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The Effect of Sedimentin Yellow River on Hydraulic Characteristics of Spray Sprinkler

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Received: 16 April 2020; Accepted: 8 May 2020; Published: 10 May 2020

Abstract: The water shortage has become a great challenge for Yellow River irrigation regions; for the high level of suspended sediment in Yellow River, sprinkler irrigation, which has achieved superior anti-clogging performance, can be an effective solution for water conservation in agriculture management. For the direct utilization of the Yellow River water resource in irrigation land as irrigated by movable sprinkler irrigation systems, a series of experiments about the effect of sediment-water on the hydraulic performance of fixed spray plate sprinkler was conducted. The results showed that peak water precipitation rate appeared as both clean and sediment-water jetting from the groove, and the differences were that sediment-water minimized peak value of water application rate and increased wetted radius efficiently. The water distribution of an individual sprinkler resembled lotus shape with different working conditions, and the application rate nearby sprinkler increased with the increase insediment concentration, resulting in higher water distribution uniformity. In addition, sediment-water increased the spray distance remarkably with a maximum increasing ratio of 7.79%; meanwhile, it led to the transfer of peak application region to the edge of the wetted circle and, consequently, the wetted area increased. The calculation result of the water diffusion coefficient indicated that sediment-water contributed to splintering water jet effectively, but the analysis of variance showed that no significant change was obtained with increasing sediment concentration. All these results suggested that the sediment-water in Yellow River could be directly utilized in agriculture irrigation with superior hydraulic performance, and it would be helpful to protect and maximize the utilization of the Yellow River resource.

Keywords: sprinkler irrigation; sediment-water; Yellow River; hydraulic performance

1. Introduction

As known for its high level of suspended sediment, the Yellow River is one of the most important water resources in north and northwest China [1,2]. After the establishment of the People's Republic of China, more and more farmlands were reclaimed in Yellow River basins, and consequently, the agricultural water consumption occupied a large proportion in the application of Yellow River water. In recent years, flood irrigation method has been widely used in these regions, especially in north China, which exacerbates the problem of water scarcity [3]. For the maximum utilization and protection of this limited water resource, water-saving irrigation technology should be promoted in Yellow River irrigation regions. As an effective and water-saving way to irrigate, drip irrigation has been applied in most farmlands [4–7]. However, there are still some bottlenecks, limiting the direct use of the Yellow River resource for drip irrigation, and the main reason is high sediment concentration. For the flow channel, the size of the emitter is about 0.5~1.2 mm for hydraulic energy dissipation, the clogging risk of the drip irrigation system exists as the sediments in water deposit in the flow path, and the irrigation uniformity will decrease and affect crops' rowth [8]. The application of the grit chamber and filter can decrease the clogging risk to some extent, but the operating cost of a drip irrigation system will increase sharply. Sprinkler irrigation is another water-saving technology with the advantage of improving field microclimate [9]. Commonly, the nozzle sizes of the sprinklers are large enough to pass the sediments and present a superior anti-clogging performance as irrigated with sediment-laden water. Therefore, despite the corrosion of the sprinkler by sediment, the water in the Yellow River can be used efficiently with a sprinkler irrigation system in agriculture management. Furthermore, the deposition of sediment on irrigation land can increase agricultural productivity and soil improvement [10].

In recent years, center-pivot and linear move sprinkler irrigation machines have been widely employed with the high automatic extent and labor-saving characteristics [11,12], exhibiting the particular potential of irrigating with Yellow River resource. Commonly, these irrigation machines are equipped with fixed spray plate sprinkler (FSPS) and rotating spray plate sprinkler (RSPS); the hydraulic characteristics of these two sprinklers, such as water distribution patterns and wetted areas, have a significant effect on irrigation uniformity [13–16]. It is noteworthy that these hydraulic performances depend on nozzle sizes, manage practice (working pressure and mounting height), weather conditions (speed and direction of the wind), and field topography. In order to discover the water distribution pattern of RSPS and FSPS, Faci et al. [17] performed experiments with different nozzles in wind condition, and the results showed that the water distribution of RSPS had a conical shape, and the FSPS concentrated in a circular crown. For analyzing the influence of percent times parameters on water distribution uniformity, an indoor experiment of FSPS was conducted to evaluate wetted diameter, effective width, and water application rate by Yan et al. [18], and the variation of these parameters with different nozzle sizes was discussed. Furthermore, Sayyadi et al. [19] discovered the effect of working pressure, nozzle size, and deflection plate specification on the distribution of water droplet size formed by FSPS with indoor tests and analyzed the changes in the wetted diameters, peak application rate, droplet sizes, and velocities. Jiao et al. [20] compared the water distribution between RSPS and FSPS with different nozzle diameters and provided insights into understanding the differences of sprinkling performance of these two sprinklers. Ouazaa et al. [21] also pointed out that FSPS was cheaper and robust, but PSPS presented a more uniform water distribution pattern, which verified the results attained by Hanson et al. [22] and Hills et al. [23]. As for the effect of wind speed, the conclusions made by Hanson were different from Hills'. In order to distinguish the influence of wind on water distribution, Rovelo et al. [24] performed a series of experiments to determine the water distribution pattern of RSPS combined with different nozzle sizes and working pressures and then characterized the water distribution in calm and windy conditions, revealing the effect of wind speed on water application. All these researches contributed to the design and application of a movable sprinkler irrigation machine and provided references with management practices. However, most of these studies focused on the influence of sprinkler type, environment, and management on water distribution; a small number of researches about the influence of sediment-water resources on sprinkler hydraulic performance were published. As the Yellow River water resource plays a decisive role in the economy and life in the north of China, the protection and maximum utilization of the Yellow River have been China's national strategy. For the maximum utilization and protection of this limited water resource, the hydraulic performance of sprinkler irrigation using Yellow River water should be conducted.

