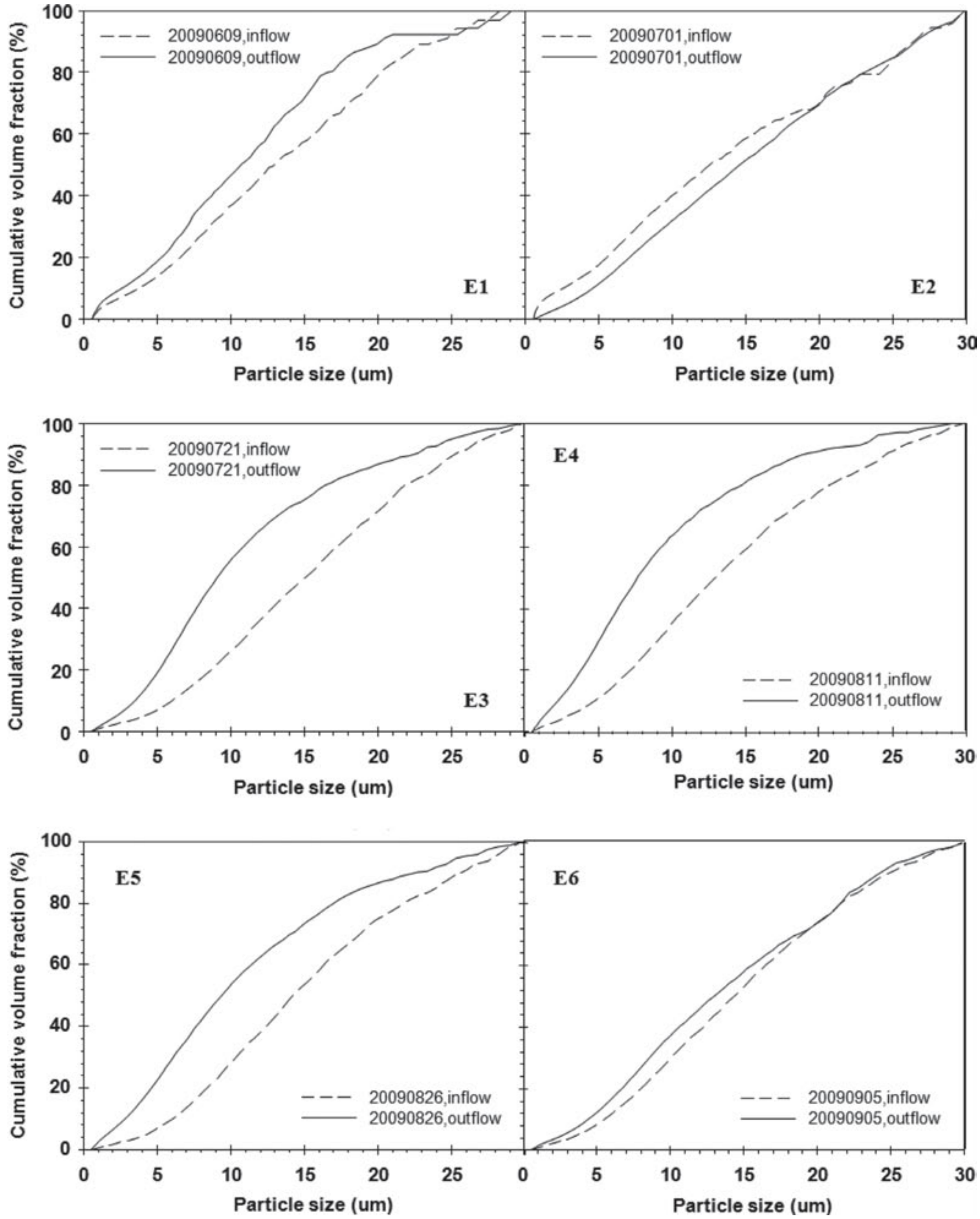

Fig. 3. The particle size distributions on dry days.

