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Influence of Reclaimed Water Quality on Infiltration Characteristics of Typical Subtropical Zone Soils: A Case Study in South China

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Abstract: Irrigation with reclaimed water (RW) can alleviate water scarcity and improve the environmental and economic benefits. However, RW contains a large number of salts, suspended particles, organic matter, etc., which can affect soil infiltration. Previous studies focused on the examination of this effect in alkaline soils, but the infiltration change of acidic soils has seldom been investigated. This study selects four typical types of soil in the subtropical area in the south of China and designs experiments using different concentrations of RW to examine the influence of RW on the infiltration of various acid soils. The short-term impact is examined based on a one-dimensional horizontal method, and the long-term infiltration characteristics are measured by a Mini Disk infiltration meter with one year’s RW irrigation. Results show that RW irrigation can restrain the short-term infiltration of red soil while accelerating that of purple soil, aquic soil and paddy soil. Regarding the long-term effect, the cumulative infiltration of red soil increases with the decline of the concentration of RW, while there is no unique trend for the other soils. After one year’s RW irrigation, physical properties such as soil particle size distribution, texture and EC have changed. For red soil, EC increased significantly with RW irrigation, from 46.7 μS/cm to 101.07 μS/cm. However, regarding aquic soil, EC decreased from 157.05 μS/cm to 123.20 μS/cm. Moreover, the infiltration rate coefficient of red soil and aquic soil exhibits a significant positive correlation with RW concentration (p < 0.01), while the silt content shows a significantly negative correlation (p < 0.01). Furthermore, soil infiltration parameters c and S value of the purple soil, paddy soil, is significantly negative correlated with pH value (p < 0.01). The results reflected that appropriate RW quality for irrigation is different among various soil types, which will influence the sustainable application of RW. It can shed insights into solving the water scarcity issue and improving water sustainability in subtropical regions.

Keywords: reclaimed water; soil infiltration; acidic soils

1. Introduction

Water scarcity is considered as one of the largest global risks, according to the latest annual report from the World Economic Forum [1]. In the context of climate change, drought has become more frequent. Even in humid regions, the seasonal drought induced by climate change significantly influences livelihoods and leads to severe socioeconomic losses with the expansion of human water demand, and intense water impairment [2–4]. Freshwater scarcity then stimulated the exploration of alternative water resources such as reclaimed water (RW). In general, RW was defined as the water after secondary treatments from sanitary sewage and industrial waste by the municipal sewage plants [5]. In addition, the use of RW for irrigation was feasible and cost-effective, which attracted worldwide attention to alleviate the water scarcity with the growing water demand for agricultural development [6–8]. However, irrigation with low-quality water might significantly decrease soil infiltration both in the short- and long-term period [9,10], which is a great concern in practical applications.
Soil infiltration rate was one of the important parameters applied in soil water movement research, which could exert significant influences on water fluxes and influence the soil drainage, irrigation runoff and soil loss [11,12]. As the main way to restock soil water resources, infiltration determined the effective storage in soils from precipitation and irrigation [13]. Soil moisture is of vital importance for plant growth, and infiltration rate determines how fast the water can be transported to the soil and be used by the plant. Poor soil infiltration makes it difficult for water to penetrate the soil. This may change the soil structure and cause a reduction in soil organic matter. Dietz et al. showed that field yield losses under water deficit conditions typically range from 30% to 90% [14,15]. A decrease in soil infiltration would hinder the access of moisture, thus reducing water and nutrient uptake efficiency in crops, and even more, it could increase the slope surface flow and soil erosion, which might cause more serious consequences and bring disasters in the subtropical monsoon climate zone where heavy rainfall hydrology occurred more frequently [16,17]. Moreover, infiltration was a key process for the transport of pollutants in soils, which can affect the sustainable utilization of RW. Therefore, it appeals to a lot of agriculture and environmental research in recent years [18,19]. So far, soil infiltration was thought to be affected by the combined effects of soil physicochemical characteristics (such as soil texture, structure, weight and organic matter, etc.) and external factors (such as source water quality, initial water content, rainfall characteristics, etc.) [20]. Given that RW might influence soil properties during irrigation, the soil infiltration could also be impacted by RW to various degrees. Thus, understanding the influence of RW on the soil infiltration can benefit improving the RW irrigation.

There have been some related studies to analyze the effects of RW irrigation on soil infiltration. However, the conclusions are not consistent among different studies, since they usually involved different factors and mechanisms. For example, some studies indicated that clay dispersion caused by larger sodium adsorption ratio (SAR) or high salinity in RW reduced the surface soil's aggregate stability. This negative effect was associated with a reduction in soil infiltration, particularly in fine-textured soils [21]. Contrary to this, better aggregate stability was found in other cases when contrasted with long-term clean water irrigation [22]. Additionally, the water flow resistance was increased by the physical clogging caused by the suspended solids and organic matter in RW, as well as the biological clogging induced by bacterial cell accumulation and extracellular polysaccharides [23]. Besides, the effect of RW on soil infiltration is also associated with soil texture. For example, the infiltration rate remained unaffected in sandy soils with larger pores. However, it would do more to harness the soil infiltration capacity of loamy soils with finer pores, especially in clay [24]. Moreover, some studies had indicated that RW irrigation increased soil compaction with decreases of soil porosity, while others had shown that RW could have larger influence on soil macroporosity instead of soil porosity [25,26], which led to a decrease in soil infiltration rate. Some researchers thought that difficulty in soil infiltration during RW irrigation was due to the accumulation of organic matter in the surface layer of soil, which promoted the development of soil water repellency [27]. However, other researchers believed that whether reclaimed water caused water repellency of soil was related to the ratio of hydrophilic to hydrophobic groups in its organic matter functional groups, and that water repellency of soil also changed over time [28]. In summary, the influences of RW on soil infiltration remained controversial in related researches, and it could be seen that the ability of soil to maintain sufficient infiltration capacity with RW irrigation might vary depending on water quality, soil type and environmental conditions.

Moreover, most of the studies mentioned above mainly focused on the effect of RW irrigation on soil infiltration in the long term. The instant response of soil infiltration to RW employment was seldomly investigated [29]. However, it was equally important to evaluate the short-term effects, as many adverse effects might only appear during a short time period [30]. Take the subtropical monsoonal regions, for example. The soil was nearly saturated with continuous rainfall, which was frequently present during the rainy season. If RW was applied in the overly wet soil at this time, it might trigger a strong storm
hydrological response because of the probable reduction in soil permeability caused by RW irrigation. Apart from this, the risk was increased in the subtropical monsoon climate zone, for its major soil types were of low permeability (e.g., red soil). Whereas, the imperfection of short-term impact researches led to the temporal evolution of soil permeability after irrigation with reclaimed water still incompletely known.

The objective of this study was to explore the suitability of subtropical soils for the application of reclaimed water and to find out the level of water quality suitable for sustainable irrigation of typical soils. Therefore, we designed two sets of experiments to respectively investigate the impact of RW quality on soil infiltration in the short term and long term, and to compare the different responses. Since the quality of irrigation water is a crucial factor affecting soil infiltration, we designed five levels of RW quality to be investigated in four typical subtropical soils in order to clarify the influences of RW on infiltration and find out the appropriate level of RW quality suitable for irrigation. Specially, the study samples included the red soil, given its special physical and chemical features. Based on the above considerations, this study’s objectives are to (i) summarize the response of soil infiltration to different RW quality; (ii) investigate the parameters influencing soil infiltration and (iii) simulate the performance of soil infiltration with RW application in four typical soils in a subtropical zone.