Hence, this study analyzed the effects of sediment-water on the hydraulic performance of FSPS. Five sediment concentrations trials cooperating with different working pressures and sprinkler mounting heights were performed, and water and sediment distribution patterns of one groove were determined with indoor experiments. The wetted area of the individual sprinkler was present by changing the angles of the measured groove. On these bases, the peak application rate and water diffusion coefficient with different sediment concentrations were analyzed.

2. Material and Methods

2.1. Indoor Experimental Setup

The experiment was conducted at the Hydraulics Laboratory of Zhengzhou University in China. The experimental platform consisted of the plastic stirred barrel, booster pump, pipes, valves, brackets, sediment-water container, pressure sensor, catch-can, and other necessary equipment, as shown in Figure 1. The diameter and height of the stirred barrel were 1 m and 1.3 m, respectively; a stirrer (motor power was 1.1 KW) was installed above the barrel, and the swing speed of the stirred paddle was adjustable. A Nelson D3000 sprinkler (Nelson Irrigation Co., Walla Walla, WA 99362-2271, USA) [25] with a nozzle diameter of 4.76 mm was selected in these experiments. Considering negligible differences among the grooves of Nelson D3000 sprinkler [12], the water distribution characteristics of this sprinkler could be acquired by measuring one spray jet. In order to measure the water distribution pattern of spray jet from one groove, the selected sprinkler was installed in a funnel-shaped box, an adjustable window was located on the shell, and only one spray jet was allowed to exist; the bottom of the box was connected with a sediment-water return pipe, and the spare sediment-water sprayed from other grooves was collected with a tank.

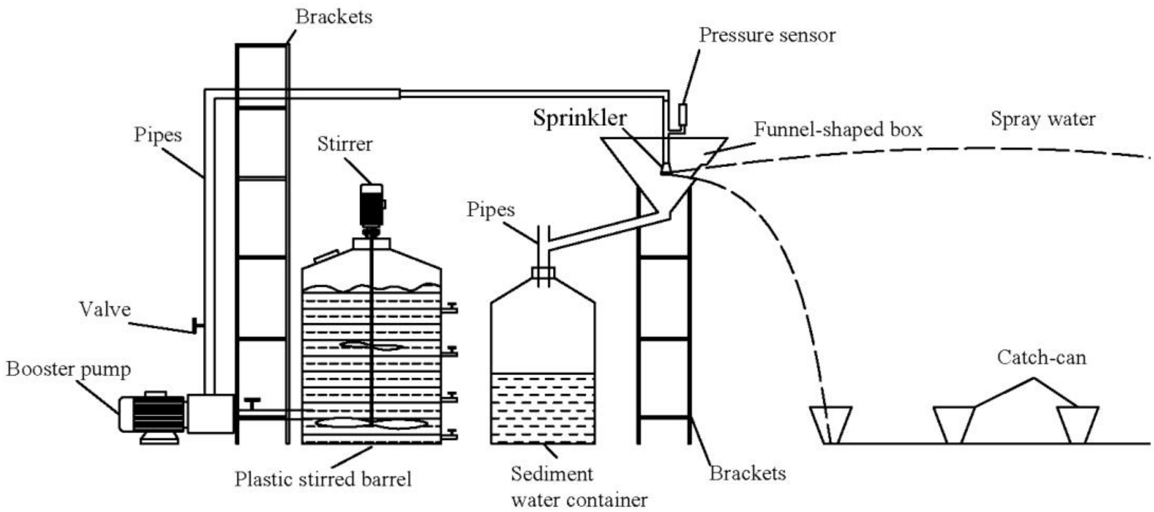

Figure 1. Experimental setup for sprinkler sediment-water distribution.

The working pressure of the sprinkler was measured with a pressure sensor, which ranged from 0 to 500 kPa with ±0.1% accuracy. Based on American Society of Agricultural and Biological Engineers (ASABE) requirement, a square matrix of catch-can (with a diameter of 23 cm and height of 29 cm) was used to determine the water distribution pattern, and the number of rows was determined by the spray distance. There were 5 adjacent catch-cans in each row; the distance of two rows was 0.5 m; in the peak application rate area, the space of two rows was 0.25 m. The discharge of the sprinkler was measured with the weighting method.

