A simple model for predicting soil infiltration rate for vertical line source irrigation

Ying Wang¹, Jiaguo Gong¹,³ and Yanwei Fan²

¹State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; ²College of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, 730050, China
³Email: jiaguogong@163.com

Abstract. In this study, HYDRUS-2D was used to simulate the soil infiltration rate of vertical line source irrigation (VLSI) under different soil textures and initial water contents, as well as for different lengths, diameters and buried depths of the line source. The soil texture, diameter and length of the line source are the dominant influential factors of the soil infiltration rate of VLSI, whereas the initial water content and buried depth of the line source are less influential. The variation of soil infiltration rate is in accordance with the Philip model. The model parameters, i.e., sorptivity (S) and steady infiltration rate (A), increase as the diameter (D) and length (L) of line source increases. A power function between S and D and L, and one between A and D and L, were established. The exponential value of the power function was determined based on the HYDRUS simulation results, thereby obtaining a simplified estimation model of the soil infiltration rate of VLSI containing D and L. The effectiveness of the simplified model was verified based on a laboratory experiment and currently available research. The MAE (mean absolute error), MAE) is 0.056–0.348, RMSE (Root mean square error, RMSE) is 0.073–0.442, PBIAS (percentage bias, PBIAS) is 1.642 – 2.893, and NSE (Nash-Sutcliffe efficiency coefficient, NSE) is close to 1 (NSE≥0.973), indicating that the model has a high accuracy and can therefore be used for estimating the soil infiltration rate of VLSI. The simplified estimation model established in this study has only two undetermined parameters that can be obtained based on only one set of experimental data, simplifying the experimental scheme and improving the work efficiency.

1. Introduction

The United Nations World Water Development Report pointed out that the global demand for water resources is increasing at a rate of 1% per year, and this rate will greatly accelerate in the next two decades [1]. Severe global water shortage has attracted considerable attention, and the efficient use of water resources is a focus worldwide [2-4]. Agriculture is the main cause of water resources stress, and irrigation water accounts for 70% of global water withdrawal and 90% of global water consumption [5, 6]. For developing countries, without considering the effects of climate change, the amount of irrigation water is expected to increase by 14% by 2030 [7]. Therefore, the efficient use of water resources lies in the efficient utilization of agricultural water resources, and the improvement of irrigation technology will play an important role in the efficient utilization of agricultural water resources.
With rich land resources, long sunshine time and large temperature difference between day and night, the arid regions of Northwest China are ideal for developing forestry and growing fruit [8]. However, rainfall in these regions is limited, and fruit growing depends on irrigation to a large extent [9, 10]. Traditional irrigation consumes large amounts of water, which is not conducive to the sustainable development of forestry and growing fruit [11, 12]. To reduce soil surface evaporation and increase the depth of wetted soil, Zeng et al. [13] proposed an underground vertical line source irrigation (VLSI) method that vertically places a plastic pipe with holes in the pipe wall into the soil with the bottom of the pipe sealed, which supplies water directly to the roots of the plants via the holes in the pipe wall. For VLSI, it is difficult to control the water head. There is often overflow of water at the top of the irrigation emitter caused by an excessively large water head. One way to solve this problem is to seal the top of the line source irrigation emitter to withstand the water supply pressure. The other approach is that the irrigation emitter is exposed to a certain height on the ground to prevent water from overflowing. If the ordinary surface drip irrigation system can be combined with the VLSI emitter arranged under the dripper, the structure of the line source irrigation emitter will be simplified, achieving the effect of underground VLSI [14].