2. Materials and Methods

The infiltration experiment is carried out at four levels of RW quality using four typical types of soils in the humid subtropical area. The sampling method is presented in Section 2.1, and the experimental methods are given in Section 2.2. Furthermore, the data processing is shown in Section 2.3.

2.1. Sampling Method

2.1.1. Soil Samples

The sampling of four typical soils [31] in subtropical China was performed randomly from the arable layer (within the 0–20 cm soil layer) in the cultivated fields of Hunan Province, China, which include red soil (28°32′49″N, 113°16′46″E), aquic soil (29°18′05″N, 112°43′47″E), purple soil (28°28′11″N, 113°32′68″E) and paddy soil (28°28′42″N, 113°26′2″E). Then the disturbed soil samples are air-dried, de-hybridized and grounded. After being sieved through a 2 mm diameter mesh, the particle size of air-dried samples is measured by hydrometer method for all the types of soil. The pH and EC are measured using the Mettler Toledo SevenExcellence™ multi-parameter tester (S470-B). The specific gravity of soil solids is determined by the specific gravity method using a specific gravity bottle. K⁺, Na⁺, Ca²⁺ and Mg²⁺ concentrations are measured by an ICP-AES spectrophotometer (TAS-990). Cl⁻ content is determined by titration of silver nitrate, and SO₄²⁻ content is measured by the barium sulfate turbid metric method. Total N (TN) is analyzed using semi-micro Kjeldahl digestion with Se, CuSO₄ and K₂SO₄ as catalysts, and the total phosphorus (TP) is determined by acid soluble aluminum antimony resistance colorimetry. Soil organic carbon (SOC) content is measured with wet digestion with H₂SO₄-K₂Cr₂O₇ and the cation exchange capacity (CEC) is determined by the ammonium acetate leaching method.

2.1.2. RW Samples

The reclaimed water used in the experiments is secondary-treated sewage, which was obtained from Huaqiao Municipal Wastewater Treatment Plant in Hunan Province, China. Segmented AAO, high efficiency settling tank and V-type filtering process are adopted by the Huaqiao Municipal Wastewater Treatment Plant. The daily treated water is about 95.7 thousand cubic meters. The concentrations of K⁺, Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, pH and EC of RW sample are determined by the same method as that used in Section 2.1.1. Total N and total P content are determined based on the spectrophotometric method with a UV-Vis spectrophotometer.
The sodium adsorption ratio (SAR) of the DWW is calculated by the Formula (1).

\[
SAR = \frac{[Na^+]}{\left[\left(\left[Ca^{2+}\right] + \left[Mg^{2+}\right]\right)/2\right]^{1/2}}
\]

Some basic properties of the RW are given in Table 1.

Table 1. The concentration of chemical matters in the reclaimed wastewater examined in this study (RW).

| K⁺ (mg/L) | Na⁺ (mg/L) | Ca²⁺ (mg/L) | Mg²⁺ (mg/L) | Cl⁻ (mg/L) | SO₄²⁻ (mg/L) | TN (mg/L) | TP (mg/L) | pH | EC (µS/cm) | SAR |
|-----------|------------|-------------|-------------|------------|-------------|-----------|----------|----|------------|-----|
| 0.1589    | 1.0400     | 7.5515      | 2.2012      | 0.0431     | 43.2852     | 21.8255   | 1.0817   | 7.600 | 1659.600   | 0.4265 |

2.2. Experimental Method

Two experiments are designed to investigate the effect of reclaimed water on the infiltration of typical subtropic soils and to screen the appropriate concentration of reclaimed water for irrigation. The first experiment is the one-dimensional horizontal infiltration test with the constant head method, which is used to determine the short-term infiltration rate. The second experiment is the one-dimensional vertical infiltration test in site, which is used to measure the long-term infiltration rate.

Both tests study two factors: water quality for irrigation and type of soil. To reduce suspended particles as well as electrolytes interfering with the infiltration rate measurement, distilled water is used for dilution. The use of distilled water as a control and especially for irrigation is not common in practice. The water with low but limited salt content (such as groundwater, tap water or surface water) is more widely used. We do not use the groundwater for there is heavy metal contamination in the local groundwater, which could influence the test results in this study. As for the surface water, its quality is highly susceptible to the rainfall, while local acid rain pollution still exists. Therefore, the pH of surface water can sometimes be acidic. The pH of irrigation water will also affect soil infiltration and it is not conducive to comparing with other research results. We do not use tap water in order to avoid chloride ions affecting the test results.

Five levels of solution gradients were adopted in this study: RW, RW-2, RW-4, RW-6 and CK, which respectively represented the raw reclaimed water solution, the RW diluted in the ratio of 1:1 with distilled water, the RW diluted in the ratio of 1:3 with distilled water and the RW diluted in the ratio of 1:5 with distilled water, and the pure distilled water which was regarded as an ambient sample. Then the reclaimed water with different concentrations were applied into the four typical soils in the subhumid area, which are red soil, aquic soil, purple soil and paddy soil. Therefore, for each experiment, there were 20 treatments and treatments were replicated 3 times.

2.2.1. Horizontal Infiltration Test

The horizontal one-dimensional soil column absorption method is used to determine the short-term soil infiltration rate, and the measurement setup is shown in Figure 1. The experiment includes two parts: one part for water supply and the horizontal soil column. The horizontal soil column has a total length of 45 cm and is made of 9 round plexiglass tubes. The tubes are all in the same axial circle, and each circle has an inner diameter of 5 cm and a height of 5 cm. In addition, a Markov bottle is used for constant water supply, and a blower dryer is used for drying the soil samples.
Figure 1. Horizontal one-dimensional soil column infiltration measuring device.

The experiment procedure is as follows:
Firstly, the soil sample is filled with a capacity of 1.3 g cm\(^{-3}\). The air-dried soil samples sieved through 2 mm mesh are weighed and divided into several portions, then filled in layers with a length of 45 cm. In addition, to roughen the contact surface between layers, the two adjacent plexiglass tubes are connected tightly by a mosaic structure and fixed with tape. The weighed soil sample is filled into the ring several times and compacted with a wooden stick. The previous process is repeated until the 9 glass tubes are filled. Secondly, regarding the water supply to the experiment, the foaming position of the Markov bottle is adjusted to the same height of the upper edge of the plexiglass tube and to make the whole container in the horizontal state. The water potential difference is not allowed. Therefore, soil water infiltration only relies on the soil’s suction head itself. Fix the position of Markov bottle and start to record the time \(t_1\). When the wetting front advances to the eighth section of the entire soil, stop water supply, and record the end water supply time \(t_2\), \(\Delta t = t_2 - t_1\). Thirdly, the soil needs to be extracted. After stopping the water supply, we immediately unscrew the four spirals, cut off the water source, and gently open the plexiglass tube quickly. Combining the electronic balance and the drying method, the moisture content of the soil sample is determined.

2.2.2. Soil Column Leaching Test
To investigate the effect of irrigation with reclaimed water on the infiltration characteristics of the in situ soil over a long period of time, the soil column leaching test is conducted to simulate the field cumulative irrigation for one year.

