


Article

# The Concentrations and Removal Effects of PM<sub>10</sub> and PM<sub>2.5</sub> on a Wetland in Beijing

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**Abstract:** Particulate matter (PM) is an essential source of atmospheric pollution in metropolitan areas since it has adverse effects on human health. However, previous research suggested wetlands can remove particulate matter from the atmosphere to land surfaces. This study was conducted in the Hanshiqiao Wetland National Nature Reserve in Beijing during 2016. The concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> on a wetland and bare land in the park, as well as metrological data, were collected during the whole year. Based on the observed data, removal efficiency of each land use type was calculated by empirical models and the relationships between concentrations and metrological factors were also analyzed. The results indicated that: (1) In general, the PM<sub>10</sub> and PM<sub>2.5</sub> concentrations on the bare land surface were higher than those on the wetland surface, in both of which the highest value appeared at night and evening, while the lowest value appeared near noon. In terms of season, the average concentration of PM<sub>10</sub> was higher in winter (wetland: 137.48  $\mu\text{g}\cdot\text{m}^{-3}$ ; bare land: 164.75  $\mu\text{g}\cdot\text{m}^{-3}$ ) and spring (wetland: 205.18  $\mu\text{g}\cdot\text{m}^{-3}$ ; bare land: 244.85  $\mu\text{g}\cdot\text{m}^{-3}$ ) in general. The concentration of PM<sub>2.5</sub> on the wetland surface showed the same pattern, while that on the bare land surface was higher in spring and summer. (2) Concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> were significantly correlated with the relative humidity ( $p < 0.01$ ) and inversely correlated with wind speed ( $p < 0.05$ ). The relationship between PM<sub>10</sub> and PM<sub>2.5</sub> concentrations and temperature was more complicated—it showed a significantly negative correlation ( $p < 0.01$ ) between them in winter and spring, however, the correlation was insignificant in autumn. In summer, only the correlation between PM<sub>10</sub> concentration and temperature on the wetland surface was significant ( $p < 0.01$ ). (3) The dry removal efficiency of PM<sub>10</sub> was greater than that of PM<sub>2.5</sub>. The dry removal efficiencies of PM<sub>10</sub> and PM<sub>2.5</sub> followed the order of spring > winter > autumn > summer on the wetland. This study seeks to provide practical measures to improve air quality and facilitate sustainable development in Beijing.

**Keywords:** particulates; wetland; concentration; meteorological factors; dry removal efficiency

## 1. Introduction

In recent years, with the rapid economic development based on industry and urbanization, serious particle pollution has occurred, especially in metropolitan areas such as Beijing, and has attracted increasing attention from the public, government, and scientific institutions worldwide. The pollution problem is not conducive to the construction of an eco-friendly society and the development of sustainability [1]. The atmospheric particles (particulate matter, PM) have posed a threat to climate change and human health [2–4], especially PM<sub>10</sub> and PM<sub>2.5</sub>, which are defined as the particles with

aerodynamic diameters of less than 10  $\mu\text{m}$  ( $\text{PM}_{10}$ ) and 2.5  $\mu\text{m}$  ( $\text{PM}_{2.5}$ ), respectively [5]. Thus, reducing the concentration of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  or removing them from the atmosphere is considered as the key in improving air quality and promoting sustainability in urban areas.

Removing mass particles from the atmosphere links to many complicated physical processes, such as deposition, interception, impaction, and resuspension, and they are all related to meteorological conditions [2], including air temperature, relative humidity, and wind conditions [6,7]. Generally, temperature has an effect on atmospheric relative humidity and air turbulence [8–10] and increasing temperature will be followed by decreasing humidity and increasing turbulence, which as a consequence decreases PM concentration and increases resuspension at the same time [8]. The low temperature and high relative humidity have a negative relationship with particle concentrations [11], while the physical mechanism still remains blurred. The deposition velocity of  $\text{PM}_{10}$  is faster than that of  $\text{PM}_{2.5}$  under the same meteorological conditions [12–14] because of the mass and size, especially on the water surface [15,16]. Besides, wind velocity and relative humidity also influence the PM concentrations dramatically. The relatively slow wind speed favors accumulation of particles resulting in elevated pollution concentrations [17]. High relative humidity slows down the diffusion of PM; besides, high relative humidity combined with high PM conditions could accelerate the further formation of water-soluble ions [18]. It is necessary to understand the mechanism of mass particle movement in the atmosphere for studying how to use vegetation and different land surfaces to remove particles from the atmosphere to surfaces more effectively.

The wetlands, which are also regarded as the “kidneys of the earth”, have been increasingly attractive to whole PM-related researchers because they play an important role in regulating, intercepting, and removing  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  [19,20]. Many studies [21–25] have drawn the conclusion that wetlands can remove particulate matter from the atmosphere to land surfaces to some extent, by changing the micro-meteorological conditions (increasing the atmospheric relative humidity and lowering the temperature within a certain range in wetlands), thus promoting particulate matter deposition [2]. Besides, plants grown in wetlands, such as *Phragmites australis*, *Typha angustifolia*, and *Canna indica* [21,26], tend to improve the air quality by changing the microenvironment of particles [5,22]. Moreover, some water-soluble ions could dissolve in the water, leading to the decrease of particle concentration [17].

The Beijing Hanshiqiao Wetland Nature Reserve is located in the southwest of Yang Village, a small town in the Shunyi District, Beijing. Its core zone has an intact wetland environment that is of the essence in environmental conservation and construction in Beijing [27]. Therefore, it is an ideal site to investigate and study how the wetland regulates and intercepts particle matter on different land uses.