2.2. Experimental Design

The sediment in experimental water was extracted in the Yellow River, Zhengzhou basin. Considering the distribution uniformity of sediment in stirred suspension, the swing speed of the motor should be verified. In this paper, the standard deviation of sediment concentration was used to evaluate sediment distribution uniformity. The standard deviation of sediment concentration could be calculated by the following Equation [26]:

$$\sigma = \sqrt{\frac{\sum_{1}^{n}\left(\frac{\phi_m^n}{\phi_m} - 1\right)^2}{n}} \quad (1)$$

where σ is the standard deviation of sediment concentration; n is the number of sampling; ϕ_m is the mass fraction of sediment. In general, the sediments present homogenous suspension status when σ is less than 0.2. The standard deviations of various sediment concentrations were measured with different swing speeds; the experimental results showed that as the swing speed of the stirrer was around 300 rpm, the standard deviations were less than 0.2.

Considering suspended sediment concentration in the Yellow River had great variability under different discharges (Figure 2), the sediment concentration in this paper was ranged from 1 to 5%. In addition, the structure of the grooves would be abraded by sprayed sediment-water, and the sprinkler was replaced with an unused one in each test. Experimental factors were sediment concentration, mounting height, and working pressure, as shown in Table 1. There were a total of 45 trials.

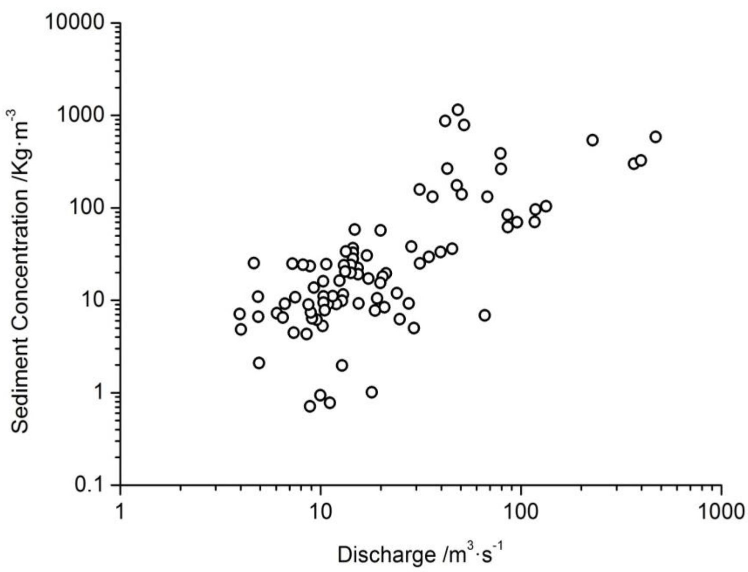

Figure 2. Suspended sediment concentration in the Yellow River.

Table 1. Experimental factors and levels.

Levels	Experimental Factors		
	Sediment Concentration (Mass Percent/%)	**Mounting Height (m)**	**Working Pressure (kPa)**
1	1	1	100
2	2	1.5	150
3	3	2	200
4	4		
5	5		

The objective working pressure was produced by setting the manual valve; catch-cans were used to measure the weight of sediment-water as soon as the pressure was stabilized, and the duration for each test was 30 min. The weight of sediment in each catch-can was obtained after filtering and drying by filter paper and oven, and then the water and sediment distribution could be acquired, respectively.

2.3. Data Analysis

In order to analyze water diffusion, a coefficient was proposed [14]:

$$r = R_a/R_p \quad (2)$$

where r is the water diffusion coefficient, the spray water is fully diffuse if the value is 1; R_p is peak application rate, mm/h; R_a is average application rate, mm/h. In this paper, R_a was the ratio of sprinkler discharge and wetted area:

$$R_a = 100Q/S \quad (3)$$

where Q is the discharge of experimental groove, L/s; S is the wetted area of the groove, m^2; S could be calculated by Equation (4),

$$S = LW \quad (4)$$

where L is the width of the wetted area, m; W is spray distance, m.

Substituting Equation (2) into Equations (3) and (4), the water diffusion coefficient could be evaluated by Equation (5),

$$r = 100Q/R_pLW \quad (5)$$

3. Results

3.1. Water and Sediment Distribution of One Groove

Water distribution characteristics of the experimental sprinkler could be evaluated by using the distribution data of one groove, so the first step in sprinkler characterization was to analyze the effect of sediment on one distinct groove water distribution. Figure 3 presents the water and sediment distribution patterns for different sediment concentrations with 2 m mounting height at 150 kPa. As shown in Figure 3, the majority of spray water landed in a limited region on the ground with any sediment concentration water, i.e., peak application rate could be observed at the end of the wetted radius. Compared with clean water (Figure 3a), the sediment-water sprayed more uniformly; as a result, water application rates closed to the sprinkler were increased, and water deposit volume in peak application area decreased. Despite sediment-water had positive effects on uniformity, the changes of the peak application rate were not remarkable with the increase in sediment concentration, and the peak application rate for clean water, 1%, 3%, and 5% sediment-water was 60.00, 51.20, 47.86, and 69.54 mm/h, respectively.