When surface drip irrigation is applied in combination with the VLSI emitter, the soil infiltration rate should match the dripper flow rate (i.e., the soil infiltration rate ≥ the dripper flow rate) to prevent water in the irrigation emitter from overflowing. Therefore, it is of great theoretical value and practical significance to study the soil infiltration rate of VLSI. The soil infiltration characteristics of VLSI are mainly determined by factors such as soil parameters (soil texture and initial water content) and specifications of the irrigation emitter (diameter, length and buried depth). As an important factor determining irrigation design parameters, soil texture should be taken into consideration while designing the underground irrigation system [15, 16]. Irrigation must be timely and appropriate; irrigation will be ineffective if conducted too early or too late, or if the irrigation water quota is too high or too low. According to Du et al. [8], a soil water content in the root zone of apple trees in the arid regions of Northwest China 50–55% lower than the field capacity (FC) will impose water stress on the growth of apple trees and the final yield. According to Zhang et al. [17], to apply spring root irrigation to pear-jujube trees in mountainous regions in North Shaanxi, two irrigation emitters per tree and an irrigation amount of 40 L per irrigation emitter every time is a suitable arrangement. The length and diameter of the line source determine the water seepage area of the irrigation emitter. As the length or diameter of the line source increases, the water seepage area becomes larger, which means that there are more channels for water to infiltrate into the soil, resulting in an increase in the amount of water infiltration within the same period of time [18, 19]. The buried depth of the irrigation emitter directly changes the moisture distribution position of the soil infiltration body, which is the key factor to achieve effective matching between the crop root system and the soil infiltration body. A small burial depth will increase evaporation of surface water, whereas a large burial depth will cause deep leakage and a water deficit in the surface soil [20, 21].

VLSI is influenced by various factors. It is often time-consuming and labor-intensive to study the soil infiltration rate of VLSI under different influential factors based on experiments. In addition, natural and human factors may cause errors in the accuracy of experimental results, which makes the experiments valueless [22]. Numerical simulation makes up for the shortcomings caused by experimentation. By simulating the soil water movement process under different soil characteristics, different specifications of irrigation emitters and design parameters, a numerical simulation provides a convenient and practical method for determining suitable irrigation technical parameters and realizing the operation of the irrigation system [23-25]. Li and Wang [26] and Fan et al. [27] verified the validity of the HYDRUS-2D simulation results of VLSI through experiments. Based on the HYDRUS-2D simulation results, Fan et al. [19] proposed a calculation model for the cumulative infiltration capacity of VLSI including the line source water seepage area, but the model requires two independent sets of experimental data, making practical application inconvenient.

In view of this problem, HYDRUS-2D software was used in this study to simulate the influences of soil texture and initial water content, as well as length, diameter and burial depth of the line source on
the soil infiltration rate of VLSI. Then, dominant factors affecting the infiltration rate were screened based on the simulated data, thereby constructing a simplified empirical model for predicting the infiltration rate. The reliability of the empirical model was verified by a soil box experiment.

2. Materials and methods

2.1. Experimental design

The experimental apparatus consisted of three parts, namely, a soil box, a Mariotte’s bottle and a line source irrigation emitter (Figure 1). Constructed of 10-mm-thick plexiglass, the soil box has a size of 50 cm×50 cm×100 cm (L×W×H). There are several vent holes (2 mm in diameter) at the bottom of the soil box to prevent air resistance. Soil holes (2 cm in diameter, with 5 cm spacing) were made on the contact surface between the line source and the soil box to measure the soil water content at the end of the irrigation. A 1/4 cylinder was used as the line source, the bottom end was sealed, and holes were evenly punched on the cylindrical surface. The Mariotte’s bottle has a diameter of 10 cm and a height of 100 cm. Before the experiment, water was added to the soil samples according to the set initial water content. After being evenly mixed, the soil samples were sealed with plastic film for one day. Once the water was uniformly distributed in the soil, the soil samples were placed in the soil box layer by layer (5 cm) according to the designed capacity to obtain uniform soil profiles. To observe the variation of the soil infiltration body, the line source irrigation emitter was wrapped with gauze and placed in a corner of the soil box to ensure that the pipe wall of the emitter was in tight contact with the soil, and the infiltration experiment was carried out the next day. In the experiment, the Mariotte’s bottle provided a constant water head, the cumulative infiltration capacity was recorded at 1, 3, 6, 10, 20, 50, 90, and 150 min, and the transport of the wetting front was drawn with a marker. The water supply was stopped once the infiltration reached the set irrigating water quota, and the soil was quickly removed from the holes on both sides of the irrigation emitter to measure the soil water content using the oven drying method (dried at 105°C for 24 h). In order to eliminate experimental error as much as possible, each experiment was repeated three times.