Table 2
Particle sizes in the inflow and outflow

Items	E1		E2		E3		E4		E5		E6		Average	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
D_{10}(μm)	3.7	2.5	2.6	4.5	6.1	3.5	4.8	2.2	6.1	2.9	5.5	4.4	4.8	3.3
D_{50}(μm)	12.9	10.7	12.6	14.4	15.2	9.1	12.9	7.7	14.4	9.3	14.4	12.9	13.7	10.7
D_{60}(μm)	15.6	12.6	15.6	17.4	17.4	11.0	15.2	9.3	16.5	11.3	16.5	15.6	16.1	12.9
U (Uniformity)	4.2	5.0	6.1	3.9	2.9	3.1	3.2	4.2	2.7	4.0	3.0	3.6	3.7	3.9

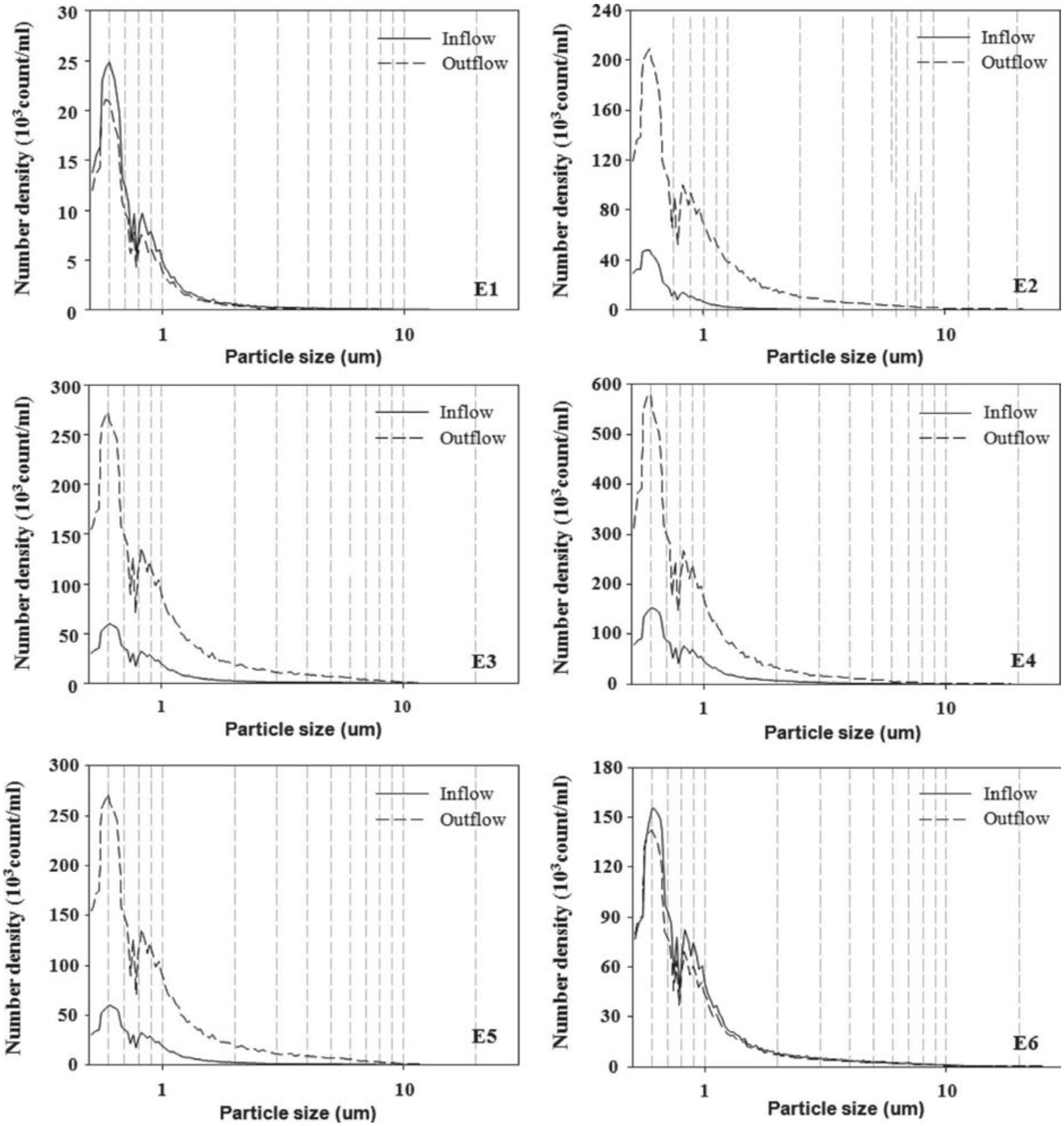

Fig. 4. Number density of particles on dry days.

Table 3
pH and DO concentrations in the inflow and outflow

Items	E1		E2		E3		E4		E5		E6	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
pH	6.52	6.69	7.06	8.37	6.93	7.18	6.80	6.96	6.85	7.08	6.82	7.12
DO (mg/l)	5.7	6.5	1.8	15	2.9	6.5	3.3	4.3	10.88	11.86	8.22	10.77

3.3. Particles removal

The particles removal was determined based on the particles number, which varied over a large range (–4000–100%) and was significantly affected by the degree of particles resuspension and ADDs (Fig. 5). Normally, greater resuspension with shorter ADDs result in negative removal efficiencies, such as E2, E3 and E4, with ADDs of 2, 2 and 3 d, respectively. Otherwise, the efficiencies were relative higher or positive, such as E1, E4 and E6, with ADDs longer than 5 d.

In terms of particles removal, a stormwater wetland can be considered as a filter due to the stems and biofilms of macrophytes, which form a non-homogeneous "fiber-bed" in the wetland. The three principal mechanisms of fiber-bed filtration are well known and documented: flow-line interception, diffusion, sedimentation and inertial deposition [9,13].

