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New Comparative Experiments of Different Soil Types for Farmland Water Conservation in Arid Regions

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Abstract: Irrigated farmland is the main food source of desert areas, and moisture is the main limiting factor of desert farmland crop productivity. Study on the influence of irrigation on desert farmland soil moisture can guide the agricultural water resource utilization and agricultural production in those regions. At present, the efficiency of irrigation water usage in Northwest China is as low as approximately 40% of the irrigated water. To understand the response of farmland soil moisture in different soil types on irrigation in the Ulan Buh Desert of Inner Mongolia of China, this experimental study takes advantage of different infiltration characteristics and hydraulic conductivities of sand, clay, and loam to determine an optimized soil combination scheme with the purpose of establishing a hydraulic barrier that reduces infiltration. This study includes three comparative experiments with each consisting of a 100 cm thick of filled sand, or clay, or loam soil underneath a 50 cm plough soil, with a total thickness of 150 cm soil profile. A new type of lysimeter is installed below the above-mentioned 150 cm soil profile to continuously measure deep soil recharge (DSR), and the ECH2O-5 soil moisture sensors are installed at different depths over the 150 cm soil profile to simultaneously monitor the soil moisture above the lysimeter. The study analyzes the characteristics of soil moisture dynamics, the irrigation-related recharge on soil moisture, and the DSR characteristics before and after irrigation, during the early sowing period from 2 April to 2 May 2017. Research results show that: (1) Irrigation significantly influences the soil moisture of 0–150 cm depths. The soil moisture increase after the irrigation follows the order from high to low when it is in the order of loam, sand, and clay. (2) Irrigation-induced soil moisture recharge occurs on all three soil combinations at 0–150 cm layers, and the order of soil moisture recharge from high to low is: clay (54.3 mm, 43.39% of the total irrigation), loam (39.83 mm, 31.83% of the total irrigation), and sand (33.47 mm, 26.75% of the total irrigation). (3) After the irrigation event, DSR below 150 cm occurs for all three soil combinations. This study reveals the characteristics of irrigation-induced soil moisture recharge and DSR, and it shows that farmland consisting of an upper 50 cm plough soil and a lower 100 cm filled clay soil can save more water resource at the study site, which is useful in agricultural control measure and water resource management in arid regions.

Keywords: Ulan Buh Desert; DSR; infiltration; desert farmland; irrigation; sustainable development; water resource utilization efficiency

1. Introduction

The great temperature difference between day and night in arid regions is beneficial for the accumulation of photosynthetic products and the reduction of respiratory effects losses [1,2]. Therefore, agricultural production in these regions are of a larger amount and higher quality compared to semi-arid and humid regions [3,4]. In general, there are more agricultural development potential in arid region if the issue of water supply for irrigation can be coped with [5,6]. From an ecological standpoint, crop planting area in arid regions is where water and fertilizer are utilized intensively and, thus, may effectively reduce the invalid soil surface evaporation [7,8]. Previous studies show that reclaiming farmland in desert regions can help improve the soil microbial structure and soil quality [9–11] and, thus, is benign for desert ecological conservation [12,13]. Over the past six decades, there is a continuous evolution of oasis and desertified land in China [14,15]. Since the 1950s, the area of oasis in China expanded from 25,000 to 104,000 km^2 [16]. Meanwhile, lands that are undergoing desertification expanded from 53,000 to 114,000 km^2 [16]. The expansion of oasis benefits the regional ecological environment and provides more space for anthropogenic activities [17,18]. However, the water resource balance of the oasis is often disrupted and regional environment begins to worsen because of irresponsible development and poor understanding of the ecohydrological system of oasis, resulting in undesirable ecological problems, such as desertification and salinization [19–21]. As water resources are the main factor of ecological balance in arid regions, better understanding the water budget is indispensable for sustainable eco-agricultural development in those regions [22–24].

The eastern edge of Ulan Buh Desert, located at the northwestern inland area of China, is a transitional area between pastoral and agricultural areas [25,26]. It is an important part of the Hetao Plain, and an important agricultural area and food base of the Inner Mongolian Autonomous Region [27]. Under natural conditions, the moisture requirement of crops cannot be met because of sporadic and unevenly distributed precipitation. Therefore, irrigation is crucial for agricultural activities in this region [14]. As soil moisture is an important factor for crops to grow [28,29], and it usually changes after irrigation and precipitation, the study on the influence of irrigation on soil moisture can guide the agricultural water resource utilization and agricultural production.