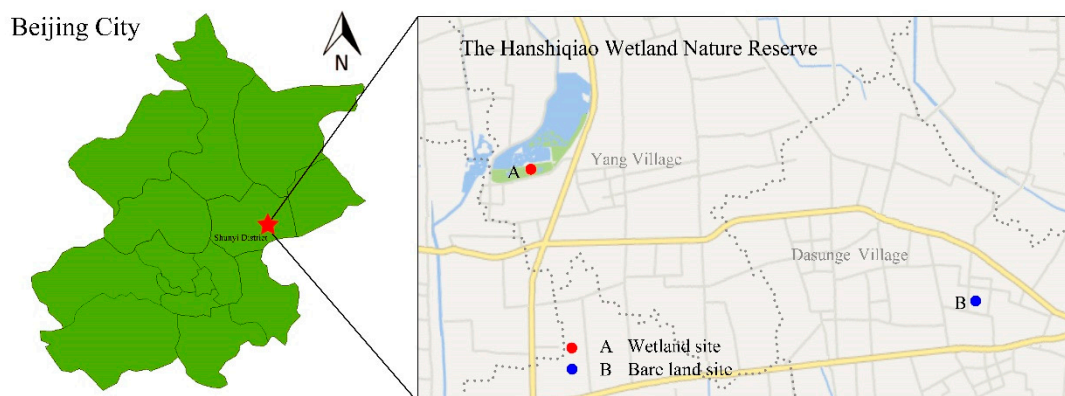
In this study, the concentrations of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  in different seasons within a year and the temperature, relative humidity, and wind speed data were collected on the wetland and bare land during the whole of 2016. The aims of the current study are as follows: (1) analyzing the daily and quarterly variations of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  concentrations on the wetland and bare land, (2) exploring the influence of meteorological factors on the concentrations of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ , and (3) comparing the dry removal efficiencies on the two land types. The results of this study may help to reduce pollutants and improve the air quality in Beijing to some extent.

## 2. Experiments

### 2.1. Study Area

The Beijing Hanshiqiao Wetland Nature Reserve (40°07' N, 116°48' E) covers a 1900  $\text{hm}^2$  area, as shown in Figure 1. The core zone, buffer area, and experimental zone take up 8.61%, 0.63%, and 90.76% of wetland natural reserve, with the area of 163.5  $\text{hm}^2$ , 12.1  $\text{hm}^2$ , and 1724.4  $\text{hm}^2$ , respectively. The dominant species mainly included *Phragmites australis*, *Echinochloa crus-galli*, and *Nymphaea tetragona*. The average temperature of this site was 11.9 °C, and the annual average precipitation was 603.1 mm.

The control site was bare land in Dasunge Village, about 10.5 km away from the Beijing Hanshiqiao Wetland Nature Reserve. The bare land includes a 70% cement pavement surface and 30% soil surface, and is 50 m in length and 20 m in width.



**Figure 1.** The location of the study area.

## 2.2. Measurements

Two 610 portable automatic weather stations (WeatherHawk instruments, USA) were installed 1.5 m above the ground in the wetland and bare land to record temperature, relative humidity, and wind speed and direction. The instrument could monitor a temperature range from  $-20$  to  $70$  °C, a relative humidity range from 5% to 95%, a wind speed range from  $0.4$  to  $40$   $\text{m}\cdot\text{s}^{-1}$ , and a wind direction range from  $0$  to  $360^\circ$ . A DustMate particle collector (Turnkey Instruments, Northwich, UK) was used to monitor the  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  concentrations, however, it is very sensitive and prone to be disturbed by human activities, leading to deviations from the real value. Therefore, we chose a monitoring point with less human activities to reduce the uncertainty of results. The installation of two handheld DustMate particle collectors was the same as the WeatherHawk 610.

The monitoring time was random in late January, April, July, and October in 2016, which include days when the weather conditions and concentrations of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  differ. The experiment was conducted for several consecutive days per quarter, and then five or six days that were representative were selected as the mean of replicate measurements in each season. The data were collected every five minutes on consecutive days and were not considered at rainy times. There was also uncertainty associated with the measurements, such as the selection of measurement points and the influence of surrounding vegetation. Therefore, we tried to choose the points where almost little can affect the monitoring results to reduce errors.

## 2.3. Estimating of the Dry Removal Efficiency of $\text{PM}_{10}$ and $\text{PM}_{2.5}$

The dry removal efficiency of the wetland and bare land should be estimated to compare the removal effects of PM on the two land types. Referring to the computation of air pollution removal by urban trees and shrubs in the United States, Santiago, and London [11,28,29], the dry removal efficiency rates  $E$ , or air quality improvement in this study were estimated using the removal quality of dry deposition, which was then contrasted with the total quality of dry deposition as follows:

$$E = \frac{M_v}{M} = (I \times T \times S) / (C^- \times H \times S). \quad (1)$$

In this formula,  $M_v$  (g) means the removal quality of dry deposition,  $M$  (g) represents the total quality of dry deposition,  $I$  ( $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) represents the hourly total dry deposition of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  on each land type,  $C^-$  ( $\mu\text{g}\cdot\text{m}^{-3}$ ) represents the hourly average concentration,  $H$  (m) represents the height from estimated surface to  $Z_0$ ,  $T$  (s) is the evaluated time, and  $S$  ( $\text{m}^2$ ) represents estimated

area. Nowak et al. found that the downward pollutant flux was estimated as the product of the deposition velocity and particle concentration [11], and due to the occurring of resuspension, the total dry deposition of PM<sub>10</sub> and PM<sub>2.5</sub> (I) was estimated as the following equation, in which R (%) means the resuspension rate of PM<sub>10</sub> and PM<sub>2.5</sub>, V<sub>d</sub> (cm/s) is the deposition velocity, and C (μg·m<sup>-3</sup>) is the PM concentration:

$$I = (1 - R) \times V_d \times C \times 100. \quad (2)$$

According to Kim's paper, the resuspension does not occur under wind conditions of lower than 3 m/s [30], therefore, the resuspension effect was neglected in this study. Based on resistance theory, deposition velocity is mainly determined by the roughness of subsurface and resistance from the constant layer and quasi laminar boundary layer [29–33]. Previous studies in Beijing conclude that the resistance is determined by the atmosphere conditions, wind speed specifically, and conclude an empirical model to calculate the deposition velocity [34,35]. In this study, the deposition velocities V<sub>d</sub> (cm/s) of the PM<sub>10</sub> and PM<sub>2.5</sub> were calculated by the empirical model as:

$$V_d = \left( -0.01 \times x^3 + 0.05 \times x^2 + 0.41 \times x - 0.05 \right) \times 0.01 \quad (3)$$

where x (m/s) is the wind velocity.