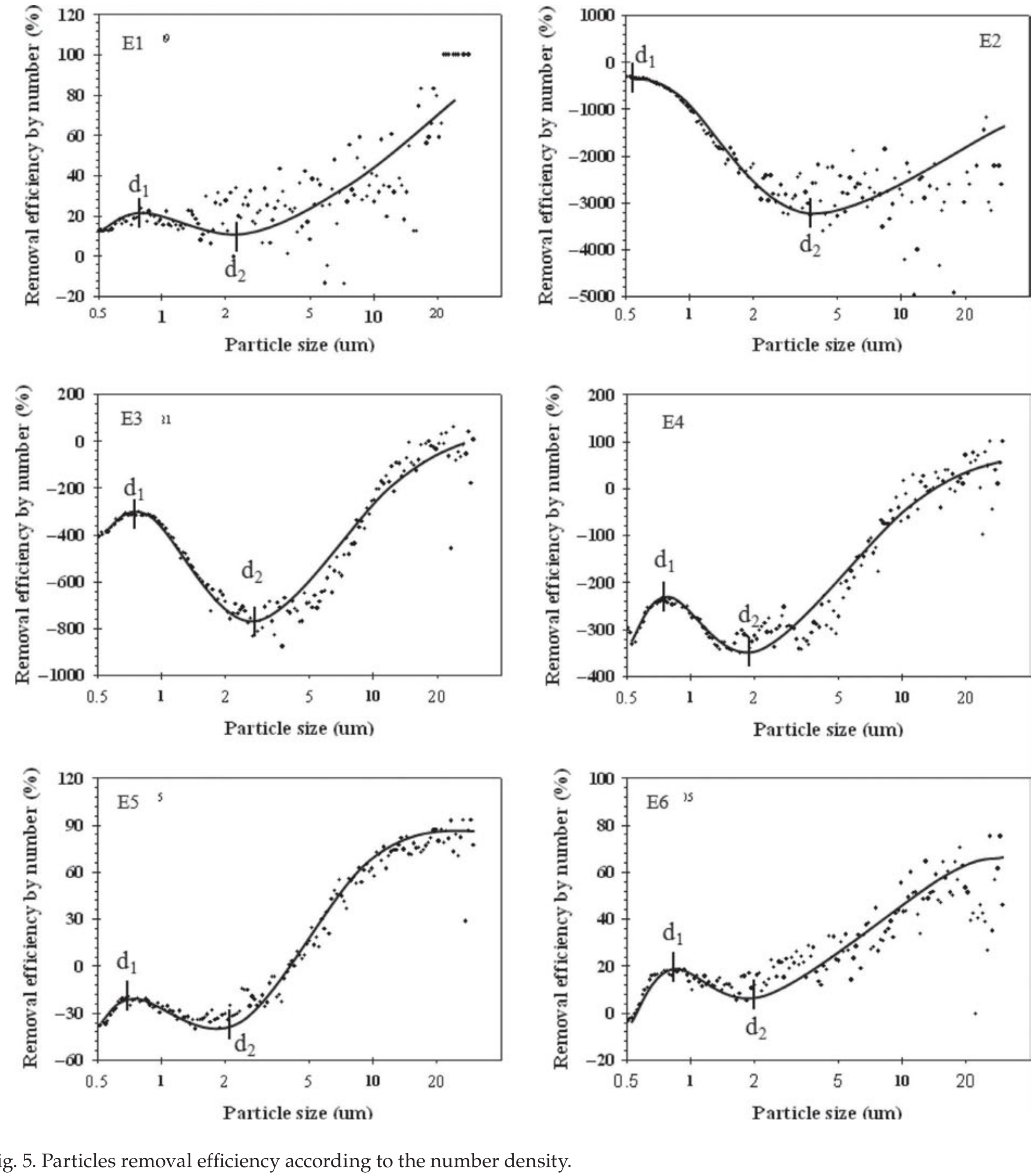

Fig. 5. Particles removal efficiency according to the number density.

The results from this study suggested that the removal curve could be divided into three parts, with two turning points: d_1 and d_2, with ranges of 0.5–1 μm and 2–5 μm, respectively.

For particles less than d_1, the removal increased with increasing particle size. This increasing trend was thought to be caused by the flocculation of fine particles within this range [14]. For particles within this range, the controlling removal mechanism would be diffusion, which is largely affected by coagulation and flocculation due to the electrostatic interactions between the particles [15].

For particles coarser than d_1, the removal decreased, to within the range of colloidal sizes, and then increased as a function of the particle size. This was because the colloidal size particle range would be too large for diffusion to be effective and too small for interception and sedimentation to be effective; thus, the removal would be lowest within this range [16].

Furthermore, particle sizes of d_1 and d_2 will depend on the particles properties (size, shape and density), water properties (temperature, flow velocity), and the characteristics of the vegetation (submerged surface area, biomass and biofilm), as well as the effect of bio-turbation [9].

The particles removal by a physical medium filter has been well studied and documented in previous investigations [1618]. The difference between these investigations and this study was related to the removal of colloidal particles (less than d_2). In this study, particles removal within this range initially increased, but then decreased; whereas, the decrease, without the initial increasing process, was observed in previous studies. This difference was thought to be caused by the different water environments. Due to biochemical activities, a stormwater wetland provides more favorable conditions for flocculation than normal medium filters.

Generally, all particles can be removed via a wetland if the hydraulic removal time is long enough. This removal would also increase as a function of the particle size due to the relative densities when other effecting parameters are not considered (Fig. 6, lines A and B). The difference between A and B is determined by the removal time. The removal can be characterized by B if the removal time is longer; otherwise, it will be characterized by A.