The first step is the column filled by soil. A PVC bucket of 25 cm in diameter and 34 cm in height is used as the soil columns. Two layers of gauze are placed at the bottom of the bucket to prevent soil and sand leakage, followed by a 5 cm thick layer of fine sand. The initial volumetric moisture content of the soil is measured to be 0.57%, the set filling volume mass is 1.05 g cm\(^{-3}\) and the total mass of soil filled was 8.8 kg. In order to avoid the test results from being affected by uneven filling, the soil column is filled in layers and the contact surface between layers is roughened. The second step is irrigation treatment. Before starting the irrigation experiment, each soil column is initially irrigated with distilled water to allow for soil pre-deposition and stabilization. Then the soil columns are air-dried naturally and irrigated with the tension of 80 kPa. Each sample is irrigated with a single irrigation volume of 6 L, and the same water quality is used to irrigate continuously for 1 year. A total of 11 irrigations are performed, with 66 L irrigated for a single soil sample. An anti-scouring screen is placed on the soil surface during irrigation to prevent the soil in the plastic bucket from being scoured during irrigation. This prevents the soil in the plastic bucket from being scoured during irrigation, which causes damage to the soil surface structure and thus affects the test results. The third step is infiltration characterization. The infiltration rate is measured in situ using a Mini Disk infiltration meter. The infiltration
water is tap water, and the water temperature is controlled at 15–20 °C. To eliminate the effect of negative infiltration pressure, the negative infiltration pressure is set at 1 cm of water head. A large number of field experiments use a Mini Disk infiltration meter to measure infiltration rate, and the infiltration rate can be stabilized within 240 s. Therefore, the infiltration rate of 240 s is used as an indicator of the soil’s infiltration capacity, and the data are recorded at 30 s.

2.3. Calculation and Data Analysis

2.3.1. Calculation Method

According to the horizontal infiltration test, the infiltration rate $i$ is derived from the cumulative infiltration volume versus the time curve [32]. The cumulative infiltration volume is obtained from the amount of water in the Markov bottle measured by a vertical ruler. The infiltration rate $i$ is calculated by the Formula (2).

$$ i = \frac{dI}{dt} \quad (2) $$

where $i$ is the infiltration rate (cm min$^{-1}$); $I$ is the accumulated infiltration volume (cm) and $t$ is the time (min).

To quantify the effect of irrigation with different RW concentrations on soil infiltration characteristics over the long term, the Philip infiltration model is used. The method of measuring cumulative infiltration and infiltration rate with the Mini Disk infiltration meter requires measuring cumulative infiltration vs. time and fitting the results with Function (3).

$$ I = S \sqrt{t} + ct \quad (3) $$

where $I$ is the cumulative infiltration volume (cm); $t$ is the infiltration time (s) and $S$ is the soil sorptivity (cm s$^{1/2}$); $c$ is related to hydraulic conductivity (cm s$^{-1}$).

The infiltration rate is calculated by Formula (4).

$$ i = \frac{c}{A} \quad (4) $$

where $c$ is the slope of the curve of the cumulative infiltration vs. the square root of time, and $A$ is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the infiltration meter disk. $A$ is computed from the instructions of the Mini Disk Infiltrometer.

2.3.2. Data Analysis

Data are statistically analyzed using Excel 2016. One-way ANOVA (one-way analysis of variance) is applied to test for the significant difference, and the determination coefficient $R^2$ is used to evaluate the simulation accuracy of the model.

2.4. Artificial Intelligence Simulation

Artificial intelligence (AI) is one of the popular methods in recent years, which has been applied to many areas, such as spam email classification, speech recognition and machine translation [33,34]. As one of the important tools in AI, machine learning (ML) has attracted attention from all over the world. It also includes many different types, such as supervised learning, unsupervised learning, reinforcement learning and learning theory. In particular, logic regression is the most basic and essential method in the ML field, and it is widely used in categorical imputation, parametric statistics and predictive modeling practices. In this study, we adopt this model to simulate the changes in soil infiltration influenced by reclaimed water.
3. Results
3.1. Effects of RW Quality on the Soil Infiltration
3.1.1. Changes of Infiltration Rate

Changes in infiltration rate over time in the CK treatment of four soils are presented in Figure 2. A similar decreasing trend for the four types of soils is observed. Especially in the starting 30 min, the infiltration rate declines sharply. For the red soil, the declining rate is as high as 0.006 cm min$^{-2}$. All four types of soil tend to be steady after 100 min. The main reason for the sharp decrease of infiltration rate at the beginning is that the suction gradient between the infiltrated location at the soil surface and the moisture front is relatively large. Thus when the soil water flux is bigger, the infiltration rate $i$ is higher; as time increases, the infiltration area expands and the water potential gradient becomes relatively small due to the increase of the infiltration distance. At this period, the infiltration rate is dominated by the gradient of pressure head and gravity head. The infiltration rate $i$ tends to be stable. The results are consistent with previous findings [12,22]. The figure shows that the infiltration rate of red soil turns to be stable around 0.03 cm min$^{-1}$, while the other types of soils stabilized in lower values (e.g., aquic soil and paddy soil at about 0.01 cm min$^{-1}$ and purple soil at 0.005 cm min$^{-1}$). The difference is mainly related to the effective porosity of the soil. For example, red soil has the highest stable infiltration rate, which could be associated with the relatively small soil capacity and high porosity among the four soils. Furthermore, the figure exhibits significant differences in the initial stage among the soils and the magnitude of the relationship on the initial infiltration rates is $i_{\text{red soil}} > i_{\text{paddy soil}} \approx i_{\text{aonic soil}} > i_{\text{purple soil}}$, which also depends on the physical and chemical properties of the soils.

![Figure 2. The changes in infiltration rate over time on CK treatment of four soils.](image)

The effects of different concentrations of RW on the infiltration rate of four soils are displayed in Figure 3. Overall, a similar declining trend is observed in the different soil types. Additionally, in the first 30 min, the infiltration rate decreases fast and tends to be stable after 100 min. However, the performance of different reclaimed water in the four soil types shows a significant difference. For example, the higher concentration of reclaimed water, the lower the infiltration rate is observed for red soil, while, the almost contrasting result can be found for the other three types of soil, which the higher concentration of reclaimed water corresponds with the higher infiltration rate. The unique variation shown in Figure 3 for red soil may be due to the fact that red soil has the highest content of clay particles. Moreover, RW with high sodium ion concentration makes the soil clay particles dispersed and swollen, and these tiny particles can block soil pores, making the water difficult to infiltrate. At the same time, red soil is a kind of clay soil and its pores are quite small, which are more easily blocked by suspended solid particles in RW, thus, hindering water infiltration. Furthermore, these restraining effects will be enhanced with the increase of RW concentration.
3.1.2. Changes of Relative Infiltration Rate

To more clearly distinguish the differences among treatments, the infiltration rate of CK is used to normalize the other instances for better illustrating the results. The normalized relative infiltration rate is calculated by Formula (5).

\[ i_R = \frac{i}{i_{CK}} \]  

where \( i_R \) is the relative infiltration rate; \( i \) is the infiltration rate of soil irrigated with various concentrations of RW, cm min\(^{-1}\) and \( i_{CK} \) is the infiltration rate of soil on CK treatment, cm min\(^{-1}\).