#### 2.4. Statistical Analysis

Data were subjected to one-way analysis of variance using SPSS 21.0 (Chicago, USA) and plotted with SigmaPlot 12.5 (Systat Software, Inc.). Significance of differences between PM mass concentrations mean values was tested using the least significant difference test (LSD) at  $\alpha = 0.05$ . To test relationships between meteorological factors and PM mass concentrations, Pearson correlation analysis was conducted at  $\alpha = 0.05$ .

### 3. Results and Discussion

#### 3.1. Meteorological Factors

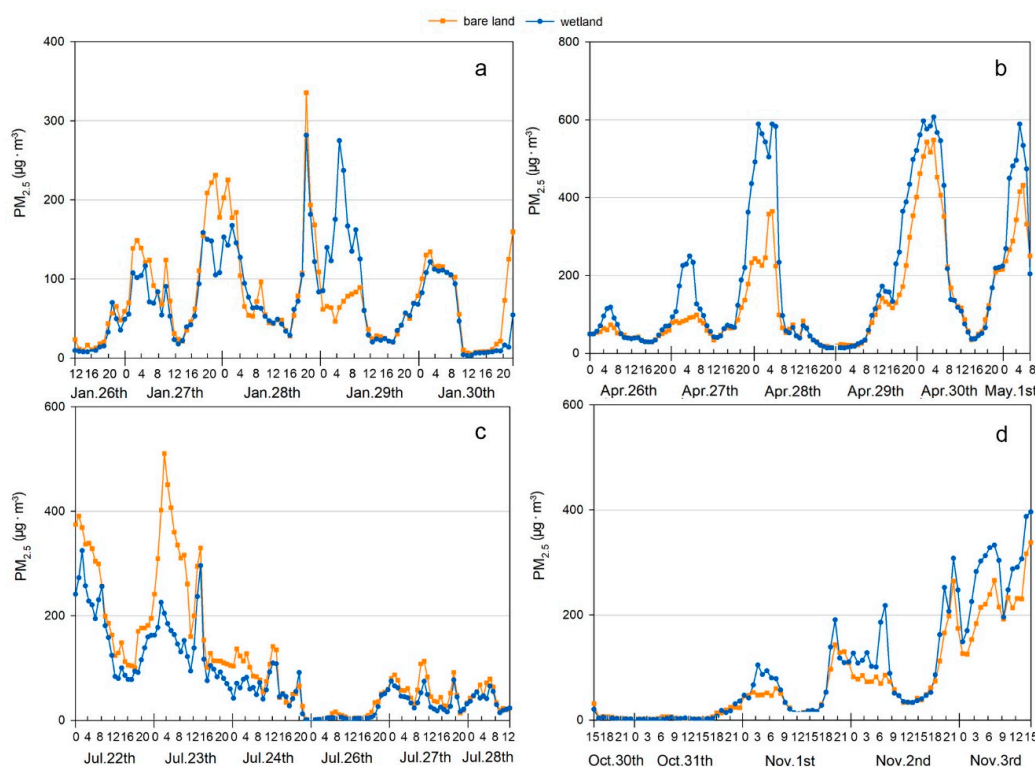
The meteorological factors, including the temperature, humidity, and wind speed, in each season on two different land surfaces are shown in Table 1. The average temperature in each season on the wetland was lower than that on the bare land, due to the freezing or evaporation of wetland waters in winter and spring [34] and the respiration and photosynthesis of wetland plants in summer and autumn. On the wetland, the averages of humidity and wind speed in winter and spring were significantly higher than those on the bare land ( $p < 0.05$ ), with ratios of 36.51%, 37.08%, 68.42%, and 100%, respectively. The variation of the relative humidity was always accompanied by the condensation of moisture in the air and water evaporation, which are beneficial for air flow. Gong et al. [36] found that compared with surrounding dry fields, marsh wetlands have a significantly cold and wet microclimate effect characterized by low temperature and high relative humidity.

**Table 1.** Temperature (°C), humidity (%), and wind speed (m/s) (mean ± standard error) in each season on two different land surfaces.