However, due to many effecting parameters (resuspension, flocculation, and algal growth) and different controlling mechanisms for particles removal, the removal can be characterized by line C in Fig. 6, where the particles removal is divided into three parts, with two turning points.

3.4. Fraction number and volume

Overall, the volume of the particles coarser than 10 μm will be much larger than that of particles finer than 4 μm.

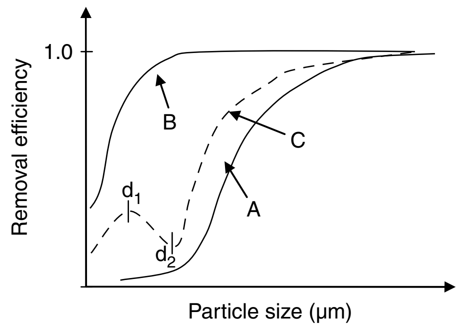

Fig. 6. Schematic diagram of the removal with particle size.

As shown in Fig. 7 and Table 4, fine particles (0.514 μm) occupied a low volume fractions of 510% in the inflow and 1020% in the outflow, although they accounted for higher number fractions of more than 96% in both the inflow and outflow. On the other hand, coarser particles within the range 1030 μm accounted for relative high volume fractions of 6070% in the inflow and 3560% in the outflow, with number fractions of no more than 1% in both the inflow and outflow. Cripps measured the number density and volume of particles in an aqua cultural effluent and obtained similar results that showed the majority of the particles were smaller than 20 μm, but the volume of the few larger particles was much greater than the many small particles [19].

The result from this study suggested that the particles volume was mainly dependent on particles coarser than 10 μm, while the particles number was mainly determined by particles finer than 4 μm. This would be natural because the particle volume is proportional to the cube of the particle size, with slight variations due to shape factors.

3.5. Fraction surface area

Fig. 8 shows the surface area fractions of particles in different size ranges. It can be seen that fine particles occupied a high surface area fraction, which was around 30% for particles finer than 2 μm in both the inflow and outflow. Particles within the range 24 μm accounted for a relative low surface area fraction, which was only about 10% in the inflow and 15% in the outflow. The fractions of particles coarser than 10 μm were around 32 and 20% in the inflow and outflow, respectively. Overall, particles finer than 4 μm accounted for more than 40% of the surface area in this study. A comparable result was observed by Atteia, who studied the particles surface area in water from a karstic aquifer, where the result suggested that particles finer than 4 μm compose 40% of the particles surface area [20].