From Figure 4, it can be obtained that the impact of different RW quality on the soil infiltration is not the same. The sensitivity of soil infiltration to RW quality also varies significantly among different types of soils. For example, for the red soil, the infiltration of RW-2 treatment is smaller than that of CK treatment at the early stage. However, the relationship between the two infiltrations is reversed in approximately 75 min, which indicates that the dilution of 2 times of RW is more suitable for infiltration in the later stage. The infiltration rate is facilitated by the RW irrigation for both aquic and paddy soil. Moreover, the distance between RW treatments and CK curve reflects the degree of the facilitation. Thus the intensity of the facilitation effect from RW treatment is most robust in aquic, while it is the RW-6 treatment that enhances the infiltration most in paddy soil. Although all the treatments show the promotion of infiltrations in purple soils applied with RW of different quality, the effect is roughly slowing down as the concentrations of RW increase, and the effect of RW treatment is the weakest. The impact of RW-4 is the strongest. In summary, the effects of RW quality on soil infiltration differ with soil types, and it is necessary to choose the appropriate concentration of RW for irrigation according to soil type.
3.1.3. Numerical Simulation of RW Infiltration Rate

In order to predict the effect of RW with different concentrations on the soil infiltration rates, a logistic regression model is used to fit the changes of infiltration rate vs. time-based on the AI simulation method, as shown in Figure 5.
Coefficient of determination ($R^2$) is the correlation measure for testing the goodness-of-fit of the regression equation and high values in $R^2$ indicate a good fit. In the above figures, all the $R^2$ are greater than 0.9998 for all curves. The fitting analysis presents that the soil infiltration rates show a power function relationship with the time of all the treatments. There are differences in the effects on soil infiltration rates which are irrigated with different concentrations of RW among soils of various types. RW irrigation treatments show inhibitory effects on infiltration in red soil but promoted effects in aquic soil, purple soil and paddy soil.

3.2. Changes of Soil Infiltration Rate a Year Later

In this part, we show the long-term effect of RW cumulative irrigation on infiltration characteristics of red soil, aquic soil, purple soil and paddy soil, based on irrigation experiment by soil column drenching test.

3.2.1. Cumulative Infiltration of RW Irrigation

Cumulative infiltration refers to the size of infiltrated water within a certain infiltration time, and it is an important parameter to measure the infiltration capacity of the soil. The cumulative infiltration of red, aquic, purple and paddy soil with the time square root curve line is shown in Figure 6. The difference in the cumulative infiltration of four soils irrigated with the same water quality is evident from the chart within the same infiltration time. At the early stage of infiltration (around 16 s), the variability of the four soils was small. With the increase of time, the difference of cumulative infiltration between the soils became larger. In the same infiltration time, the cumulative infiltration amounts show the following relationship: $I_{\text{red soil}} > I_{\text{paddy soil}} > I_{\text{purple soil}} > I_{\text{aquic soil}}$. The reason for the small difference between the four soils in the early stage is that the water flows mainly from the large pores early, while few differences were seen in macroporosity of the four soils. As time increases, effects of gradual increases in the soil matrix potential on soil infiltration are observed.

Figure 6. Curve of cumulative infiltration of four soils under CK treatment with time square root.

The infiltration characteristics of four soils irrigated with different concentrations of RW over one year are measured to further analyze the effect of RW quality on soil infiltration over the long term and the variation curves of the cumulative infiltration of each soil with the square root of time are shown in Figure 7. It shows that the cumulative infiltration volume increases gradually during the whole infiltration process for all the types of soil. However, the increasing slope differs among soils. In the early stage of
infiltration, there is no significant difference among various treatments and the effect of RW on the cumulated infiltration amount is still relatively weak. However, as the infiltration process proceeded, especially after 16 s, the effect of RW on soil infiltration tended to be stronger and the difference among treatments showed more obvious. After 210 s, the cumulative infiltration of red soil is respectively reduced by 85.71% (RW), 81.63% (RW-2), 69.39% (RW-4) and 40.82% (RW-6), comparing with that of CK. Moreover, the slopes of infiltration curves of treatments from red soil all increase over time and the slopes grow faster with the increase of dilution times of RW. The overall relationship presented is $I_{\text{CK}} > I_{\text{RW-2}} > I_{\text{RW-6}} > I_{\text{RW-4}} > I_{\text{RW}}$, which means that the effect of RW on soil infiltration becomes less as the dilution times increase. During the infiltration process, the relationship of cumulative infiltration among various treatments is $I_{\text{RW-4}} > I_{\text{RW-6}} > I_{\text{CK}} > I_{\text{RW-2}} > I_{\text{RW}}$ for aquic soil, while it turns out to be $I_{\text{RW-2}} > I_{\text{RW-4}} > I_{\text{RW-6}} > I_{\text{CK}} > I_{\text{RW}}$ for purple soil and $I_{\text{RW-6}} > I_{\text{RW-2}} > I_{\text{RW-4}} > I_{\text{CK}} > I_{\text{RW}}$ for paddy soil. From the cumulative infiltration data alone, it can be seen that the RW treatment reduced the infiltration of four soils, and the greatest difference in the effect of different concentrations of RW on soils is the different sensitivity of the soils to the same dilution level. For example, CK treatment has the fastest infiltration rate for red soil, while in the other three types of soil, the infiltration rate is much slower than the other treatments. It indicates that the effect of different concentrations of RW on the soil properties is different and the impact is not linearly related to the dilution factor. Therefore, the appropriate dilution of RW should be selected for irrigating different types of soils.

![Figure 7. Cumulative infiltration of four soils under reclaimed water irrigation.](image-url)

The fitted parameters of Philip infiltration model for cumulative infiltration are shown in Table 2. As shown in the table, the $R^2$ of all the simulation results are above 0.99, which reflects that the fit is well adapted and the accuracy is high. For red soil and aquic soil, the higher the dilution of reclaimed water, the higher coefficient $c$ related to infiltration rate. Moreover, the CK and RW-2 treatments have the lowest and highest $c$ value for purple soil and paddy soil, while the RW and RW-6 treatment have the lowest and highest $c$ value for paddy soils. For the red soil, the coefficient $S$ related to soil sorptivity rate is significantly higher in the instance of RW irrigation than that of distilled water irrigation, with the
increases by 10.16% (RW), 30.51% (RW-2), 84.75% (RW-4) and 98.30% (RW-6), respectively. Similarly, the $S$ values of aquic soils with RW are also significantly higher than those of CK treatment. It shows the smallest $S$ values in both purple soils and paddy soils at RW treatment. The results indicate the different response of soils to different concentrations of RW irrigation is associated with infiltration characteristics and suction characteristics.

Table 2. The fitted hydrodynamic parameters.

| Soil Type   | Fitted Parameters | RW   | RW-2  | RW-4  | RW-6  | CK    |
|-------------|-------------------|------|-------|-------|-------|-------|
|             | $c$               | 0.0021 | 0.0022 | 0.0036 | 0.0077 | 0.0146 |
| Red soil    | $s$               | 0.0062 | 0.0073 | 0.0122 | 0.0138 | 0.003  |
|             | $R^2$             | 0.9999 | 0.9978 | 0.9991 | 0.9998 | 0.9994 |
| Aquic soil  | $c$               | 0.0008 | 0.0015 | 0.0022 | 0.0035 | 0.0043 |
|             | $s$               | 0.026  | 0.0409 | 0.0731 | 0.0184 | 0.0006 |
|             | $R^2$             | 0.996  | 0.9995 | 0.9992 | 0.9991 | 0.9951 |
| Purple soil | $c$               | 0.0043 | 0.0075 | 0.0047 | 0.0058 | 0.0005 |
|             | $s$               | 0.0094 | 0.0603 | 0.07   | 0.0242 | 0.0314 |
|             | $R^2$             | 0.9964 | 0.9982 | 0.9985 | 0.9987 | 0.9986 |
| Paddy soil  | $c$               | 0.0082 | 0.0112 | 0.0132 | 0.0144 | 0.0095 |
|             | $s$               | 0.0098 | 0.0667 | 0.0374 | 0.0771 | 0.0307 |
|             | $R^2$             | 0.9958 | 0.9977 | 0.9977 | 0.9996 | 0.998  |