Until presently, scientists have conducted numerous research on the correlation of vertical soil moisture distribution and corn production [30,31]. Some investigators have also conducted research on the relationship of amount of irrigation and quality of irrigated water on soil salt redistribution and spring corn water consumption [32,33]. However, such studies are rarely focused on the comparison of soil moisture responses to irrigation for different soil types, with even fewer field experiments on the real-time evolution of deep soil recharge (DSR) [34,35]. Soil moisture content is related to moisture pressure head [36] and soil unsaturated hydraulic conductivity [37]. When soil moisture content is relatively high, soil with larger particle sizes has a higher hydraulic conductivity; when soil moisture content is relatively low, soil with smaller particle sizes has a higher hydraulic conductivity [38,39]. Such a ubiquitous feature of unsaturated hydraulic conductivity and the soil moisture relationship can be taken into consideration for reducing infiltration loss in irrigated farmland in arid regions. Using the difference of hydraulic conductivities of two different soil particle sizes, one may put a different soil type (such as sand, clay, or loam) underneath the plough soil layer to effectively reduce the infiltration loss, achieving the goal of saving water resources in arid regions. This new measure can replace the current practice of using impermeable plastic films at certain depths of soil to prevent irrigation-induced infiltration in the arid regions, which is expensive and not environmental benign as a large quantity of plastic film is being used.

The objective of this study is to take advantage of different infiltration characteristics and hydraulic conductivities of sand, clay, and loam to determine an optimized soil combination scheme with the purpose of establishing a hydraulic barrier that reduces infiltration in arid farmlands. This study includes three comparative experiments with each consisting of a 100 cm thick filled sand, or clay, or loam soil underneath a 50 cm plough soil at the eastern edge of Ulan Buh Desert of China, with a total thickness of 150 cm soil profile. A new type of lysimeter is installed below the above-mentioned

150 cm soil profile to continuously measure DSR, and the ECH2O-5 soil moisture sensor is installed at different depths over the 150 cm soil profile to simultaneously monitor the soil moisture above the lysimeter. The responses of soil moisture and DSR to irrigation will be analyzed. The study provides the basis for sustainable water resource management in arid farmlands, such as the eastern edge of Ulan Buh Desert of China.

2. Study Area and Methods

2.1. Overview of the Study Area

The study site as shown in Figure 1 is at the Field I of the Desert Forestry Experimental Center administrated by the Chinese Academy of Forestry in Dengkou County at the northeastern part of Ulan Buh Desert of China. The geographical coordination is 40°19′7.81″ N, 106°56′2475″ E, with an altitude of 1043.0 m above mean sea level (m.s.l.). The study site has a typical temperate continental climate and a multi-year average temperature of 7.8 °C. The average annual sunshine is 3181 h, and the average annual frost-free period is 146 days. The multi-year average precipitation is 140.3 mm, and the site has a typical arid climate. The main soil type is irrigation silt, and this region has ample surface water resource supply from Yellow River [40,41].
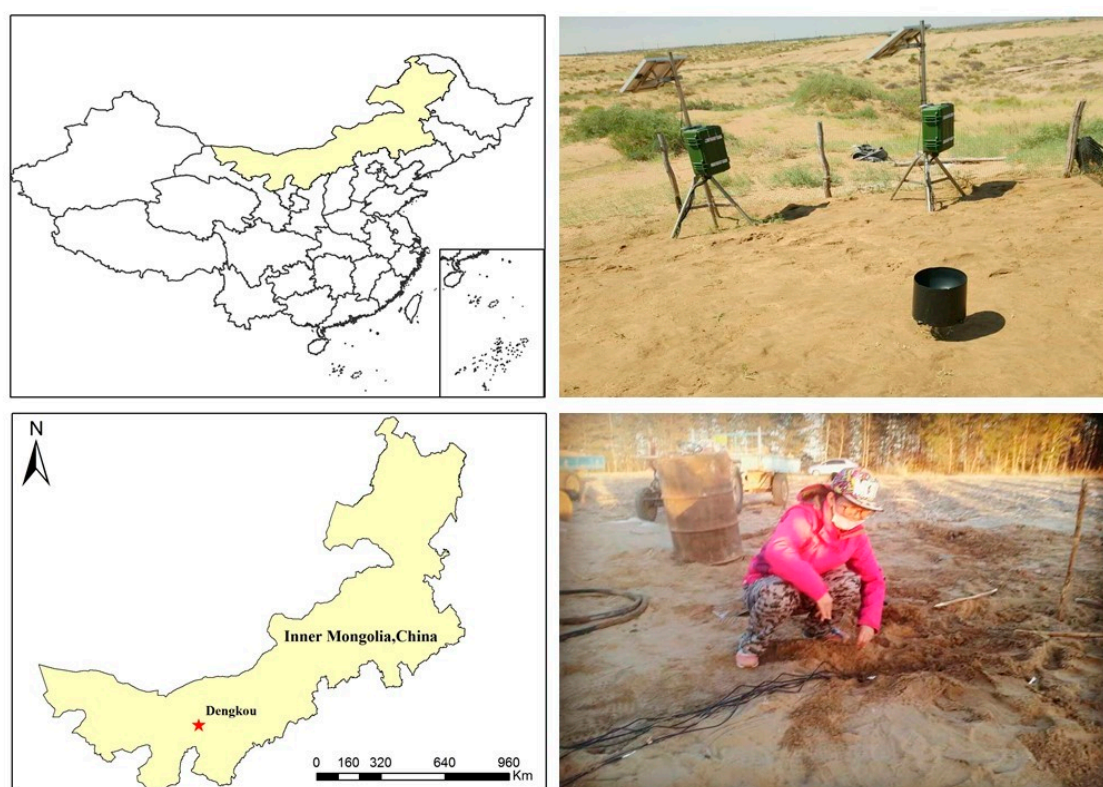