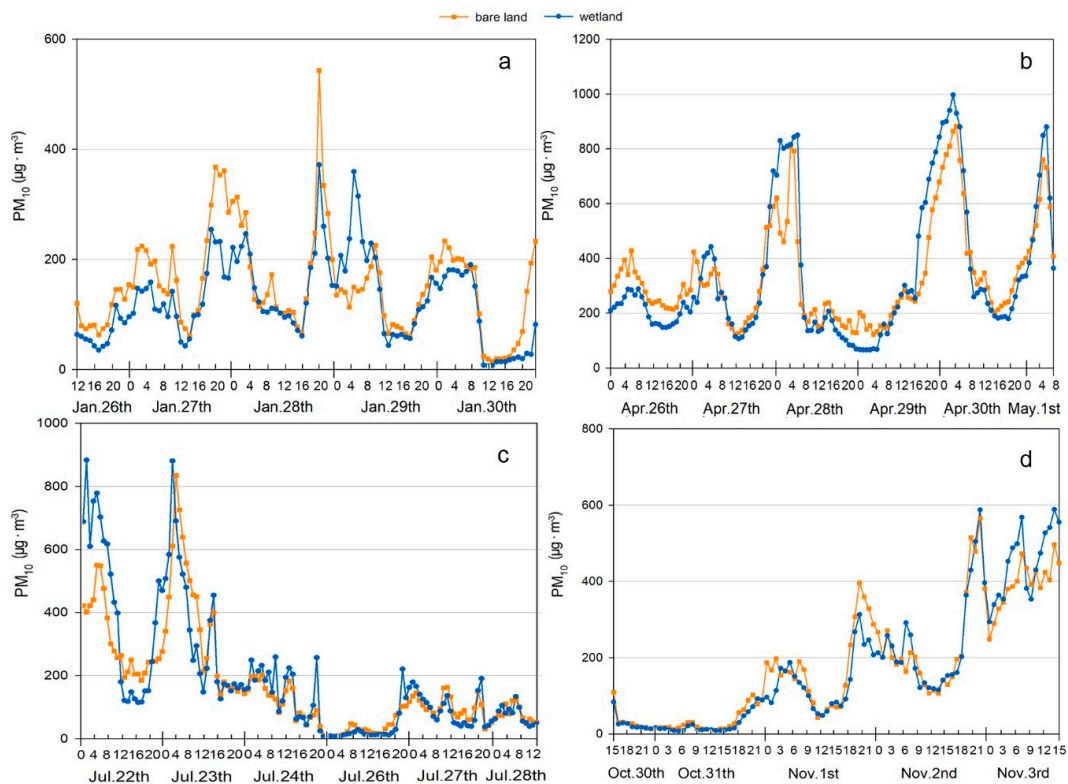
Type	Season	Temperature (°C)	Humidity (%)	Wind Speed (m/s)
Wetland	Winter	−6.43 ± 0.47	52.38 ± 3.01	0.32 ± 0.05
	Spring	17.27 ± 0.47	55.49 ± 2.63	0.38 ± 0.04
	Summer	26.92 ± 0.31	67.19 ± 2.45	0.06 ± 0.01
	Autumn	1.98 ± 0.51	50.89 ± 3.69	0.16 ± 0.03
Bare land	Winter	−3.95 ± 0.42	38.37 ± 1.53	0.19 ± 0.03
	Spring	18.94 ± 0.46	40.48 ± 1.63	0.19 ± 0.03
	Summer	28.41 ± 0.36	67.85 ± 2.08	0.23 ± 0.04
	Autumn	3.42 ± 0.47	49.22 ± 2.92	0.38 ± 0.06

### 3.2. PM Mass Concentration

Variations in the average concentration of PM<sub>10</sub> and PM<sub>2.5</sub> on the wetland and bare land during different seasons are presented in Figures 2 and 3. During the whole year, as shown in Figures 2 and 3, the daily change trends of the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> in each season on the wetland and bare land were approximately similar, with the highest value at night and evening while the lowest was near noon, which was similar to the results in the Cuihu wetland [34] and Shelterbelt Site in Beijing [17]. This is probably because the temperature is relatively lower, and the humidity is higher during the night and evening, which is to the disadvantage of the air flow and diffusion of PM<sub>10</sub> and PM<sub>2.5</sub> [37]; besides, the heavy traffic event during rush hours in the early morning and at evening is another reason [38]. Nguyen et al. also concluded that the PM<sub>2.5</sub> concentration is highest in the morning [39]. In terms of PM<sub>10</sub>, its average concentrations became higher in winter and spring than those in summer and autumn on both bare land and wetland. The concentrations of PM<sub>2.5</sub> on the wetland also became higher in winter and spring, whereas the PM<sub>2.5</sub> concentrations on the bare land were higher in spring and summer. There was much coal combustion in winter, and according to Witkowska's study [40], carbonaceous aerosols, regarded as the important component of PM<sub>10</sub> and PM<sub>2.5</sub> pollution, are durable and probably transported far away from the source. In spring, with the increase of temperature, primary organic carbon, calcium, potassium, and ammonium nitrate increased in aerosols due to emission from the surrounding fields and forests, leading to the increase in PM<sub>10</sub> and PM<sub>2.5</sub> concentrations. Given the similar surroundings of the wetland and bare land, such as roads and villages, meteorological factors were mainly considered in analyzing the difference of PM<sub>10</sub> and PM<sub>2.5</sub> between the two land types in this study. However, we found that wind direction, solar irradiance, and barometric pressure did not present a regular variation pattern and had little effect on the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub>, which was different from several other studies that indicated wind direction was crucial in the variation of particle concentration [41,42]. Therefore, the effects of temperature, relative humidity, and wind speed on the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> were mainly discussed.



**Figure 2.** Variation in the average concentration of PM<sub>10</sub> on the wetland and bare land during different seasons. (a–d) is winter, spring, summer, and autumn.



**Figure 3.** Variation in the average concentration of  $PM_{2.5}$  on the wetland and bare land during different seasons. (a–d) is winter, spring, summer, and autumn.

In winter,  $PM_{10}$  and  $PM_{2.5}$  on the bare land were higher than those on the wetland, as shown in Figures 2a and 3a. The average value of  $PM_{10}$  on the bare land was  $27.27 \mu\text{g}\cdot\text{m}^{-3}$  higher than that on the wetland with the ratio of 19.84%. The  $PM_{2.5}$  of bare land was 4.70% higher than that of wetland. This was because the wind speed on the wetland was higher than that on the bare land, as shown in Table 1, especially at 8:00–17:00 in winter. The average wind speed on the wetland was  $0.32 \text{ m}\cdot\text{s}^{-1}$ , approximately twice as high as the bare land. Due to the higher wind speed being conducive to air flow and particulate matter diffusion [41],  $PM_{10}$  and  $PM_{2.5}$  on the wetland were lower than that on bare land, and the effect of the wetland on the diffusion of  $PM_{10}$  was more obvious. However,  $PM_{10}$  and  $PM_{2.5}$  of the wetland on 29 January were significantly higher than those of the bare land, which was because the air relative humidity continued to be 100% on the wetland from 1:00 to 8:00 in the morning on 29 January, while it was 60–70% on the bare land, and there was no wind on the wetland. The weather conditions were conducive to the accumulation of particulate matter instead of its diffusion [21].