In the one-year irrigation test, red soil exhibited higher coefficients $c$ with higher dilution of reclaimed water. Coefficient $S1$ was significantly higher under reclaimed water irrigation than distilled water irrigation, with increases of 10.16% (RW), 30.51% (RW-2), 84.75% (RW-4) and 98.30% (RW-6), respectively. This is because the soil is irrigated with reclaimed water for a long time; a large amount of alkaline cations $Ca^{2+}$ and $Mg^{2+}$ contained in the reclaimed water form solids with the acidic anions in the soil, thus blocking the pores. The large pores gradually become smaller, the medium pores become small pores, the small pores become smaller pores or are blocked and the hydraulic conductivity of the soil decreases accordingly. The greater the concentration of reclaimed water, the more obvious the change in soil pore space is. Moreover, the large and medium pores decrease, so the hydraulic conductivity of RW is the lowest. Soil absorption is a phenomenon of soil water movement under the action of soil matrix potential. Under long-term reclaimed water irrigation, the salt ions in the soil keep increasing, the pore space gradually decreases and the soil absorption increases. With the decrease of dilution times, the absorption channels of the soil are instead blocked by solids formed by $Ca^{2+}$ and $Mg^{2+}$ [35], and with the higher concentration of the amount of ionic substances, the effect of restriction is greater, so that the absorption rate of RW is instead the smallest.

3.2.2. Steady Infiltration Rate

Stable infiltration rate is the infiltration value when soil infiltration reaches stability, which is a crucial indicator to evaluate the infiltration performance of soil. Figure 8 shows the stable infiltration rate of four soils in the CK treatment. The figure exhibits that the stable infiltration rates of the four soils have a relationship of $K_s$ (red soil) > $K_s$ (paddy soil) > $K_s$ (purple soil) > $K_s$ (aquic soil). This result is mainly due to the fact that the test red soil is developed from the Quaternary laterite parent material. Its clay grain minerals are mainly kaolinite, which is not easy to swell in water. Additionally, the mineral particles are coarser than the other three soils, so the water diffusion channel is smoother. Therefore, the diffusion rate is faster.
According to Figure 9, for red soils, the soil infiltration rate increases with increasing dilution of RW, and the infiltration rate of each treatment is 0.14 times (RW), 0.15 times (RW-2), 0.248 times (RW-4) and 0.527 times (RW-6) of CK, respectively. The RW treatment has the lowest soil infiltration rate of 1.84 cm h$^{-1}$, and the RW-6 treatment has the highest soil infiltration rate of 6.76 cm h$^{-1}$. For aquic soils, the minimum value of stable infiltration rate is shown in the RW-2 treatment, and the maximum value is observed in the RW-6 treatment with a value of 2.20 cm h$^{-1}$. The overall relationship for aquic soil is $K_s$(RW-6) > $K_s$(RW) > $K_s$(RW-4) > $K_s$(RW-2). However, for purple soils, there is no obvious differences among water quality treatments, with the maximum in RW-6 treatment and the minimum in RW-4 treatment. The largest stable infiltration rate for paddy soil is found in the RW-4 treatment, indicating that of these five concentration gradients, the RW-4 treatment is the most favorable for water transfer. The closer the concentration is to the 4-fold dilution, the greater promotion effect we can obtain.

Figure 8. The stable infiltration rate of four soils at CK treatment.

Figure 9. The stable infiltration rate of four soils at each treatment. (a) red soil; (b) aquic soil; (c) purple soil; (d) paddy soil.
3.2.3. Properties of the Four Soils before and after Irrigation for One Year

The physico-chemical properties of four soils before and after one year are shown in Tables 3 and 4. After one year’s RW irrigation, physical properties such as soil particle size distribution, texture and EC have changed. For example, in terms of red soil, EC increased significantly with RW irrigation, from 46.7 µS/cm to 101.07 µS/cm. However, regarding aquic soil, EC decreased from 157.05 µS/cm to 123.20 µS/cm. For all the soils, most of the chemical concentrations increased after one year’s irrigation, except $K^+$, TN and OM.

Table 3. Basic physical properties of four soils before and after irrigation for one year.

| Soil Type  | Water Quality for Irrigation | Soil Particle Size Distribution | Texture | EC (µS/cm) | pH |
|------------|----------------------------|---------------------------------|---------|------------|-----|
|            | Initial                    | 2 − 0.02 mm | 0.02 − 0.002 mm | <0.002 mm |        |      |
| Red soil   |                             | 0.12      | 0.32            | 0.56       | Clay  | 46.70 | 5.05 |
|            | CK                         | 0.110     | 0.342           | 0.548      | Clay  | 32.97 | 4.94 |
|            | RW-6                       | 0.084     | 0.363           | 0.553      | Clay  | 53.30 | 4.90 |
|            | RW-4                       | 0.066     | 0.379           | 0.555      | Clay  | 55.58 | 4.89 |
|            | RW-2                       | 0.111     | 0.406           | 0.483      | Clay  | 67.42 | 4.96 |
|            | RW                         | 0.07      | 0.396           | 0.534      | Clay  | 101.07 | 4.80 |
| Aquic soil |                             | 0.15      | 0.47            | 0.38       | Silt clay | 157.05 | 5.69 |
|            | CK                         | 0.200     | 0.412           | 0.388      | Loamy clay | 34.81 | 5.93 |
|            | RW-6                       | 0.204     | 0.424           | 0.372      | Loamy clay | 66.26 | 5.95 |
|            | RW-4                       | 0.208     | 0.428           | 0.364      | Loamy clay | 68.30 | 6.01 |
|            | RW-2                       | 0.183     | 0.454           | 0.364      | Silt clay | 84.32 | 5.96 |
|            | RW                         | 0.200     | 0.444           | 0.356      | Loamy clay | 123.20 | 5.96 |
| Purple soil|                             | 0.34      | 0.33            | 0.33       | Loamy clay | 196.20 | 7.50 |
|            | CK                         | 0.324     | 0.316           | 0.360      | Loamy clay | 105.76 | 8.16 |
|            | RW-6                       | 0.300     | 0.338           | 0.342      | Loamy clay | 129.72 | 8.12 |
|            | RW-4                       | 0.310     | 0.348           | 0.342      | Loamy clay | 130.84 | 8.06 |
|            | RW-2                       | 0.268     | 0.292           | 0.440      | Loamy clay | 150.52 | 8.07 |
|            | RW                         | 0.273     | 0.304           | 0.424      | Silt clay | 169.13 | 8.10 |
| Paddy soil |                             | 0.25      | 0.49            | 0.26       | Silty clay loam | 96.60 | 5.03 |
|            | CK                         | 0.212     | 0.524           | 0.264      | Silt clay | 116.52 | 5.59 |
|            | RW-6                       | 0.206     | 0.514           | 0.280      | Silt clay | 153.88 | 5.56 |
|            | RW-4                       | 0.226     | 0.518           | 0.256      | Silt clay | 131.60 | 5.63 |
|            | RW-2                       | 0.234     | 0.512           | 0.254      | Silt clay | 160.27 | 5.61 |
|            | RW                         | 0.250     | 0.490           | 0.260      | Silty clay loam | 183.08 | 5.81 |