Spray distance presented an increased tendency with an increase in sediment concentration. Compared with clean water, the increasing rate of the wetted radius with 1, 3, and 5% sediment concentration was 4.43, 7.60, and 5.06%, respectively. All the peak application regions moved to the edge of the wetted area. The reason might be that the inertia force of sediments in spray water reduced the attenuation of jet velocity in the horizontal direction. As a consequence, water sprayed farther, driven by sediments. Figure 3 also shows that sediment distribution was similar to the water distribution, and the majority of sediments deposited in the peak application rate region. However, different from the water distribution, the volume and peak application rate of sediment were both increased obviously with the increase in sediment concentration, and the peak application rate of sediment was 7.55, 12.56, and 26.33 $gcm^{-2}\ h^{-1}$. Despite all this, sediment-water had a benefit of the diffusion of the spray water and increased spray distance.

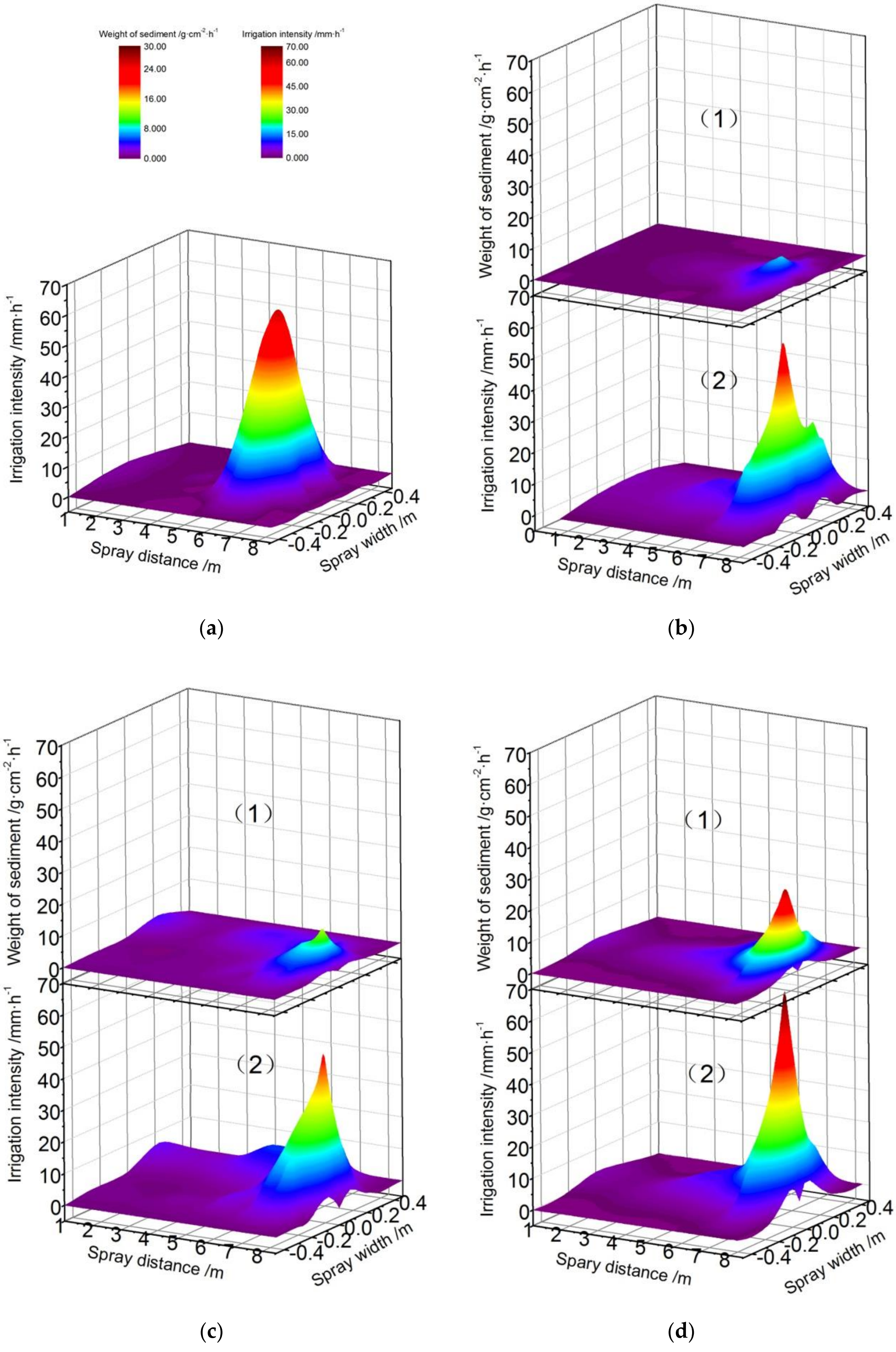

Figure 3. Water and sediment distribution patterns of one groove with 2 m mounting height at 150 kPa. Note: (**a**) clean water; (**b**) 1% sediment concentration; (**c**) 3% sediment concentration; (**d**) 5% sediment concentration.