In spring,  $PM_{10}$  on the bare land was higher than that on the wetland during the daytime, which was opposite to the night and the dawn, while for  $PM_{2.5}$ , its concentration on the wetland exceeded that on the bare land on the whole, as shown in Figures 2b and 3b. This was because the average wind speed on the wetland during the daytime was higher than that on the bare land, which can help the diffusion of larger particles in the air [43]. During the night,  $PM_{10}$  and  $PM_{2.5}$  increased more rapidly on the wetland, especially under cloudy and moderately hazy weather (28 April, 30 April, and 1 May). By analyzing and comparing the variations of  $PM_{10}$  and  $PM_{2.5}$  concentrations from 0:00 to 7:00 of the three days, the average concentrations of  $PM_{10}$  and  $PM_{2.5}$  on the wetland were  $120.33 \mu\text{g}\cdot\text{m}^{-3}$  and  $157.23 \mu\text{g}\cdot\text{m}^{-3}$ , respectively, higher than that on the bare land, with the ratios of 19.51% and 45.41%. The reason was that the air relative humidity under the cloudy and hazy weather lasts for 100% at night, which is to the disadvantage of the diffusion of atmospheric particulate matter and promotes the accumulation of fine particulate matter in forests on the contrary [44]. Therefore, the wetland under

cloudy and hazy weather in spring will aggravate the accumulation of particulate matter, while it may reduce the concentration of particulate matter on sunny days.

In summer, according to Figures 2c and 3c, there was no obvious difference of PM<sub>10</sub> concentration between the two land types except for the two days, 22 and 23 July, which was similar to that of PM<sub>2.5</sub>. High relative humidity in summer may be the main cause of insignificant difference between the two land types. On 22 and 23 July, the concentration of PM<sub>10</sub> on the wetland exceeded that on the bare land at night, both with greater change amplitudes, but during the daytime (9:00–18:00) it was lower than the bare land. However, PM<sub>2.5</sub> concentration on the wetland was lower than that on bare land all day. This was due to the weather conditions with cloud and thundershowers on the two days, and as a result, the relative humidity on the wetland was higher at night, which was beneficial for the accumulation of coarse particulate matter, while during the daytime, it decreased with the increase of temperature. In addition, it is estimated that the plants grown in the wetland and the waters could capture, absorb, and dissolve the particulates, particularly the fine particles [45]. Li [27] compared the capturing and dissolving capacity of seven different plants including *Phragmites australis*, *Typha angustifolia*, *Scirpus tabernaemontani*, *Iris tectorum*, *Zizania aquatica*, *Eichhornia crassipes*, and *Sagittaria sagittifolia* grown in wetlands, and calculated the amounts of particles captured and absorbed by the plants. Liu [23] proved the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> were lower over lakes than bare land because of the absorption of water.

In autumn, no significant difference in the concentrations of PM<sub>10</sub> was found between the bare land and wetland, while PM<sub>2.5</sub> concentration on the wetland was higher than that on the bare land all day, as shown in Figures 2d and 3d. Compared with meteorological factors on the bare land, wind speed on the wetland was slower, which was 0.42 times of the data on the bare land, as shown in Table 1. These meteorological conditions would be adverse to diffusion and deposition of mass particles [21,43]. In addition, the PM<sub>2.5</sub> was more sensitive to meteorological conditions [23], and as a result, the PM<sub>2.5</sub> concentration on the wetland was higher than that on the bare land. The result was consistent with previous studies [12,23].

On the whole, the average concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> on the wetland and bare land did not show significant regularity ( $p > 0.05$ ) during the whole year [46]. It indicated that the average concentrations of the wetland and bare land have a large fluctuation during the whole monitoring period. The result was similar to Liu's study [23], which pointed out that the concentrations of PM<sub>2.5</sub> on lakes and bare land were unstable.

### 3.3. Effect of Meteorological Factors on PM<sub>10</sub> and PM<sub>2.5</sub> Concentrations

Correlation analysis between PM<sub>10</sub> and PM<sub>2.5</sub> concentrations and meteorological factors on different land types is displayed in Table 2. A complicated relationship was found between the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> and temperature. Specifically, PM<sub>10</sub> and PM<sub>2.5</sub> concentrations were significantly negatively correlated with temperature ( $p < 0.01$ ) in winter and spring on the two land types. However, in summer, only the correlation between the PM<sub>10</sub> concentration and temperature on the wetland was significant ( $p < 0.01$ ), but for PM<sub>2.5</sub>, it was insignificant, of which the reason may be that in summer, high temperatures changed some constituents of fine particles; moreover, according to a few previous studies [12,23,47], the small size of the particles seems to be more sensitive to meteorological factors. In addition, there was also no significant correlation between PM<sub>10</sub> and PM<sub>2.5</sub> concentrations and temperature in autumn and the whole year on two land types except that of PM<sub>10</sub> of the whole year on the wetland, which indicated the significantly positive correlation ( $p < 0.05$ ). This is likely because that high temperature in a year could help to accelerate the photochemical reaction between precursors, further influencing the formation of particles [41]. Therefore, the effects of temperature on particle concentrations are complex [8,9]. For instance, in summer, high temperature promotes the formation of particulate sulfate, but dissociates parts of particulate nitrate [48–50], hence, it was hard to present the definite relationships between temperature and PM<sub>10</sub> and PM<sub>2.5</sub> concentrations. In general, temperature plays a significant role in regulating

PM<sub>10</sub> and PM<sub>2.5</sub> concentrations by changing the humidity and wind speed, and it tends to have some effects on air disturbance and relative humidity [39]. In spring, the conditions of the wetland were characterized by lower temperatures, high relative humidity, and lower wind speeds during the night, therefore, the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> were higher than that on the bare land. As for significant correlations, the absolute value of R ranged from 0.100 to 0.495 for PM<sub>10</sub>, and from 0.121 to 0.540 for PM<sub>2.5</sub>, as shown in Table 2, which were both lower than that between PM<sub>10</sub> and PM<sub>2.5</sub> concentrations and humidity and wind speed, respectively.

**Table 2.** Correlation coefficients between PM<sub>10</sub> and PM<sub>2.5</sub> mass concentrations and meteorological factors on two different land surfaces during a year.