Table 4. Basic chemical properties of four soils before and after irrigation for one year.

| Soil Type  | Treatments | $K^+$ (g/kg) | $Na^+$ (g/kg) | $Ca^{2+}$ (g/kg) | $Mg^{2+}$ (g/kg) | $Cl^-$ (g/kg) | $SO_4^{2-}$ (g/kg) | $TN$ (g/kg) | $TP$ (g/kg) | $OM$ (g/kg) | $CEC$ (cmol/kg) |
|------------|------------|--------------|---------------|------------------|------------------|--------------|------------------|-------------|-------------|-------------|-----------------|
| Initial    | 0.6646     | 0.2968       | 0.7275        | 0.0696           | 0.01917         | 0.0046       | 0.6763           | 0.3223      | 2.2844      | 13.0858     |
| Red soil   | CK         | 0.149        | 0.082         | 3.646            | 0.577            | 0.075        | 0.033            | 0.639       | 0.348       | 1.284       | 13.024         |
|            | RW-6       | 0.163        | 0.265         | 3.321            | 0.595            | 0.151        | 0.013            | 0.672       | 0.404       | 1.371       | 13.234         |
|            | RW-4       | 0.266        | 0.346         | 3.617            | 0.623            | 0.173        | 0.027            | 0.611       | 0.360       | 3.123       | 12.936         |
|            | RW-2       | 0.316        | 0.679         | 3.961            | 0.677            | 0.171        | 0.034            | 0.574       | 0.361       | 5.580       | 12.603         |
|            | RW         | 0.572        | 0.722         | 4.322            | 0.785            | 0.220        | 0.039            | 0.650       | 0.360       | 7.037       | 13.354         |
Table 4. Cont.

| Soil Type | Treatments | \( K^+ \) (g/kg) | \( Na^+ \) (g/kg) | \( Ca^{2+} \) (g/kg) | \( Mg^{2+} \) (g/kg) | \( Cl^- \) (g/kg) | \( SO_4^{2-} \) (g/kg) | \( TN \) (g/kg) | \( TP \) (g/kg) | \( OM \) (g/kg) | \( CEC \) (cmol/kg) |
|-----------|------------|-----------------|-----------------|-------------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| Aquic soil | Initial | 1.4517 | 0.5641 | 1.9823 | 0.02698 | 0.0948 | 1.1805 | 0.7356 | 15.2594 | 14.5958 |
|            | CK       | 0.596 | 1.665 | 9.270 | 0.08 | 0.015 | 1.207 | 0.195 | 15.657 | 16.032 |
|            | RW-6     | 0.599 | 1.742 | 9.430 | 0.082 | 0.028 | 1.324 | 1.437 | 16.652 | 16.782 |
|            | RW-4     | 0.581 | 1.747 | 9.452 | 0.102 | 0.023 | 1.207 | 0.736 | 16.783 | 15.903 |
|            | RW-2     | 0.586 | 1.747 | 9.431 | 0.092 | 0.035 | 1.383 | 1.518 | 20.123 | 16.411 |
|            | RW       | 0.656 | 2.128 | 9.309 | 0.152 | 0.040 | 1.383 | 1.518 | 20.123 | 16.411 |
| Purple soil | Initial | 2.0599 | 0.5608 | 3.9534 | 0.1820 | 0.06674 | 0.0720 | 1.6488 | 1.3791 | 18.6673 | 20.3767 |
|            | CK       | 0.820 | 2.008 | 20.999 | 4.319 | 0.084 | 0.026 | 1.159 | 1.814 | 15.412 | 17.207 |
|            | RW-6     | 0.852 | 2.091 | 22.396 | 4.530 | 0.110 | 0.022 | 1.300 | 2.391 | 30.653 | 17.871 |
|            | RW-4     | 0.886 | 2.169 | 24.099 | 4.762 | 0.124 | 0.018 | 1.732 | 2.391 | 30.653 | 17.871 |
|            | RW-2     | 0.884 | 2.161 | 23.462 | 4.725 | 0.126 | 0.023 | 1.599 | 2.391 | 30.653 | 17.871 |
|            | RW       | 0.843 | 2.300 | 22.374 | 4.417 | 0.147 | 0.025 | 1.924 | 2.437 | 30.064 | 19.758 |
| Paddy soil | Initial | 0.4356 | 0.4740 | 1.4639 | 0.1149 | 0.05041 | 0.0590 | 1.2563 | 0.6963 | 15.0878 | 10.2387 |
|            | CK       | 0.610 | 1.825 | 6.800 | 2.072 | 0.064 | 0.041 | 1.184 | 1.395 | 25.736 | 10.473 |
|            | RW-6     | 0.623 | 1.930 | 6.823 | 2.000 | 0.158 | 0.041 | 1.274 | 0.364 | 30.204 | 11.827 |
|            | RW-4     | 0.618 | 2.056 | 6.502 | 1.874 | 0.116 | 0.034 | 1.019 | 1.106 | 30.905 | 13.479 |
|            | RW-2     | 0.628 | 1.797 | 6.437 | 1.885 | 0.126 | 0.045 | 1.008 | 0.613 | 25.611 | 13.620 |
|            | RW       | 0.658 | 2.028 | 7.274 | 2.146 | 0.138 | 0.023 | 1.111 | 0.923 | 27.835 | 12.763 |

3.3. Correlation Relationship between Soil Infiltration Rate and Hydrodynamic Parameters during RW Irrigation

To further investigate the relationships between hydrodynamic parameters (e.g., stable infiltration rate \( K_s \), soil infiltration rate coefficient \( c \) and soil sorptivity \( S \)) and physicochemical properties of soil, correlation analysis is complemented. The correlation coefficients are shown in Tables 5 and 6.

Table 5. Basic Correlation between soil physical properties and hydrodynamic parameters (n = 15).

| Soil Type | Hydrodynamic Parameters | Dilution Factor | Sand Particle Content | Silt Particle Content | Clay Particle Content | EC | pH |
|-----------|-------------------------|-----------------|----------------------|----------------------|----------------------|----|----|
| Red soil  | \( K_s \)               | 0.351           | −0.247               | −0.310               | 0.441                | −0.313 | 0.052 |
|           | \( c \)                 | 0.888 **        | 0.513                | −0.926 **            | 0.425                | 0.425 | 0.401 |
|           | \( S \)                 | 0.361           | −0.052               | −0.134               | 0.152                | −0.414 | 0.396 |
| Aquic soil| \( K_s \)               | 0.735 **        | 0.395                | −0.796 **            | 0.760 **             | −0.528 * | −0.723 ** |
|           | \( c \)                 | 0.993 **        | 0.337                | −0.893 **            | 0.946 **             | −0.923 ** | −0.465 ** |
|           | \( S \)                 | −0.425          | 0.117                | 0.384                | −0.612 *             | 0.256 | 0.974 ** |
| Purple soil| \( K_s \)              | 0.408           | 0.048                | 0.048                | 0.055                | −0.222 | 0.209 | 0.548 * |
|           | \( c \)                 | −0.569 *        | −0.736 **            | −0.148               | 0.399                | 0.600 * | −0.751 ** |
|           | \( S \)                 | 0.049           | 0.101                | 0.216                | −0.103               | −0.210 | −0.645 ** |
| Paddy soil| \( K_s \)              | 0.008           | −0.292               | 0.256                | 0.177                | −0.018 | −0.463 |
|           | \( c \)                 | 0.359           | −0.624 *             | 0.487                | 0.452                | −0.251 | −0.697 ** |
|           | \( S \)                 | 0.423           | −0.664 **            | 0.592 *              | 0.388                | −0.246 | −0.873 ** |

