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Particle size distribution mathematical models and properties of suspended solids in a typical freshwater pond☆

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ABSTRACT

Many countries, such as China, today are facing the scarcity and pollution issues of freshwater resources. Suspended solids, as wastewater contaminants, may contain components such as nitrogen, phosphorus, heavy metals and pathogens that are harmful to the environment and human health, it is essential to know the size distribution regularity of the solids with a view to guiding the management of freshwater resources for sustainability. Particle size distribution (PSD) mathematical models and properties of suspended solids in a typical freshwater pond were investigated in this study. Particle size was measured using a laser particle size analyzer (measurement range: 0.01–3500 μm). The power law model and the variable-β model were tested for their ability to fit the numeric distribution of suspended solids; Gaussian (*i.e.*, normal) distribution and log-normal distribution models were used to evaluate the volumetric distribution of suspended solids. The results showed that: by number, about 80% of the particles contributed to only 10% of total particle volume, while the remaining 20% contributed about 90% of the total volume. For numeric distribution, the variable–β model ($R^2 = 0.975 \pm 0.011$) was better than the power law model ($R^2 = 0.899 \pm 0.033$); for the volumetric distribution, the log-normal distribution model ($R^2 = 0.968 \pm 0.020$) clearly outperformed the Gaussian distribution model ($R^2 = 0.655 \pm 0.093$). Overall, the variable–β model and log-normal distribution were shown to accurately describe the numerical and volumetric distribution of pond water suspended solids, respectively. PSD model parameters can be related to some compositions in the wastewater and can provide guidance for suspended solids further treatment, be it physical, biological, chemical or synthetic methods.

1. Introduction

An intensification of land use and urbanization, coupled with rapid socioeconomic development and increasing population, has led to recent increases in domestic, agricultural and industrial wastewater discharges worldwide. For China, this has left several of its socioeconomic sectors, and in particular the most water-intensive sector, agriculture, facing both environmental pollution and severe water scarcity issues (Liu and Yang, 2012; Dalin et al., 2014; Jin et al., 2014; Zhao and Chen, 2014; Bian et al., 2015; Zhou et al., 2017). The rapidly developed intensive agriculture has been shown to: (*i*) increase erosion, leading to higher sediment load in watercourses (*ii*) leach nutrients (*e.g.*, nitrogen, phosphorus); and chemicals (*e.g.*, fertilizers, pesticides) into groundwater, streams and rivers (Foley et al., 2005; Chen et al., 2017). For example, world aquaculture production has increased by 67% from 1995 to 2014 (FAO, 2016), resulting in an increased production of nutrient-rich wastes, particles accumulation and wastewater requiring treatment (Sfez et al., 2015; Leal et al., 2016). Freshwater

Abbreviations: PSD, Particle size distribution; PDF, Probability density function; CDF, Cumulative distribution functions; ESS or SSE, The error sum of squares; TSS or SST, The total sum of squares; SD, Standard deviation; COD, Chemical oxygen demand; TN, Total nitrogen; TP, Total phosphorus; BOD, Biological oxygen demand; OUR, Oxygen utilisation rate; MDW, Molasses distillery wastewater; MBR, Membrane bioreactor; UF, Ultra-filtration; RO, Reverse osmosis; NF, Nano-filtration; LFUS, Low frequency ultrasound; UV-C, Ultraviolet-C; RASs, Recirculating aquaculture systems; FIB, Fecal indicator bacteria.

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pond aquaculture plays a key role in global aquaculture, especially China; accordingly, large volumes of aquaculture wastewater are discharged directly into surrounding rivers and lakes, where waterborne pollutants not only adversely affect the local environment (*e.g.*, death of aquatic animals and plants, water eutrophication), but may also pose a threat to human health (*e.g.*, spreading pathogens) (Moazeni et al., 2017).

As they can carry pollutants and pathogens and result in water turbidity, solids in wastewater contribute significantly to its adverse effects on the environment and public health. Moreover, if organic suspended solids settle, it will offer a site for anaerobic fermentation, which can lead to the further deterioration of water quality. Such particles are classified according to their diameter (D_p) as: dissolved ($D_p < 0.001$ μm), colloidal (0.001 μm $\leq D_p \leq$ 1 μm), supra-colloidal or fine solids (1 μm $\leq D_p \leq$ 100 μm) and settleable solids ($D_p >$ 100 μm) (Dulekgurgen et al., 2006). While large particles are relatively easy to remove, reducing the concentration of wastewater's small suspended solids presents an imposing challenge in water treatment and reuse (Pau et al., 2013).