Type	Season	Particulate	Parameters	Climate Factors		
				Temperature	Humidity	Wind Speed
Wetland	Winter	PM <sub>10</sub>	R	−0.495 **	0.700 **	−0.553 **
			<i>p</i> Value	0.000	0.000	0.000
		PM <sub>2.5</sub>	R	−0.540 **	0.729 **	−0.541 **
			<i>p</i> Value	0.000	0.000	0.000
	Spring	PM <sub>10</sub>	R	−0.391 **	0.797 **	−0.442 **
			<i>p</i> Value	0.000	0.000	0.000
		PM <sub>2.5</sub>	R	−0.400 **	0.816 **	−0.454 **
			<i>p</i> Value	0.000	0.000	0.000
	Summer	PM <sub>10</sub>	R	−0.239 **	0.526 **	−0.149
			<i>p</i> Value	0.006	0.000	0.088
		PM <sub>2.5</sub>	R	−0.115	0.412 **	−0.087
			<i>p</i> Value	0.188	0.000	0.319
	Autumn	PM <sub>10</sub>	R	−0.068	0.594 **	−0.446 **
			<i>p</i> Value	0.511	0.000	0.000
	PM <sub>2.5</sub>	R	−0.109	0.595 **	−0.404 **	
		<i>p</i> Value	0.286	0.000	0.000	
year	PM <sub>10</sub>	R	0.100 *	0.555 **	−0.238 **	
		<i>p</i> Value	0.031	0.000	0.000	
	PM <sub>2.5</sub>	R	−0.003	0.544 **	−0.260 **	
		<i>p</i> Value	0.941	0.000	0.000	
Bareland	Winter	PM <sub>10</sub>	R	−0.369 **	0.506 **	−0.385 **
			<i>p</i> Value	0.000	0.000	0.000
		PM <sub>2.5</sub>	R	−0.407 **	0.472 **	−0.355 **
			<i>p</i> Value	0.000	0.000	0.000
	Spring	PM <sub>10</sub>	R	−0.340 **	0.813 **	−0.347 **
			<i>p</i> Value	0.000	0.000	0.000
		PM <sub>2.5</sub>	R	−0.229 **	0.801 **	−0.220 *
			<i>p</i> Value	0.009	0.000	0.012
	Summer	PM <sub>10</sub>	R	−0.131	0.457 **	−0.393 **
			<i>p</i> Value	0.133	0.000	0.000
		PM <sub>2.5</sub>	R	−0.134	0.467 **	−0.392 **
			<i>p</i> Value	0.123	0.000	0.000
	Autumn	PM <sub>10</sub>	R	−0.081	0.725 **	−0.535 **
			<i>p</i> Value	0.432	0.000	0.000
	PM <sub>2.5</sub>	R	0.006	0.632 **	−0.431 **	
		<i>p</i> Value	0.952	0.000	0.000	
year	PM <sub>10</sub>	R	0.076	0.402 **	−0.385 **	
		<i>p</i> Value	0.103	0.000	0.000	
	PM <sub>2.5</sub>	R	0.121 **	0.511 **	−0.329 **	
		<i>p</i> Value	0.009	0.000	0.000	

Note: R means Pearson correlation coefficients; \* correlation is significant at the 0.05 level (two-tailed). Similarly, thereafter; \*\* correlation is significant at the 0.01 level (two-tailed).