** Extremely significant correlated in 0.01 level (bilateral); * Significant correlated in 0.05 level (bilateral).

Firstly, for the stable infiltration rate \( (K_s) \), \( K_s \) values of four soils are positively correlated with the dilution times of RW and negatively correlated with the \( EC \) value. Especially for aquic soil, the positive correlation with the dilution times of RW is observed high significantly \((p < 0.01)\) while it is significantly negatively correlated with the \( EC \) value \((p < 0.05)\). In addition, \( K_s \) of red and purple soils are positively correlated with soil \( pH \), while aquic and paddy soils are negatively correlated with soil \( pH \). The correlation between stable infiltration rate and soil particle composition also differed among the four soils, with aquic soils showing a significant negative correlation \((p < 0.01)\) with silt particle content.
and reaching a significant positive correlation \((p < 0.05)\) with clay particle content. Second, as for soil infiltration rate coefficient \(c\) and soil sorptivity \(S\), the \(c\) value of red soil reaches a highly significant positive correlation \((p < 0.01)\) with the dilution times and reaches a highly significant negative correlation with powder content \((p < 0.01)\); then \(S\) value of red soil is positively correlated with dilution factor, clay content, soil \(pH\) and negative correlation with sand content, silt content and \(EC\) value.

Table 6. Correlation between soil chemical properties and hydrodynamic parameters (\(N = 15\)).

| Soil Type | Hydrodynamic Parameters | \(K^+\) | \(Na^+\) | \(Ca^{2+}\) | \(Mg^{2+}\) | \(Cl^-\) | \(SO_4^{2-}\) | \(TN\) | \(TP\) | \(OM\) | \(CEC\) |
|-----------|--------------------------|---------|---------|-----------|-----------|-------|--------|-------|-------|-------|-------|
| Red soil  | \(K_s\)                 | -0.710 ** -0.886 ** -0.527 * -0.726 ** -0.941 ** -0.217 | 0.409 | -0.074 | -0.802 ** -1.141 |
|           | \(c\)                    | -0.710 ** -0.885 ** -0.537 * -0.725 ** -0.940 ** -0.217 | 0.410 | -0.073 | -0.801 ** 0.143 |
|           | \(S\)                    | -0.597 * -0.329 -0.800 ** -0.590 * -0.055 | -0.867 ** -0.006 | 0.668 ** -0.531 * -0.216 |
| Aquic soil| \(K_s\)                 | 0.129 | -0.226 | -0.533 * 0.338 | -0.070 | -0.702 ** -0.009 | -0.222 | -0.475 | 0.548 * |
|           | \(c\)                    | -0.480 | -0.750 ** -0.180 | 0.783 ** -0.539 * -0.964 ** -0.542 * -0.592 * -0.905 ** 0.151 |
|           | \(S\)                    | -0.334 | 0.021 | 0.736 ** 0.090 | -0.102 | 0.411 | -0.236 | 0.094 | 0.150 | -0.448 |
| Purple soil| \(K_s\)              | -0.397 | -0.417 | -0.480 | -0.292 | -0.361 | 0.310 | -0.620 * -0.202 | -0.233 | -0.274 |
|           | \(c\)                    | 0.795 ** 0.448 | 0.738 ** 0.688 ** 0.603 * | -0.454 | 0.418 | 0.929 ** 0.877 ** 0.195 |
|           | \(S\)                    | 0.788 ** -0.152 | 0.721 ** 0.891 ** -0.053 | -0.704 ** 0.072 | 0.314 | 0.291 | -0.470 |
| Paddy soil| \(K_s\)                | -0.270 | 0.263 | -0.597 * -0.784 ** 0.577 * | 0.307 | -0.133 | -0.589 * 0.707 ** 0.540 * |
|           | \(c\)                    | -0.507 | 0.116 | -0.569 | -0.673 ** 0.430 | 0.475 | 0.182 | -0.533 * 0.685 ** 0.187 |
|           | \(S\)                    | -0.593 * -0.489 | -0.697 ** -0.664 ** 0.251 | 0.870 ** 0.185 | -0.611 * 0.118 | 0.046 |

**Extremely significant correlated in 0.01 level (bilateral); * Significant correlated in 0.05 level (bilateral).**

Likewise, the \(c\) value of aquic soils showed a highly significant positive correlation \((p < 0.01)\) with dilution times and clay content and reaches a highly significant negative correlation \((p < 0.01)\) with silt content and soil \(EC\) value. In contrast, \(S\) values of aquic soils reach a significant negative correlation with clay content \((p < 0.05)\) and a highly significant positive correlation with soil \(pH\) \((p < 0.01)\). Besides, the \(c\) value of purple soil reaches a significant negative correlation with dilution times, sand content and \(pH\), and a significant positive correlation with \(EC\) \((p < 0.05)\); then the \(S\) value of purple soil reaches a highly significant negative correlation with \(pH\) \((p < 0.01)\). Furthermore, the \(c\) value of paddy soil reaches a significant negative correlation with sand content and \(pH\); the \(S\) value of rice soil reaches a significant negative correlation with sand content and \(pH\), and a significant positive correlation with powder content \((p < 0.05)\).

The correlation analysis between soil chemical properties and hydrodynamic parameters is shown in Table 6. From the table, it can be seen that the correlation between hydrodynamic parameters and soil chemical ions differed significantly with soil types, among which \(K_s\) and \(c\) values of red soil show a highly significant negative correlation \((p < 0.01)\) with soil \(K^+\), \(Na^+\), \(Mg^{2+}\), \(Cl^-\) and organic matter content, and reach negative correlation \((p < 0.05)\) with \(Ca^{2+}\) content; then red soil \(S\) values show negative correlation with soil \(K^+\), \(Ca^{2+}\), \(Mg^{2+}\), \(SO_4^{2-}\) and organic matter content, and highly significant positive correlation with total phosphorus content \((p < 0.01)\). In addition, aquic soil \(K_s\) is significantly negatively correlated with \(Ca^{2+}\) and \(SO_4^{2-}\) and positively correlated with cation exchange \((p < 0.05)\), and the \(c\) value of aquic soils is significantly and negatively correlated with \(Na^+\), \(Cl^-\), \(SO_4^{2-}\), total nitrogen content, total phosphorus content and organic matter content; then \(S\) value of aquic soils reaches a highly significant positive correlation with \(Ca^{2+}\) content \((p < 0.01)\). Moreover, purple soil \(K_s\) reaches a significant negative correlation with total N content \((p < 0.05)\) and its \(c\) values are correlated with \(K^+\), \(Ca^{2+}\), \(Mg^{2+}\), \(Cl^-\) and total phosphorus content and organic matter content, with \(Cl^-\) reaching a significant level \((p < 0.05)\), then purple soil \(S\) values reaching a highly significant positive correlation with \(K^+\), \(Ca^{2+}\) and \(Mg^{2+}\) \((p < 0.01)\) and a significant negative correlation with \(SO_4^{2-}\) \((p < 0.05)\). Moreover, the \(c\) value of rice soil reaches a significant negative correlation with \(Ca^{2+}\), \(Mg^{2+}\) and total phosphorus content. Its \(K_s\) reaches a significant negative correlation with \(Cl^-\),
organic matter content and cation exchange amount reaches a significant positive correlation ($p < 0.05$), and its $c$ value and organic matter content showed a highly significant positive correlation with organic matter content ($p < 0.01$). Then, the $S$ values reach a significant negative correlation with $K^+$, $Ca^{2+}$, $Mg^{2+}$ and total phosphorus content, and a highly significant positive correlation with $SO_4^{2-}$ ($p < 0.01$).