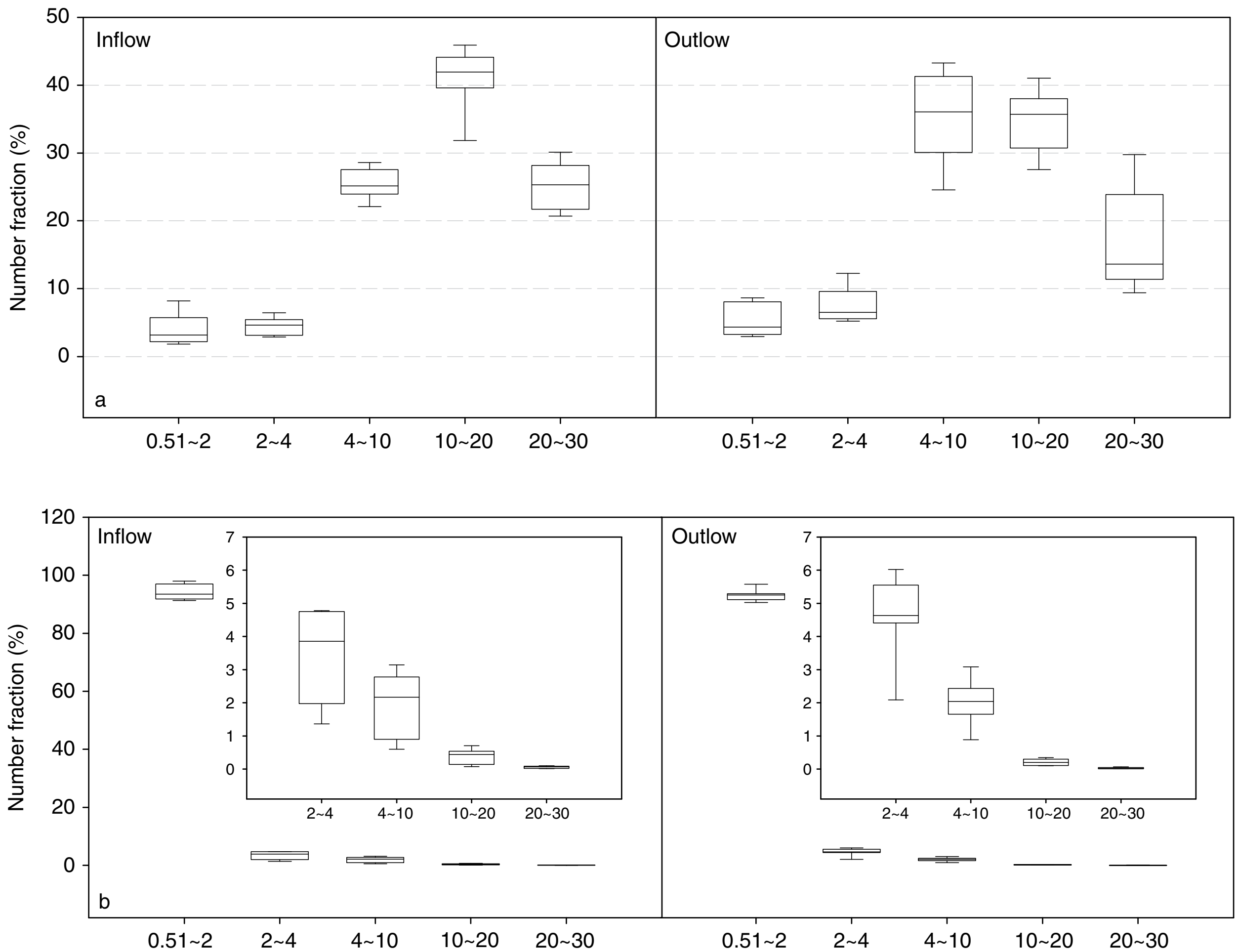

Fig. 7. Particles fractions within different size ranges. (a) Volume fraction, (b) number fraction.

Table 4
The volumes and number fractions for particles smaller than 2 and coarser than 10 μm

Item		E1		E2		E3		E4		E5		E6	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Volume	0.51–4μm	10.8	15.0	14.4	8.4	5.1	12.9	7.8	21.5	4.7	16.5	5.9	8.7
Fraction (%)	10–30μm	62.8	52.5	60.5	68.2	73.2	43.7	64.3	35.9	71.6	45.8	69.6	62.0
Number	0.51–4μm	99.0	99.1	99.4	97.3	97.3	96.7	97.5	98.3	96.1	98.1	96.7	97.5
Fraction (%)	10–30 μm	0.16	0.12	0.08	0.42	0.60	0.27	0.42	0.11	0.83	0.17	0.63	0.35

It is well known that fine particles, due to their high surface area, are strongly associated with pollutants; even small amounts of fine particles can play an important role in the transport of pollutants [20]. Therefore, effective stormwater wetland design relies on how to treat the fine particles caused by resuspention.