A measure of the volumetric or numerical contribution of particles of different sizes, particle size distribution (PSD) is an important assessment parameter for physical, chemical and biological treatment processes in different wastewaters (Dulekgurgen et al., 2006; Karahan et al., 2008). The analysis of PSD has been applied to drinking water, urban wastewater or municipal wastewater (*e.g.*, humus effluents), industrial effluents (*e.g.*, from textile plants, tanneries, molasses distilleries and olive oil mill), agricultural wastewater (*e.g.*, swine manure) and natural waters (*e.g.*, groundwater) (Sophonsiri and Morgenroth, 2004; Dulekgurgen et al., 2006; Pronk et al., 2007; Karahan et al., 2008; Dogruel et al., 2009; Beek et al., 2010; Arimi et al., 2016; Hargreaves et al., 2018; Ravndal et al., 2018). Most of these studies reported the chemical composition of particles within each size interval, however, few studies have dealt with the PSD of suspended solids in freshwater ponds or its mathematical model. With an increasingly strict management of agricultural wastewater within China and across the world, an investigation of the PSD of suspended solids in freshwater ponds is likely to prove of some theoretical significance and practical value.

The monitoring and modelling of the PSD of suspended solids in a freshwater pond undertaken in the present study sought: (*i*) to establish numerical and volumetric distribution models for suspended solids in a freshwater pond; (*ii*) to employ said models to provide theoretical guidance in developing better water quality management protocols. Since a PSD contains information regarding both the absolute count value of various size ranges that make up the PSD and the relationship of the counts for the various size fractions (Ceronio and Haarhoff, 2005), it can be important in understanding the particles' properties. Moreover, PSD is also related to water quality parameters such as suspended solids, turbidity and chemical oxygen demand (COD), it is of great significance in wastewater characterization (García-Mesa et al., 2010a; b).

2. Materials and methods

2.1. Water sample collection and PSD analysis procedure

The freshwater pond was constructed in a farm that has been breeding common Chinese commercial freshwater fish (*e.g.*, snakehead (*Channa argus*), black carp (*Mylopharyngodon piceus*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), etc.) since 2014. The pond is located in Yuhang District, Hangzhou City, Zhejiang Province, China, with a total area of 1.33 ha, an average depth of 2 m. Uneaten feed and fish feces are the major source of pollutants which contribute a lot to the production of solid wastes and water quality deterioration. To address this serious problem, Chinese Government and local government have, in recent years, paid increasing attention to these issues and invested large sums of money into environmental protection, promulgating a series of environmental governance measures targeted at speeding up the transformation and upgrading of the fish production industry. From March to April 2017, some small fish (approximately 65500 in total) were released into the pond, together with some hydrophytes: water hyacinth (*Eichhornia crassipes*) (Planting area is approximately 15% of total pond area). Over a 180-day period (June to December 2017), a total of 198 water samples were collected from the freshwater pond. To avoid alterations in water composition and ensure the reliability of PSD analyses, samples were quickly and gently transported to the Environmental Engineering Analytical Laboratory of Zhejiang University (Hangzhou, China). All the samples were analyzed for both numerical and volumetric distribution.

According to our knowledge, there are several kinds of ways to measure particle size, three main methods exist to measure particle size in aqueous solutions: electrical resistance, sequential filtration (Dulekgurgen et al., 2006; Karahan et al., 2008), and laser scattering (Wu et al., 2009; He et al., 2013). Given its easy operation, fast measurement, large measurement range, good repeatability and high accuracy, a laser method was chosen to determine PSDs for the present study. The laser particle size analyzer (Model 3000 Plus, Bettersize Instrument Ltd., China) employed to measure the PSD of suspended solids in water from the freshwater pond had the capacity to measure particle diameters (D_p) within the range of 0.01–3500 μm (Fig. 1).

Prior to pouring a sample into the analyzer's sample cell, the sample bottle was gently and carefully mixed to evenly distribute the particles in the water, without breaking up larger particles and affecting the accuracy of the PSD. Because, if the water is not mixed, large particles will remain at the bottom of the sample bottle so that the measured PSD results will not be correct. After the sample was mixed, pouring the sample into the sample cell for particle size analysis. Mixing of water is also necessary during the analysis process. The stirrer controlled by the speed controller was kept running during the whole analysis process to make the water sample in a motion state to prevent particles from settling. Then set relevant options according to the experimental requirements, the laser measurement, signal conversion transmission and control system will perform analysis. After this process was completed, the results were exported for subsequent analysis and then used the cleaning function to wash the sample cell three or more times to ensure cleanness and avoid affecting the results of the next experiment.

In fact, the actual particles (especially solid particles) are not

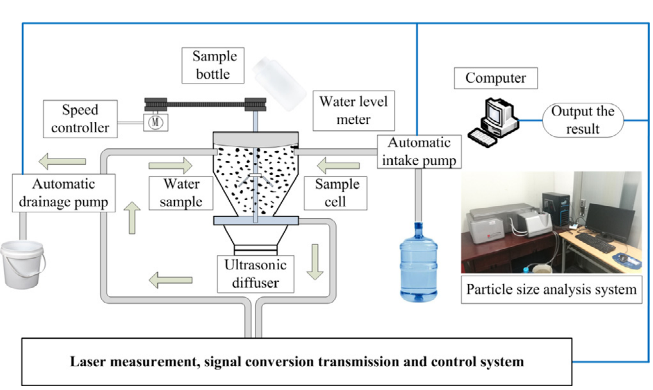

Fig. 1. Particle size analysis system of the laser particle size analyzer.