Based on the above analysis, it is found that irrigation with RW has a significant effect on the infiltration of soils, which is not only related to the soil type, the dilution times of RW, soil particle composition, soil EC value and pH value, but also closely related to the content of each soil ion. On the one hand, the long period of continuous irrigation with RW of high EC value, where a large number of salt ions enter the soil, leads to the compression of the diffuse double electron layer of the soil toward the surface of the mucilage. The repulsion between soil particles decreases, so that it contributes to the formation of agglomerate structure. Then the soil pore space and infiltration rate increase, but on the other hand, during salt accumulation, a large amount of sodium ions were exchanged with $Ca^{2+}$ and $Mg^{2+}$ adsorbed in soil colloids, leading to the release of $Ca^{2+}$ and $Mg^{2+}$. The insoluble substances are formed and the corresponding anions block the pores, which play some certain roles in weakening the infiltration of the soil.

For red soil, RW irrigation reduced soil infiltration. Additionally, the higher the concentration of RW, the stronger the inhibitory effect. Regarding aquic soil, RW also has an inhibitory effect, but 2 times dilution shows the greatest restraint. In addition, the infiltration of purple soil is restrained in RW, RW-2 and RW-4 treatments but is accelerated in RW-6 treatment. However, on the contrary, the infiltration of the paddy soil is accelerated by all kinds of treatments and reaches the maximum in the RW-4 treatment. However, among all the physical and chemical properties examined in this study, there is no significant relationship to explain this phenomenon, which needs further study in future research. Furthermore, there is no obvious difference of pH between pre- and post-irrigation with RW. It may be due to the high concentration of soluble salts in the soil solution which prevents the hydrolysis of the exchangeable sodium adsorbed on the soil colloidal surface.

4. Discussion

Reclaimed water contains a large amount of salts, suspended particles, organic matter, etc., which can affect soil infiltration [33]. Studies show that the infiltration rate of acidic soils has a different response compared with that of neutral or alkaline soils when irrigating with RW. However, the previous study area was mostly located in the dry area. This study locates in southern China with acidic soils, it quantifies the effects of different mineralization levels on soil infiltration characteristics and enriches the research results in this direction. All the four typical subtropical soils selected for this study (i.e., red soil, aquic soil and paddy soil) are all acidic soils. The red soil has the widest distribution in southern China, and the different influence of RW on soil infiltration was observed for red soil in this study. For example, in the short-term infiltration test, the higher the concentration of RW, the lower the infiltration rate for the red soil. This could be induced by the soil clogging, which is related to the special hydraulic conductivity and soil pore size of red soil [36]. Compared with sandy loam, chalky clay loam and other sandy coarse-textured soils, the main cementing substances of red soil in southern China include clay particles and free iron oxide aluminum. A large number of clay particles absorb water and swell, making the soil macropores and conductive pores smaller [31]. At the same time, the exchange reaction of $Na^+$ in the infiltrating water with soil colloidal particles and the original $Ca^{2+}$, $Mg^{2+}$, and $Al^3+$ plasma further changes the soil structure and pore characteristics [35]. Partial collapse of soil pores and movement of clay particles under the action of water flow cause pore blockage and hinder soil water infiltration [37]. Precipitates generated by exchanged cations and hydroxide ions block pore spaces with water infiltration and may also be one of the reasons for restraining water infiltration in red soils [20]. Understanding the effects of regenerated water quality on infiltration characteristics of acid soils will shed some insights into the development and utilization of unconventional water resources in southern China.
Moreover, with the irrigation of RW, the short-term infiltration rate of purple soil, aquic soil and paddy soil increased, and the long-term infiltration rate does not show any significant decrease, indicating the feasibility of RW irrigation for these types of soil. However, the infiltration rate of red soil had an obvious reduction after RW irrigation, both in the short term and long term, which reflects the potential harm of direct RW irrigation for red soil. The adverse effects on soil infiltration rate can be mitigated by controlling the concentration of RW or using alternative RW-clear water irrigation. Since RW irrigation has the effect of fertilization, using treated RW for agricultural irrigation can not only improve crop yields, but can also help farmers save money on fertilizers and improve their income [38]. Currently, China produces nearly 2.23 million m$^3$/d of domestic sewage per year [39]. Wu et al. showed that reclaimed water irrigation can reduce nitrogen fertilizer application by 10–15% [40], which has obvious market benefits. At the same time, the RW irrigation can reduce the pollution emission, which could not only alleviate the water pollution to ecological environment in the south of China, but could also save the fresh water resource. The environmental benefits brought by RW irrigation are also very substantial [41–43].

Nonetheless, there are some limitations to this study. Firstly, the results have shown that there is a significant influence of RW quality on its sustainable reuse. However, we did not specify the parameters of RW quality which has the dominant role, which needs further effort in future study. For example, humic acid and elemental characteristics are important to predict the effect of reclaimed water, which should be further investigated in the next research. Secondly, the soil infiltration could impact on crop growth, which is an important implication for improving the sustainable reuse of RW. However, we do not have the particular data to quantify the influence. This will also be considered in the future.

5. Conclusions

In this study, we investigated the influence of RW irrigation on soil infiltration in the short term and long term. The infiltration rate varies with different concentrations of RW and a significant difference is observed in red soil. Regarding the short-term test, a one-dimensional horizontal infiltration test is conducted on red soil, aquic soil, purple soil and paddy soil irrigated with different concentrations of RW. In terms of the long-term test, the reclaimed water were measured in situ by Mini Disk infiltration meter to simulate effects of RW on soil infiltration.

The RW of different concentrations has different effects on the soil infiltration rate both in the short and long term. The infiltration of paddy soil is increased for all the treatments irrigated with RW, while for purple soil, a promoting effect was observed at the beginning and the restrain effect was observed later. For red and aquic soil, only the original RW treatment accelerates infiltration, but the rest of the treatments show an inhibiting effect. Under RW irrigation for one year, the cumulative infiltration of red soil increases with the decline of the concentration of RW. At the same time, for other soils, no distinct regularities are found except that the lowest infiltration was observed in RW treatment. Compared with the CK treatment, changes in infiltration capacity of soil irrigating with RW treatments differ among soil types. The absorption rate coefficients undergo a significantly 10.16–98.3% increase for red soil and aquic soil, and on the contrary, the coefficients exhibit the smallest for purple soil and paddy soil. Results show that the use of RW may have adverse effects on soil infiltration, and it is better to choose a rational irrigation solution to reduce adverse effects according to the RW quality and soil properties.

Correlation analysis shows that the infiltration performance of soil irrigated with RW is influenced by the RW quality and soil properties. For instance, the infiltration coefficient of red soil and aquic soil shows a significantly positive correlation with reclaimed water ($p < 0.01$). However, it shows a significant negative correlation with soil silk ($p < 0.01$). In contrast, infiltration parameters $c$ and $S$ value of the purple soil, and paddy soil are significantly negative with $pH$ value ($p < 0.01$). Based on these parameters, the logic regression model shows a good simulation for infiltration rate with reclaimed water. The
results benefit the appropriate RW reuse and shed insights into the water sustainability in subtropical regions.

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