Figure 1. Overview of the experiment plot.

### 2.2. Experimental Design

2.2.1. Sample Settings

The shallow soil (0–50 cm) are under constant influence of cultivation, resulting in different soil physical and chemical properties (soil bulk density and mechanical composition, etc.) between uncultivated and cultivated soils, thus further affecting the dynamic changes of soil moisture. To simulate different soil types, sand, loam, and clay are used to replace the native soil below 50 cm depth, where the particle size distributions of the filled sand, loam and clay are listed in Table 1.

Table 1. Mechanical composition of three soil profile types.

Soil Type	Soil Mechanical Composition/μm									
	0.71–1.00	1.00–2.00	2.00–5.00	5.00–10.00	10.00–20.00	20.00–50.00	50.00–100.00	100.00–200.00	200.00–500.00	500.00–1000.00
Plough layer	22.84%	53.47%	23.07%	0.62%	0	0	0	0	0	0
Sand	1.05%	2.49%	1.03%	0.02%	0.04%	0.68%	2.59%	70.41%	21.33%	0.36%
Loam	50.41%	49.56%	0.03%	0	0	0	0	0	0	0
Clay	69.18%	30.82%	0	0	0	0	0	0	0	0

To compare and analyze the characteristics of soil moisture change and DSR for different soil types under the irrigation condition, comparative experiments have been run for three soil types of sand, loam, and clay. Using a typical cultivated land as the study site, after excavating an experimental pit of 200 cm long, 200 cm wide, and 300 cm deep, a DSR recorder is installed 150 cm below ground surface. The layers from the depth of 50 cm down to 150 cm are replaced by the sand, or loam, or clay listed in Table 1. To ensure the accuracy of experiments, plastic films are placed on four vertical surfaces of the experimental pit to separate the filled soil from the native soil outside. By doing so, one can prevent any possible lateral soil moisture migration because of soil heterogeneity. Caution has been taken to make sure no preferential flow occurring between the vertical plastic films and the soil. The used vertical plastic films will not affect any vertical migration of soil moisture in this experiment.