3.2. Water Distribution

Considering each water jet is relatively independent among the 36 grooves of the Nelson D3000 sprinkler, and ignorable differences of water distribution pattern with any other grooves, the water distribution pattern of other grooves can be obtained by changing the angles of the measured groove [24]. Figure 4 shows the effect of sediment concentration in irrigation water on the water distribution of an individual sprinkler with 1.5 m mounting height at 150 kPa, and the sprinkler was located in a (0, 0) coordinate point. It could be seen from Figure 4 that the water distribution patterns resembled lotus shape (two-dimension) with different working conditions, similar to the circle crown (three-dimension) presented by Faci [17]; however, there were some differences for water distribution due to the diversities of supply water. Figure 4a presents the wetted pattern irrigated with clean water. Most of the water was distributed around the edge of the wetted circle, resembling slender rugby. The point of the peak application rate was in the center of this region, while the area closed to the sprinkler received less water. When irrigated with sediment-water, the water spread out perpendicular to the spray direction, and the water concentrated area was similar to oval shape (Figure 4b–f). The water depositing area and peak application rate all had a decreasing tendency with an increase in sediment concentration, and more water landed on the region nearby sprinkler. This was due to the elastic collision of the sediments; as water splashed on the deflector plate, these sediments separated and brought out a lot of water from the spray jet, and then much more water was peeled from the spray water with the increase in sediment concentration. Consequently, increasing sediment concentration properly could obtain high uniformity of an individual sprinkler. Figure 4 also illustrates that the spray distance was increased with the increase in sediment concentration of irrigated water.