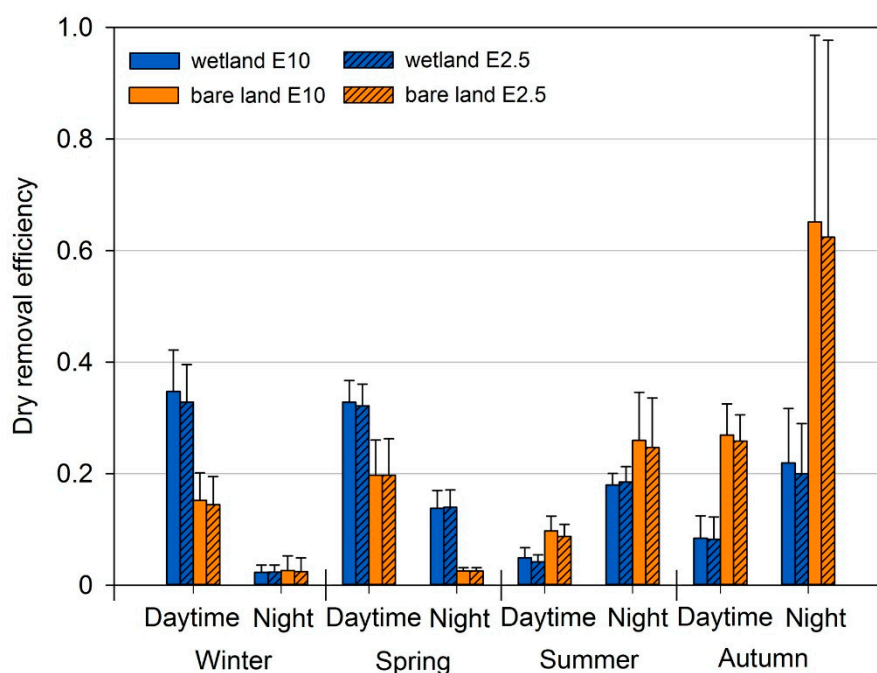


The relationships between concentrations of  $PM_{10}$  and  $PM_{2.5}$  and humidity presented significantly positive correlations ( $p < 0.01$ ) in different seasons within a year on two land types, as shown in Table 2. It was also proven by Liu et al., Zhu et al., and Qiu et al. in their research [21,22,34]. For example, in our study, the daily concentrations of  $PM_{10}$  and  $PM_{2.5}$  reached the highest value at night and evening, while the lowest was near noon in general due to the higher humidity during the night and evening with lower humidity at noon. Moreover, cloudy and polluted weather conditions (28 and 30 April, 1 May) would come along with higher relative humidity (almost 100%), and under this situation, concentrations of  $PM_{10}$  and  $PM_{2.5}$  on the wetland were greater than that on bare land, respectively, which was the same as Liu's study [23]. High relative humidity is to the disadvantage of diffusion of  $PM_{10}$  and  $PM_{2.5}$ , besides, high relative humidity combined with high particle concentrations could accelerate the further formation of water-soluble ions [48,49]. The significant effect of humidity and wind speed on the pollution concentration has been proven by some previous studies [23,51]. The absolute value of R between concentrations of  $PM_{10}$  and  $PM_{2.5}$  and humidity ranging from 0.402 to 0.797 for  $PM_{10}$ , with an average of 0.608, was higher than that between  $PM_{10}$  and  $PM_{2.5}$  concentrations and two other meteorological factors. For  $PM_{2.5}$ , the average of R (0.598) was also the highest, which is similar to the result of Liu et al. [23]. Whereas the relative humidity was found to bring less effects in the study of meteorological influence in four locations in Guangzhou, China [43], possibly due to the difference of climate in Beijing and Guangzhou.

There was a significantly negative correlation observed between  $PM_{10}$  and  $PM_{2.5}$  concentrations and wind speed ( $p < 0.05$ ) except in summer on the wetland; during that time, there was no significant correlation between both, as shown in Table 2. This was because wind speed in summer is the lowest ( $0.06 \pm 0.01$ ) among the different seasons on the wetland, and low wind speed may have a smaller effect on the diffusion of  $PM_{10}$  and  $PM_{2.5}$  [37]. The relatively slow wind speed favors accumulation of particles resulting in elevated pollution concentrations [17]. Humidity and wind speed influence the concentration by affecting the dry deposition velocity and resuspension [50–52]. For example, in spring during the daytime,  $PM_{10}$  concentration on the wetland was lower than that on the bare land, however, there was an opposite case during night. Maybe the causes for this were due to higher average wind velocity during day on the wetland which was conducive to diffusion of particles. However, wind velocity would slow down at night, which caused higher concentrations of  $PM_{10}$ .

### 3.4. Removal Effects

Previous studies paid more attention to the turbulence and boundary layers in which the deposition is highly influenced by the micrometeorological conditions as well as the particle concentrations [12,53–56], and the velocity was considered to be a constant value [57,58]. However, particle dry deposition at lower heights ( $Z/Z_0$  less than 100) is greatly influenced by the surface attributes and different from those within the turbulence and boundary layer [59], but with a very limited amount of research [22,23] and thus in this study, we calculated the deposition as well as the removal efficiency in the lower height layer. Figure 4 shows the dry removal efficiencies of  $PM_{10}$  and  $PM_{2.5}$  on the wetland and bare land during daytime and night in different seasons. In winter and spring, the dry removal efficiencies of  $PM_{10}$  and  $PM_{2.5}$  on the two land types were significantly higher during daytime than those during the night ( $p < 0.05$ ) and they were also higher on the wetland and lower on the bare land, except for the values during the night in winter. By contrast, in summer and autumn, the dry removal efficiencies of  $PM_{10}$  and  $PM_{2.5}$  during the night were significantly higher than those during the daytime; in addition, they were higher on the bare land and lower on the wetland. Although there was no significant difference between the dry removal efficiencies of  $PM_{10}$  and  $PM_{2.5}$ , on the whole, the dry removal efficiency of  $PM_{10}$  was greater than that of  $PM_{2.5}$ , which did conform with the results of Wu et al. and Yang et al. [60,61]. On the wetland, the dry removal efficiency of  $PM_{10}$  followed the order of spring > winter > autumn > summer, similar to that of  $PM_{2.5}$ , which was consistent with the results of Yang et al. [61], whereas  $PM_{10}$  and  $PM_{2.5}$  dry removal efficiencies on the bare land ranked as autumn > summer > winter > spring.



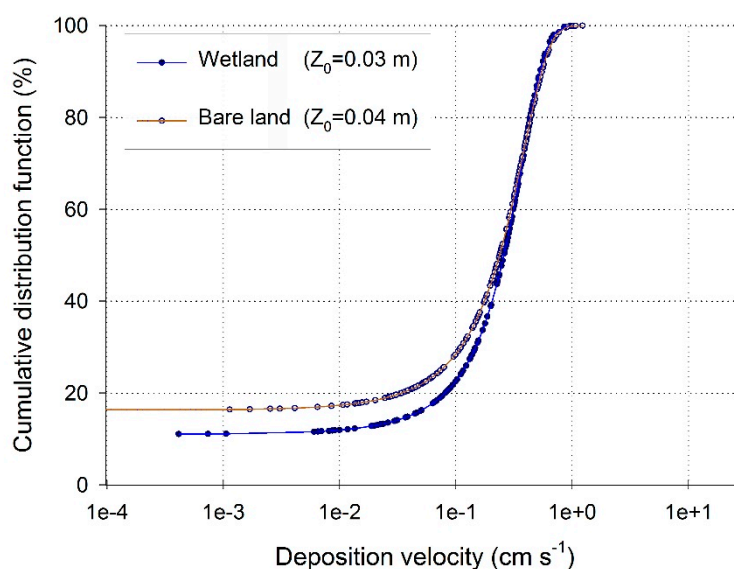
**Figure 4.** Dry removal efficiencies of PM<sub>10</sub> and PM<sub>2.5</sub> on the wetland and bare land in different seasons.

According to Equation (1), the removal effects depend on the dry deposition and the mass particles' average concentration [11,28,29]. The dry deposition of particles near the ground is more sensitive to meteorological variations and human activities [61]. In addition, it tends to be affected by the deposition velocity, which has a close positive relationship with the wind speed [61–63]. The removal effects were also influenced by anthropogenic and other meteorological factors, such as the temperature, relative humidity, and irradiance [60,63]. There was a negative relationship between the temperature and dry deposition of PM<sub>10</sub> and PM<sub>2.5</sub>: with the decrease of the temperature, the dry deposition increased, whereas the relative humidity had a positive effect on the dry deposition [23,45]. Inversely, Yang et al. showed the influences of temperature and relative humidity on dry deposition were uncertain [61].