To ensure the normal growth of crops, excavated soil over the upper 50 cm depth (which is named the plough soil hereinafter) is put back on the top of filled soils, and the ground surface is leveled afterwards, as shown in Figure 2.
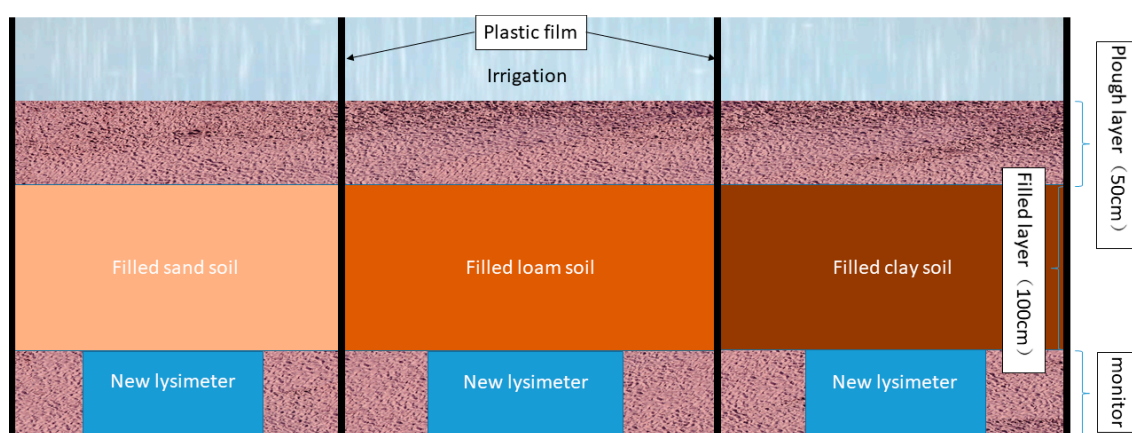
Figure 2. Three kinds of soil substitutions were carried out for the original soil. Each plot is separated by plastic film as an independent system.

2.2.2. Determination Indicators and Methods

1. DSR monitoring

The new DSR recorder (or lysimeter) is used to monitor the DSR of different soil types [42]. From the bottom up, the recorder consists of a drainage part (15 cm), a measuring part (35 cm), a flux collecting part (5 cm, filled with gravel and ceramic), and a capillary water holding part (65 cm filling with the tested soil). The measurement resolution is 0.2 mm, and the measurement accuracy is ±2%. After putting the DSR recorder in place, one needs to wait one to two months for the soil to settle naturally.

2. Soil moisture monitoring

The ECH$_2$O-5 soil moisture sensor (±3% accuracy, Decagon, Pullman, WA, USA) is used to monitor the soil moisture. For the monitoring of soil moisture and temperature dynamic changes at the upper 150 cm layer, ECH$_2$O-5 soil moisture sensors are placed at 5 cm, 50 cm, 100 cm, and 150 cm below ground surface.

3. Soil moisture storage calculation

Soil moisture storage, or the soil storage capacity (mm) of a certain soil thickness, is calculated using the following equation:

$$W = \sum_{i=1}^{n} \theta_i h_i \tag{1}$$

where W is the soil storage capacity (mm) of a given soil thickness, θ_i is the average moisture of the i-th soil layer (dimensionless), h_i is the thickness (cm) of the i-th soil layer (i = 1, 2, 3, ... , n), and n is the number of soil layers to the given soil thickness.

4. Soil particle size distribution

When installing the DSR recorder, a soil texture analysis is conducted for the upper 150 cm soil, and soil particle size and porosity samples are collected. The soil mechanical composition is determined using a Malvern mastersizer 200 laser particle size analyzer (England, accuracy: 0–1000 μm), as shown in Table 1. Soil moisture holding capacity and the field moisture holding capacity are measured by the cutting ring method as baseline data.

As shown in Table 1, the particle size distribution differences are obvious for the four types of soil including the plough soil, and the filled sand, loam and clay soils. The soil particle size in plough soil is mainly of 1–2 μm, which represents 53.47% of the total particles of this soil type. The soil particle size in sand is mainly of 100–200 μm, which represents 70.41% of the total particles of this soil type. The soil particle size of loam is mainly of 0.71–1 μm and 1–2 μm, which are 50.41% and 49.56% of the total particles of this soil type, respectively. The soil particle size of clay is mainly of 0.71–1 μm, which is 69.18% of the total particles of this soil type.

The study site mainly relies on Yellow River for supplying irrigation water. This experiment uses the typical flooding irrigation method that is commonly utilized by the local farmers. During the irrigation process, a portable LS300-A flow meter is used to measure the amount of irrigation. Pre-seeding irrigations were conducted on 17 April and 19 April 2017 in the study site, lasting for 109 min and 41 min, respectively. The amounts of irrigation were 118.64 mm and 6.5 mm, with a total of 125.14 mm.