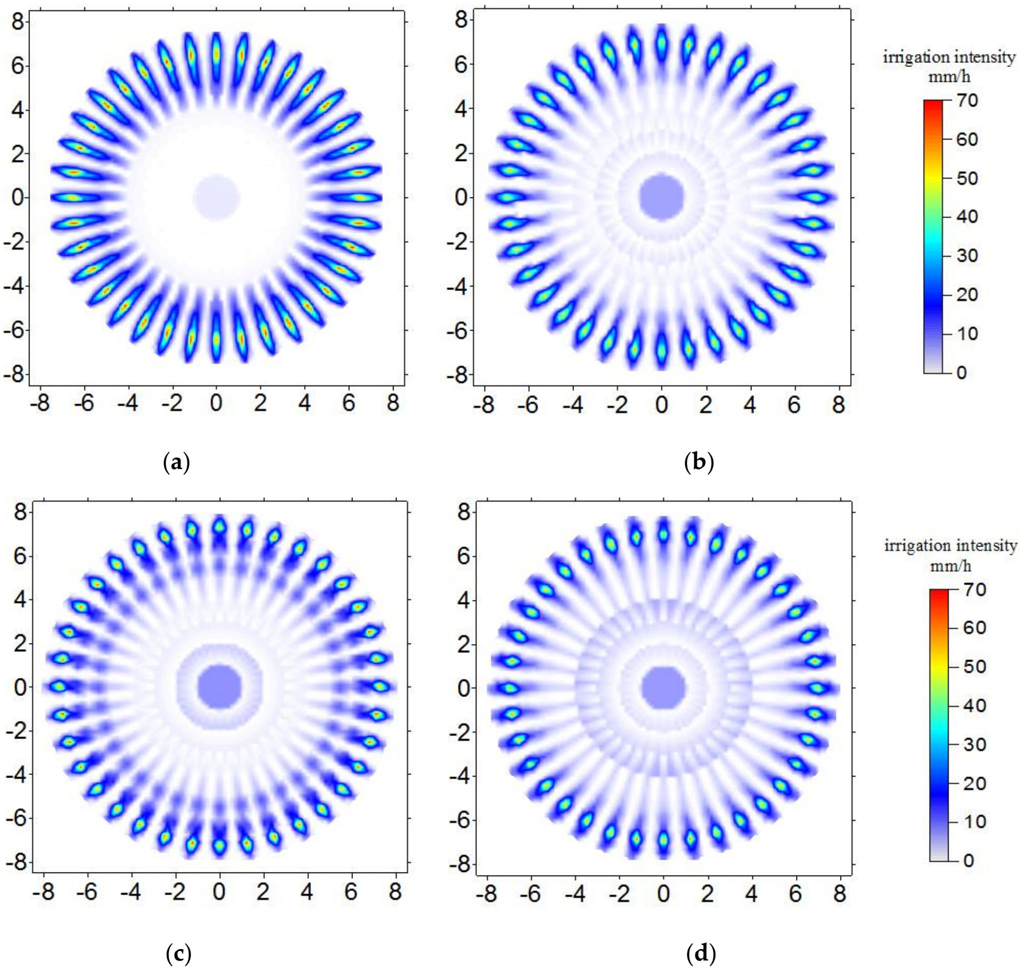

Figure 4. *Cont.*

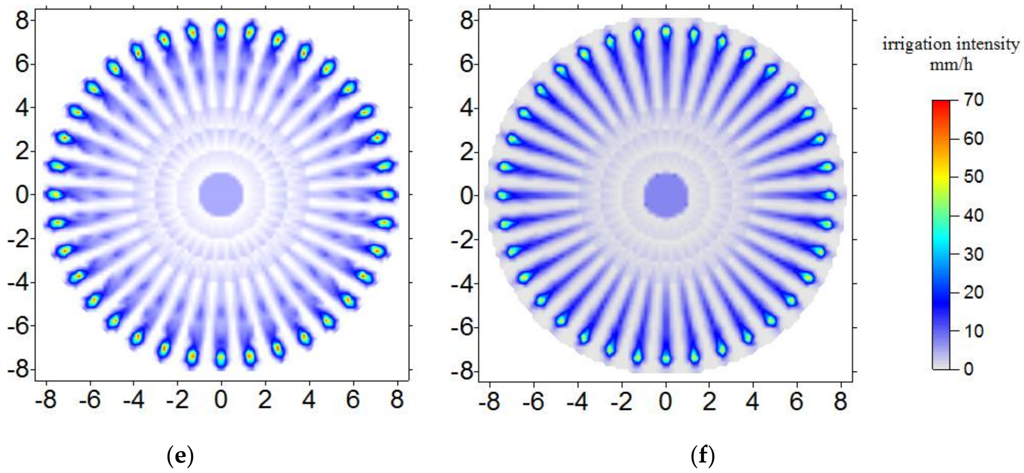

Figure 4. The effect of sediment contents on water distribution pattern with 1.5 m mounting height at 150 kPa. Note: (**a**) clean water, (**b**) 1% sediment content, (**c**) 2% sediment content, (**d**) 3% sediment content, (**e**) 4% sediment content, (**f**) 5% sediment content.

3.3. Spray Distance

Spray distance is an important parameter, which decides the overlapping space in sprinkler's irrigation design. Table 2 presents the spray distance with different sediment concentrations. For the same working pressure, wetted radiuses irrigated with sediment-water were larger than clean water, the increasing ratio of spray distance for 100 kPa ranged from 2.42%~6.25% with different mounting heights, and the maximum increasing ratio was 7.79% and 6.74% when the working pressure increased from 150 kPa to 200 kPa. For the same sediment concentration and working pressure, the increasing trend of spray distance was not obvious at increased mounting height. In addition, the increase in sediment concentration contributed to the increase in spray distance, although regulation of the fluctuations affected by concentration was not obvious. This phenomenon might result in the probability of elastic collision as sediments struck on the deflector plate. For a high sediment concentration, the probability value of the elastic collision event was high, then more water would be peeled out the water jet, and the jet crashed by the sediment scattered in all directions, leading to the change in spray distance.

Table 2. Spray distance (m) with different sedimentconcentrations.

Working Pressure/kPa	Sediment Concentration/%	Mounting Height/m			Increasing Ratio/%		
		1	1.5	2	1	1.5	2
100	0	6.20	6.40	6.50	0	0	0
	1	6.50	6.80	6.80	4.84	6.25	4.62
	2	6.35	6.75	6.75	2.42	5.47	3.85
	3	6.40	6.75	6.90	3.23	5.47	6.15
	4	6.50	6.80	6.75	4.84	6.25	3.85
	5	6.50	6.70	6.75	4.84	4.69	3.85
150	0	7.20	7.70	7.90	0	0	0
	1	7.40	8.00	8.25	2.78	3.90	4.43
	2	7.30	8.00	8.20	1.39	3.90	3.80
	3	7.50	8.10	8.50	4.17	5.19	7.59
	4	7.50	8.30	8.40	4.17	7.79	6.33
	5	7.60	8.25	8.30	5.56	7.14	5.06
200	0	8.00	8.70	8.90	0	0	0
	1	8.25	9.00	9.40	3.13	3.45	5.62
	2	8.30	8.90	9.50	3.75	2.30	6.74
	3	8.10	8.75	9.25	1.25	0.57	3.93
	4	8.40	9.00	9.50	5.00	3.45	6.74
	5	8.30	9.00	9.20	3.75	3.45	3.37

3.4. Peak Application Rate

Peak application rate appeared as the majority of spray droplets landed on a limited region, which had a negative influence on the irrigation performance, such as soil crust and run off. Figure 5 is the migration of the peak application rate with different working conditions. In Figure 5, the x-axis is the peak application rate location; it is the ratio of the distance from peak point to sprinkler and wetted radius; y-axis is the sediment concentration, and the diameter sizes of bubbles represent the value of peak application rate. As shown in Figure 5, sprinkler mounting height, working pressure, and sediment concentration all had a significant influence on peak application rate. For a given working pressure, the peak application rate decreased with the increase in mounting height for both clean water and sediment- water. For example, when the working pressure was 100 kPa (Figure 5a), the peak application rate was 104.80 mm/h, 76.40 mm/h, and 64.80 mm/h for clean water; as the mounting height increased from 1 to 2 m, the peak application rate decreased to 90.85 mm/h, 62.55 mm/h, and 55.89 mm/h for sediment-water with 1% sediment concentration. This was the result of ahigh probability of water jet fragmentation with the increase in sprinkler mounting height. Figure 5 also shows that the peak application rate decreased as the working pressure increased at constant mounting height and sediment concentration. In addition, peak application rate could hardly be observed as irrigated with sediment-water (three times in forty-five trials), i.e., sediment-water led to a smaller peak application rate under most working conditions; meanwhile, the peak application zones moved to the end of the wetted area. All the results of the peak application rate indicated that sediment-water was conducive to improving the irrigation quality.