3.6. Particles and TSS and turbidity

Table 5 shows the correlations between the particle number density of different sizes and the turbidity/TSS. In summary, a close correlation existed between the number density and turbidity/TSS. Turbidity was more closely related to particles smaller than 10 μm,

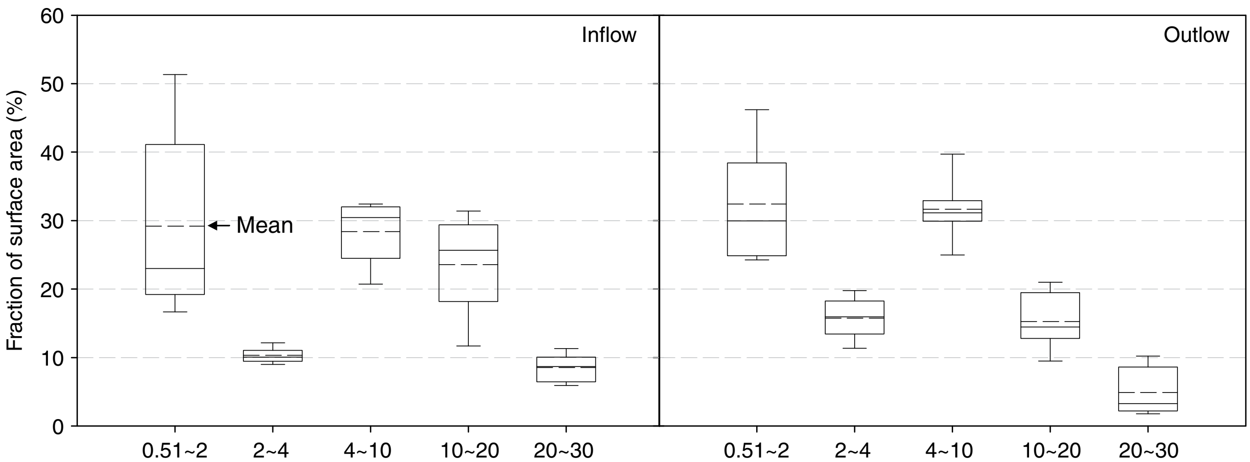

Fig. 8. The surface area fractions of particles within different size ranges.

Table 5
Correlations between the particles number densities of different sizes and the turbidity/TSS

Parameter	Correlation coefficient				
	0.51–2µm	2–4µm	410–µm	10–20µm	20–30µm
Turbidity	0.819	0.921	0.905	0.649	0.407
TSS	0.585	0.691	0.787	0.873	0.722

while TSS was more affected by particles coarser than 4 µm (r >0.7).

This is because turbidity is mainly dominated by light scattering due to fine particles, which have larger surface to volume ratios [2]. Conversely, TSS is primarily contributed to by the amount of particles, which is determined by the product of the particle's density and volume, where the particles volume is proportional to the cube of the particle size. Therefore, TSS is more likely to be affected by coarse particles. Cripps studied the relationship between particles and TSS, and his results indicated that the total particles volume, which was mainly contributed to by coarse particles, was significantly correlated with the TSS concentration [17]. This result suggests that different treatment mechanisms should be considered in the design of a stormwater wetland for the removals of turbidity and TSS.

4. Conclusions

Samples collected from wetland surface water on dry days were analyzed, and the results indicated that the particles were finer in the outflow than the inflow due to the resuspension of fine particles and algal growth in the wetland on dry days.

The particles removal efficiency varied over a wide range due to the effects of resuspension and ADDs. The wetland functioned as a fiber-bed filter for the removal of particles due to the presence of vegetation. Particles within different size ranges showed different removal characteristics because of the different controlling mechanisms (interception, diffusion and sedimentation). The removal curve could be divided into three parts, with two turning points.

On dry days, the volume fraction of fine particles (less than 4 µm) was no more than 20%, although they occupied more than 96% based on the particles number in both the inflow and outflow. Particles within different size ranges play different roles in their contributions to turbidity and TSS values; turbidity is mainly related to particles less than 10 µm; whereas, TSS are generally dependent on particles coarser than 4 µm.

In summary, the success of a stormwater wetland depends on how the resuspension of highly pollutant-related fine particles is controlled and particles with different size ranges are treated via appropriate design efforts.

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