3. Results and Analysis

3.1. The Dynamic Response of Different Type Soil Moisture on Irrigation

The soil moisture of the cultivated land is influenced by multiple factors, such as precipitation, irrigation, and crop growth. Since the study site is located in Northwestern China with scarce precipitation, and there are no precipitation events during the experimental period, the influence of precipitation on soil moisture can be ignored. As the experimental period proceeds the seeding season, the influence of crop growth on soil moisture can also be ignored.

To analyze the dynamic response of soil moisture to irrigation for different soil types, this experiment use 31-day soil moisture data from 2 April to 2 May 2017 to analyze the temporal variation of vertical soil moisture at different soil layers. During the experimental period, the maximum and minimum soil moistures at different layers as a function of time can be seen in Table 2. Statistical analysis shows that the 125.14 mm irrigation amount has a significant effect on soil moisture of the upper 150 cm soil layer.

Figure 3A–C shows the daily dynamic change of soil moisture at the upper 150 cm soil layer under different experimental treatments. It shows that the antecedent soil moisture levels of three different types of soil are relatively low before the irrigation event. This is mainly because the experimental field is located in an arid region with very limited winter and spring precipitations and no irrigation recharge.

The soil moistures in three types of soils at the upper 150 cm all fluctuated 15 days after irrigation, but with quite different variational patterns. The coefficient of variation (C.V.) can be compared by the degree of dispersion of the three sets of data. A larger C.V. means a larger irrigation influence on soil moisture. From the C.V. listed in Figure 3D, one can draw the following conclusions. Firstly, for soil

moisture variation at the upper 50 cm layer, the degree of irrigation influence declines when the filled soil type changes from sand to loam, and then to clay. Secondly, for soil moisture variation at depths of 50–150 cm, the degree of irrigation influence declines from when the filled soil type changes from loam, to sand, and then to clay.

Table 2. Time change peak value of soil volume water content in the study site.

Soil Depth	Soil Type	Date (Month-Day)	Water Content Maximum/%	Date (Month-Day)	Water Content Minimum/%
5 cm	Sand	4-17	31.35	5-2	18.11
	Loam	4-17	31.31	4-12	19.11
	Clay	4-17	30.91	4-12	24.56
50 cm	Sand	4-17	25.29	4-2	7.158
	Loam	4-17	28.96	4-16	14.72
	Clay	4-20	30.83	4-16	25.37
100 cm	Sand	4-17	20.56	4-2	8.87
	Loam	4-18	31.29	4-2	14.2
	Clay	4-20	32.53	4-2	24.24
150 cm	Sand	4-20	22.12	4-2	12.11
	Loam	4-18	25.21	4-2	12.93
	Clay	4-23	27.41	4-2	20.5
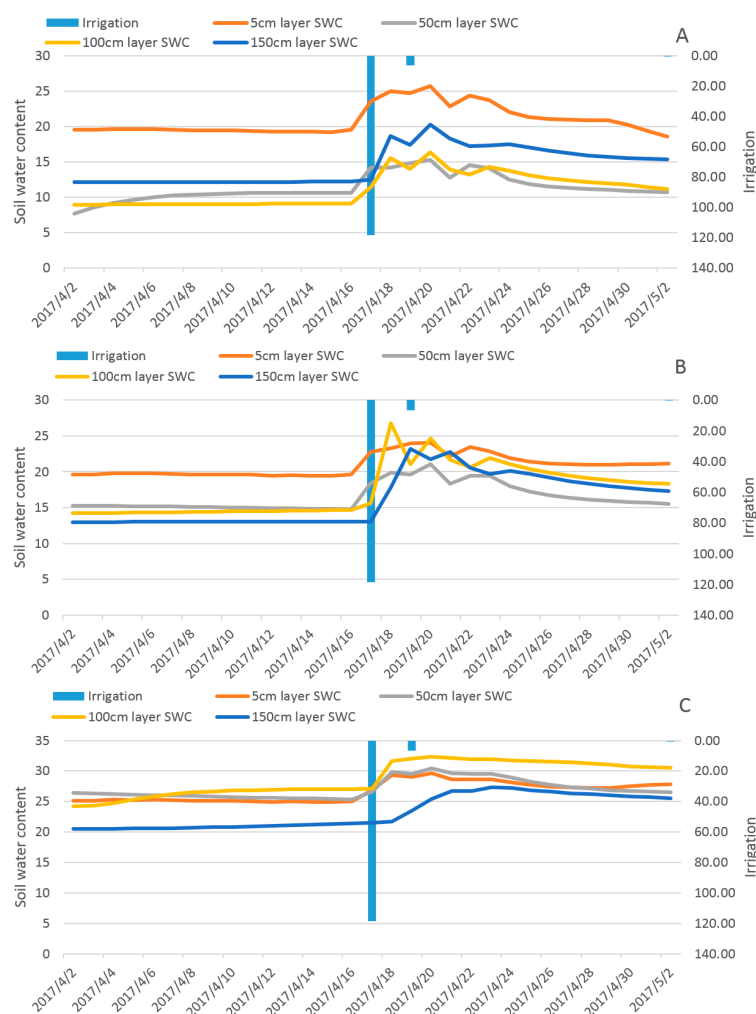
Figure 3. *Cont.*
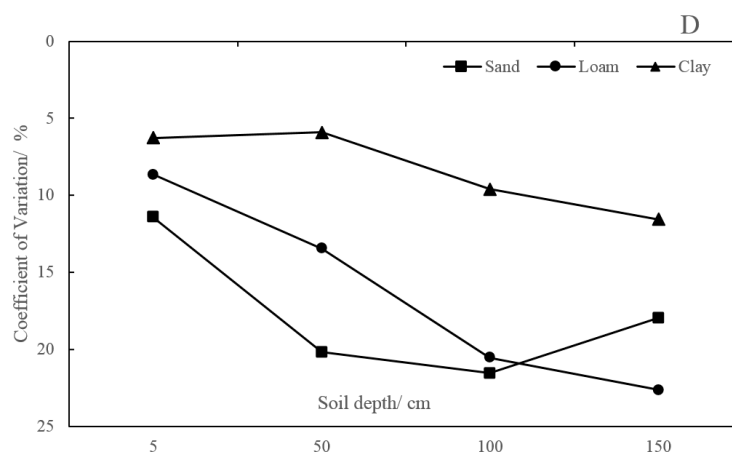
Figure 3. Different depth soil volume water content dynamic. (**A**) Sand soil; (**B**) loam soil; (**C**) clay soil; (**D**) C.V.