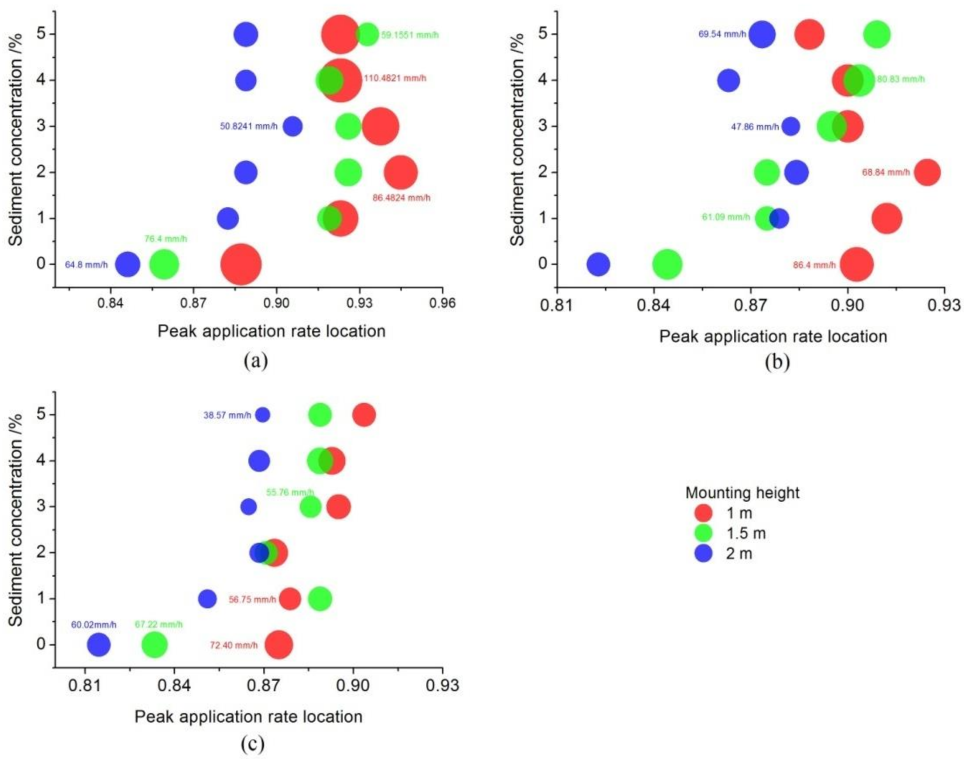

Figure 5. Migration of peak application rate with different sediment concentrations. Note: (**a**) 100 kPa, (**b**) 150 kPa, (**c**) 200 kPa.

3.5. Spray Water Diffusion

The changes of peak application rate revealed the spray water diffusion partly; for the further analysis of water diffusion, water diffusion coefficients were calculated with Equation (5). Figure 6 shows the influence of sediment concentration on the water diffusion coefficient with various working pressures. As shown in Figure 6, sediment-water contributed to splintering water jet in most cases in contrast with clean water; however, increasing sediment concentration couldn't develop an increasing tendency of water diffusion. Water diffusion coefficient ranges were 0.036~0.074, 0.047~0.080, and 0.063~0.107 when the working pressure increased from 100 kPa to 200 kPa, respectively, i.e., working pressure had a significant influence on water diffusion. Besides, the water diffusion coefficient increased as mounting height increased. It is noteworthy that values of water diffusion coefficient were smaller than 0.11 at any working condition, implying that the water jet-spray from Nelson D3000 sprinkler robust resistance in fragmentation.