In this study, the wind speed in winter and spring on the wetland was higher than that in summer and autumn, which is in contrast to the circumstance on the bare land, where the wind speed in summer and autumn exceeded that in the other two seasons, as shown in Table 1. Additionally, there was the lower temperature and higher humidity in winter and spring on the wetland compared with the other two seasons. As a result, the dry removal efficiencies of PM<sub>10</sub> and PM<sub>2.5</sub> in winter and spring on the wetland were higher than those of the other two seasons, which was opposite to the situation on the bare land. However, there was an exception during the night in winter, where the dry removal efficiencies of PM<sub>10</sub> and PM<sub>2.5</sub> on the wetland were lower than those on the bare land. This was because the higher concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> on the bare land led to higher dry deposition and, accordingly, the dry removal efficiencies increased [60]. Surprisingly, we found the dry removal efficiencies of PM<sub>10</sub> and PM<sub>2.5</sub> in summer were lower than those in other seasons. Nevertheless, in summer, the plants grown in the wetland have the ability to absorb and capture particles; moreover, some water-soluble ions could dissolve the particles into water [48–50]. Thus, in theory, the dry removal efficiency in summer should be higher than the other seasons. As for this phenomenon, we discovered the wind speed in summer was too slow and almost close to zero, which led to the lower dry removal efficiency. Besides, the removal efficiency (E) of wetlands and bare lands in the lower height layer were estimated. In previous studies the removal efficiency [23,58] was calculated by the ratio of dry deposition flux ( $\mu\text{g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) and concentration ( $\text{g}\cdot\text{m}^{-3}$ ), however, this efficiency

( $\text{m}^{-1}\cdot\text{s}^{-1}$ ) lacks physical meaning. We improved this algorithm and  $E$  was estimated by the ratio of deposited particle matter and total particle matter.

The deposition velocity was calculated by Equation (3) in the current study, and using its cumulative distribution function, Figure 5 was obtained. Due to the difference between Equation (3) in this study and the empirical formula of NUREG/CR-7161, the deposition velocities of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  were considered as a whole and were not regarded as an independent variable here. Even so, compared with the results acquired from the empirical formula which used the cumulative probability density function of deposition velocity (NUREG/CR-7161;  $Z_0 = 10 \text{ m}$ ,  $V = 2 \text{ m}\cdot\text{s}^{-1}$ ) [30], the distribution tendency of the data on the wetland and bare land in this study agreed with this formula, as well as the ranging from  $0.0001$  to  $1.2263 \text{ cm}\cdot\text{s}^{-1}$ , as shown in Figure 5. The structure of this model is relatively simple, and the data required are easy to collect compared with the physical process-based model [35]. Previous studies in Beijing estimated this model and found that the results based on the model were considered to be credible [34,45]. However, uncertainties of this study should be also highlighted here. First of all, we used the same empirical model to calculate the deposition velocities on both land types. In addition, the structure of the empirical model itself, like other physical-based models, is a source of uncertainty. The deposition velocity is determined by both the atmosphere conditions and the roughness of different land covers, and wetlands and bare lands have similar roughness [35]. In previous studies, parameterized roughness coefficients of these two land covers are estimated to be the same [23,45]. Besides, the empirical model was developed and verified in Beijing where our research was conducted and thus the calculated results are reliable. The difference of dry deposition and removal efficiency on the two land cover types comes from different atmosphere conditions, especially wind speed and the concentration of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ . Another uncertainty that should be highlighted is that we considered the deposition velocity within the lower height layer remained constant based on resistances theory [53,64,65] and a narrow range of the height. Thus, we calculated the removal efficiency based on the deposition at the middle of the lower height layer. The replace surface ( $Z_0$ ) of wetlands and bare lands are  $0.03 \text{ m}$  and  $0.04 \text{ m}$ , respectively, [35] and thus  $H$  in Equation (1) was defined as the difference from the middle of the lower height layer ( $1.5 \text{ m}$ ) to the replace surface ( $Z_0$ ). While the deposition regulation remains blurred in this layer, the integral value of depositions at different heights might be another option to represent the deposition, but still requires further experiments.



**Figure 5.** Deposition velocity of  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  on the wetland ( $Z_0 = 0.03 \text{ m}$ ,  $V = 0.28 \text{ m/s}$ ) and bare land ( $Z_0 = 0.04 \text{ m}$ ,  $V = 0.25 \text{ m/s}$ ) using its cumulative distribution function.

#### 4. Conclusions

This study indicated that the daily change trends of the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> in each season on the wetland and bare land were approximately similar, with the highest value at night and evening, while the lowest was near noon. The average concentration of PM<sub>10</sub> reached the higher value in winter and spring on both the two land types, and the PM<sub>2.5</sub> concentration on the wetland also came up to the higher value in winter and spring, whereas, on the bare land, it was higher in spring and summer. As for the relationships between meteorological factors and concentrations of PM<sub>10</sub> and PM<sub>2.5</sub>, relative humidity and wind speed were significantly correlated with the PM<sub>10</sub> and PM<sub>2.5</sub> concentrations on the wetland and bare land ( $p < 0.05$ ). The dry removal efficiency of PM<sub>10</sub> was greater than that of PM<sub>2.5</sub>. Strong wind speed, lower temperatures, and higher relative humidity could facilitate the dry deposition and accordingly increase the removal process.

The results of this study show the importance of removing PM<sub>10</sub> and PM<sub>2.5</sub> from the atmosphere, further improving the air quality in Beijing through effective approaches and management. Given the irregular variation of PM<sub>10</sub> and PM<sub>2.5</sub>, and various factors affecting the concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> and complicated mechanisms in the process of removing atmospheric particles, further research about the changes of chemical constitutions and particle characteristics in the study area should be conducted. How to further reduce particle concentrations through improving the microclimate in wetland ecosystems is valuable to be discussed, and other factors and their synergistic effects affecting the dry deposition and dry removal efficiency of particles still need to be explored in the future.

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