The study shows that after the fill-in of three different soil types below the upper 50 cm plough soil, under the same irrigation condition, different soil types show very different hydraulic conductivity and water storage capacity. Because the particle size of plough soil is close to that of loam, irrigation water can infiltrate faster into loam and increase the soil moisture content of loam. The particle size difference between clay and the plough soil is the most distinctive, so irrigation water infiltrates the least into the clay layer.

One can see that in the sand soil on the left plot in Figure 2, the particle sizes are mainly distributed in the range of 100–200 micrometers, which represents 70.41% of the total particles of sand soil. For such large grain sizes, a unique hydrological feature is notable. When the sand soil moisture content is relatively high (close to saturation), the hydraulic conductivity of such a type of soil is, of course, much greater than those of loam soil and clay soil. However, when the sand soil moisture content is relatively low, the hydraulic conductivity becomes even smaller than those of loam soil and clay soil at the same soil moisture content. Such a dramatic reduction of hydraulic conductivity of sand soil after the declines of soil moisture has been recognized for a long time in soil physics. This means that when the soil moisture content of the fill sand soil is relatively low, it can actually serve as a hydrologic barrier to prevent further loss of soil moisture from the above plough soil [43,44]. This explains why the sand soil in Figure 2 is included in the comparison study. Nevertheless, if the soil moisture content in the sand soil has increased above a certain level, such a hydrologic barrier effect will disappear and water can flow downward quite easily through such a fill sand soil layer.

In summary, above analysis implies that if one replaces the original cultivated soil layer right below the upper plough soil with clay, one can effectively reduce irrigation water infiltration below the plough soil layer, thus achieving the goal of saving water resource in arid regions.

From Figure 3A–C, one can see that during a certain time period after irrigation, the soil moistures at different layers for different soils universally increase. As time goes on, soil moisture at different layers gradually decreases. For the sand soil, the soil moisture at the upper 50 cm layer is obviously higher than that below 50 cm. For the loam soil, the soil moisture is distributed relatively evenly over the upper 50 cm. For the clay soil, the soil moisture over the 50–150 cm depth is obviously higher than other layers.