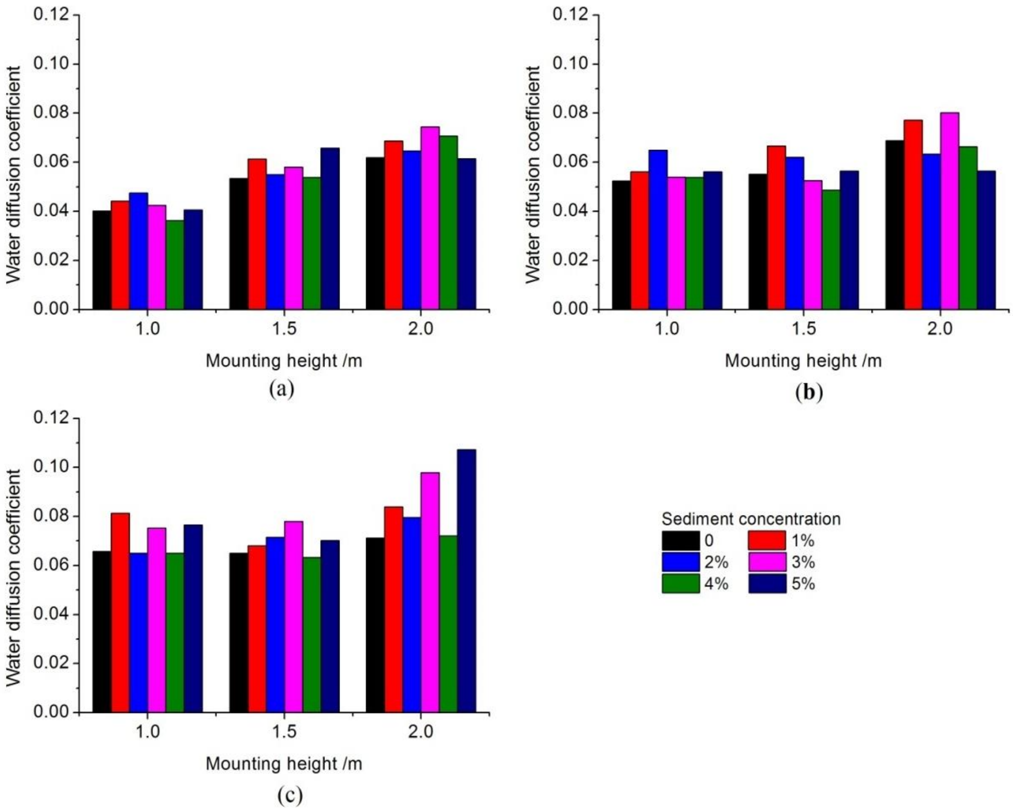

Figure 6. Spray water diffusion coefficient with various sediment contents at different working heights. Note: (**a**) 100 kPa, (**b**) 150 kPa, (**c**) 200 kPa.

To fully analyze the direct and interactive effects of sediment concentration, mounting height, and working pressure on water diffusion, an analysis of variance (ANOVA) was presented using the SPSS statistical software program. Table 3 summarizes the results of this analysis. This analysis revealed (95% confidence interval) that sediment concentration had no significant effect on water diffusion (significance value (sig) is 0.130, larger than 0.05), whereas mounting height and working pressure had a significant effect on water diffusion. As proposed by the magnitude of associated F-values, working pressure had a greater impact on water diffusion than mounting height, i.e., working pressure should be considered in priority order when higher levels of uniformity are required during irrigation with sediment-water.

Table 3. Analysis of water diffusion results.

Factors	Mean Square	F	sig	Significance
Sediment concentration	40.927	8.185	0.130	
Mounting height	204.287	102.143	0	**
Working pressure	254.920	107.460	0	**

**: highly significant.

4. Discussion

This research discussed the water distribution patterns of Nelson D3000 sprinkler during irrigation with sediment-water, which contributed to the direct utilization of sediment-water in the Yellow River without a water filtration system. The water distribution patterns indicated that sediment-water could not only minimize peak application rate and promote irrigation uniformity but also increase the wetted area and have a positive influence on irrigation quality. The point is that these results obtained in this paper just indicated an increase in the uniformity of an individual sprinkler, and the uniformity coefficient for an existing irrigation machine should be reappraised with the overlapping method. However, there are also some negative effects of irrigation with Yellow River water. For example, sediment promotes the fragmentation of spray jet, and there is an increase in the amount of water falling near the sprinkler, resulting in an increase in irrigation uniformity of individual sprinkler, but the droplet nearby the sprinkler is smaller and most easily evaporated and drifted by wind, leading to an increased probability of wind drift and evaporation losses, resulting in the decrease in the efficiency of water application. Besides, the kinetic energy may increase during irrigation with sediment-water, and mechanical damage of the plants may occur with the increase in the kinetic energy. Additionally, the sediment landed on the plant leaves may affect photosynthesis, leading to a decrease of yield. In addition, the coating material in the inner part of the pipe in the irrigation system would be corroded during the transportation of sediment-water, which would decrease the service life of the irrigation system. Moreover, the sediment-water would spray on the deflector plate, cutting the interface of the plate and nozzle, and the structure of the sprinkler would be abraded, resulting in the variation of water distribution. Therefore, further research should be made about the influence of sediment-water on the erosion of the pipe and sprinkler plate of the irrigation system, cooperating with its influence on water distribution.

5. Conclusions

Considering water resource is insufficient and sediment-laden in the Yellow River basin, sprinkler irrigation technique can protect water resource effectively. For the direct utilization of the high sediment-water resource, a series of experiments were performed to evaluate the influence of sediment-water on the hydraulic performance of fixed spray plate sprinkler. The results showed that peak water precipitation rate appeared during irrigation with both clean and sediment-water; in contrast with clean water, sediment-water not onlyminimized peak value of water application rate but also increased the water application rate closer to the sprinkler, consequently, making water distribution more uniform. Furthermore, sediment-water increased spray distance remarkably for the great inertia force of sediments; this resulted in the transfer of peak application region to the edge of the wetted circle and an increase of the wetted area. This meant increasing overlapping space and minimizing investment while designing an irrigation system. In order to evaluate the effect of sediment on spray water diffusion, water diffusion coefficients were calculated. It appears that sediment-water contributed to splintering water jet effectively; however, the analysis of variance showed that no significant change was obtained with increasing sediment concentration. All these results suggested that the sediment-water in Yellow River could be utilized in agriculture irrigation with superior hydraulic performance, and it would be helpful to protect and maximize the utilization of the Yellow River resource.

Author Contributions: Writing, original draft preparation, Y.Z. Writing, review, and editing, J.G. Funding acquisition, H.W. Performed the experiments, Y.Z. Visualization, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by The National Natural Science Foundation of China (No. 51739009 and No. 51879244) and The Key Subjects in Colleges and Universities of the Education Department in Henan Province (No. 20B570002), for which the authors are grateful.

Acknowledgments: I would like to show my deepest gratitude to the editors and reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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