This study concerns the early sowing period between 2 April and 2 May. Thus, the result represents the features of spring; the results of other periods of the year need more research.

3.2. Recharging Effects of Recharge on Soil Moisture of 0–150 cm Layers

Compared to soil moisture, soil water storage can intuitively reflect the regional soil moisture supply capacity. Figure 4 shows the dynamic changes of soil water storage of the upper 150 cm layers for different soils from 2 April to 2 May 2017. From this table, one can see that after a certain time

period since the cease of irrigation, the soil water storage of different soils have all altered greatly, demonstrating that the irrigation has significantly influenced the soil water storage of different soils at the 150 cm soil layer. The average post-irrigation soil water storage of the upper 150 cm layer for different soils are 426.10 mm for clay, 299.67 mm for loam, and 243.67 mm for sand.
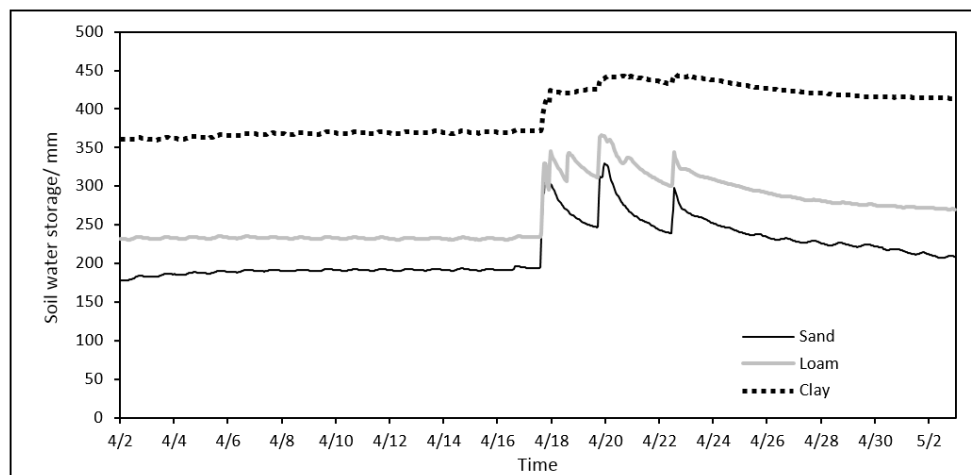

Figure 4. Soil water storage dynamic variation of different type dunes.

Table 3 shows soil water storage and their changes for different soils at the upper 150 cm layers for both pre-irrigation (2 April) and post-irrigation (2 May). This table shows that after the 2 April irrigation event, the soil water storage of sand, loam and clay soils all increase by 2 May. This means that irrigation has certain recharging effect on all the different soils at the upper 150 cm layers, and the amounts of recharge decline in the order of clay (54.3 mm), loam (39.83 mm), and sand (33.47 mm). For the upper 150 cm layer, sand, loam, and clay soils respectively store 26.75%, 31.83%, and 43.39% of the irrigated water during the period from 2 April to 2 May 2017. This leads to the conclusion that one replaces the original cultivated soil below the 50 cm plough soil with filled clay to effectively increase soil water storage for the entire 150 cm soil profile.

The soil moisture recharge variation under the same irrigation event at the upper 150 cm layer is mainly caused by different filled soil types, with soil water retention capacity closely correlated with soil clay content. Specifically, a higher soil clay content leads to a stronger soil water retention capacity. Table 1 shows that the clay content is the greatest in the filled clay soil, the least in the filled sand soil. Therefore, the field water storage capacity declines in the order of clay, loam, and sand. The post-irrigation water storage capacity also follows this pattern.

Table 3. Irrigation on soil water supply with different soil textures.

Soil Type	2 April 2017 Storage/mm	2 May 2017 Storage/mm	Difference of 2 April and 2 May 2017/mm
Sand	178.10	211.57	33.47
Loam	231.09	271.91	39.83
Clay	360.45	414.75	54.30

3.3. DSR Characteristics of Different Soil Types

Figure 5 shows the daily variational characteristics of DSR below different 150 cm soil profile. This figure shows that during the 15 days post-irrigation period, DSR appears for all three soil types. For the sand soil, DSR happens 13 h after irrigation, and lasts for 157 h, with a total amount of 110.87 mm. For the loam soil, DSR happens 72 h after irrigation with a total amount of 12.2 mm. For the clay soil, DSR happens 257 h after irrigation with a total amount of 0.2 mm.
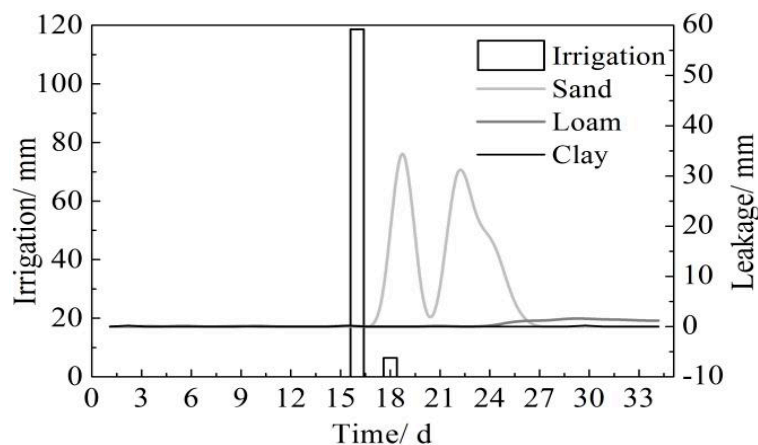
Figure 5. Daily variation of deep soil water leakage below 150 cm of different soil textures.

Soil clay content is an important factor influencing DSR, and a smaller soil clay content leads to a stronger infiltration capacity and greater DSR. Therefore, under the same irrigation condition, the amount of DSR should follow the declining order of sand, loam, and clay. Furthermore, DSR is negatively correlated to the post-irrigation soil water storage. Porosity is another important factor influencing DSR. Specifically, clay soil has a very poorly connected pore space and a very low effective porosity. In addition, colloids in clay soil swell after irrigation, leading to pore contraction and decreased soil permeability. All of this will result in a very small infiltration capacity and DSR for clay soil. Meanwhile, other factors such as the soil structure (layered, blocked, fragmented, etc.) also affect soil moisture infiltration capability and DSR.

The data used for this study come from farmland currently undergoing cultivation. Irrigation amount is based upon the routine cultivation use by local farmers. Therefore, one cannot guarantee that the irrigation amount currently in use is the optimized amount. The best irrigation amount should meet both the needs of crop growth and minimize the water resource waste such as DSR. In the future, a controlled experiment should be conducted to find out the best irrigation amount based on the soil profile.

4. Conclusions

The following conclusions can be obtained from this study:

1. Accumulative irrigation in the experimental field from 2 April to 2 May is 125.14 mm. For the upper 150 cm soil layer, irrigation has significant influence on soil moisture. For the upper 50 cm plough soil layer, the irrigation influence on different soils follows the declining order of sand, loam, and clay soils under the same irrigation strength and pattern. For the filled soil layer at depth of 50–150 cm, the irrigation influence on different soils follows the declining order of loam, sand, and clay soils under the same irrigation strength and pattern.
2. Irritation has recharging effect on soil moisture for all three types of soil at the upper 150 cm soil layer, and the recharge amounts follow the order of clay (54.3 mm, which is 43.39% of the total irrigation amount), loam (39.83 mm, which is 31.83% of the total irrigation amount), and sand (33.47 mm, which is 26.75% of the total irrigation amount).
3. Post-irrigation DSR appears in all three types of soil below 150 cm. The time when DSR occurs is 13 h after irrigation for sand, 72 h after irrigation for loam, and 257 h after irrigation for clay. The 15-day total DSR is 110.87 mm for sand, 12.2 mm for loam, and 0.2 mm for clay.
4. If one replaces the original cultivated soil layer right below the upper 50 cm plough soil whose particle sizes are mostly in the range of 1–2 μm with a 100 cm thick filled clay soil whose particles are primarily in the range of 0.71–1 μm, one can effectively reduce DSR below the 150 cm soil profile, thus achieving the goal of saving water resources for farmland in arid regions.

Author Contributions: Yiben Cheng designed the experiments, analyzed data and wrote the whole paper; Yanli Li collected field data and analyzed data; Hongbin Zhan guided the writing of the article and revised the article; Wenbin Yang designed the experiments and helped to select experimental area; Hairong Liang designed the experiments and acquired data; Yingming Zhao managed the experimental site; Taojia Li maintained the instrument.

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

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