2.2. Mathematical modelling

2.2.1. Basic equations. Assuming that the soil is homogeneous and isotropic, VLSI is conceptualized as an axisymmetric three-dimensional infiltration process and is simulated in HYDRUS-2D [28]. The soil water movement is controlled by the Richards equation:

\[
\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[ r K(h) \frac{\partial h}{\partial r} \right] + \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} \right] + \frac{\partial K(h)}{\partial z}
\]  

(1)

where \(r\) and \(z\) denote the radial and vertical coordinate, respectively (cm), \(\theta\) is the soil water content (cm³/cm³), \(h\) is the pressure head (cm), \(t\) denotes the time (min), and \(K(h)\) represents the soil unsaturated hydraulic conductivity (cm/min).

The soil water characteristic curve and soil unsaturated hydraulic conductivity are described by the van Genuchten-Mualem (VG-M) equations [29,30]:

\[
s = \frac{\theta - \theta_s}{\theta_i - \theta_s} = \frac{1}{\left(1 + \left|\theta_i - \theta_s\right| \theta_i - \theta_s\right)}
\]  

(2)
Figure 1. Experimental equipment used for VLSI and the detailed structure of the emitter.

Figure 2. The computational domain with initial and boundary conditions: D, L and B represent the diameter, length and buried depth of the line source, respectively; K and J are the highest and lowest points of the line source, respectively.

\[
K(h) = K_s S_r^{0.5} \left[ 1 - \left( 1 - S_r^{0.5} \right)^n \right]^{0.5}
\]  

(3)

where \( S_r \) denotes the soil relative saturation, \( \theta_r \) and \( \theta_s \) are the residual and saturated soil water content, respectively (cm³/cm³), \( \alpha, n \) and \( m \) are the empirical parameters (\( m=1-1/n \)), the unit of \( \alpha \) is cm⁻¹, and \( K_s \) is the soil saturated hydraulic conductivity (cm/min).

2.2.2. Definite conditions. Figure 2 shows the initial and boundary conditions used to simulate different modeling scenarios in this study.

In all simulation scenarios, the soil water content was set per the initial water content. The upper boundary EF was affected by atmospheric conditions, and considering that the surface was a dry soil layer during irrigation, its evaporation was small; therefore, it was set as the zero flux plane for a simplified calculation. The lower boundary GH was not affected by irrigation and was freely drained, so it was set as the zero flux plane. The left boundary HI was the central axis of the irrigation emitter, and EK was the plastic pipe wall, both of which had no water exchange; thus, they were set according to the zero flux plane. Since the irrigation water failed to reach the right boundary FG, it was set per the zero flux surface. GH was sealed at the bottom of the line source and set as a zero flux boundary. Lastly, since the water infiltration surface boundary adopted the sufficient water supply mode and soon reached saturation after water supply, it was then regarded as a fixed water head boundary [19, 26, 27].

Thus, the initial conditions were expressed as:

\[
\theta = \theta_0, t = 0, (r,z) \in \Omega
\]  

(4)

where \( \theta_0 \) is the initial soil water content (cm³/cm³) and \( \Omega \) denotes the calculation domain (Figure 2). The boundary conditions were expressed as:
2.2.3. Simulation scheme. Single factor analysis was used to simulate the influences of different soil textures and initial water contents, as well as different diameters, lengths and buried depths of the line source on the soil infiltration rate of VLSI. The soil texture van Genuchten–Mualem model parameters were taken from the study conducted by Carsel and Parrish [31] (Table 1).

| Soil texture       | $\theta_r$ (cm$^3$·cm$^{-3}$) | $\theta_s$ (cm$^3$·cm$^{-3}$) | $\alpha$ (cm$^{-1}$) | $n$ (-) | $K_s$ (cm·min$^{-1}$) |
|-------------------|-------------------------------|-------------------------------|----------------------|---------|----------------------|
| Sand              | 0.045                         | 0.43                          | 0.145                | 2.68    | 0.495                |
| Loamy sand       | 0.057                         | 0.41                          | 0.124                | 2.28    | 0.2432               |
| Sandy loam       | 0.065                         | 0.41                          | 0.075                | 1.89    | 0.0737               |
| Sandy clay loam  | 0.1                           | 0.39                          | 0.059                | 1.48    | 0.0218               |
| Loam             | 0.078                         | 0.43                          | 0.036                | 1.56    | 0.0173               |
| Silt loam        | 0.067                         | 0.45                          | 0.02                 | 1.41    | 0.0075               |
| Silt             | 0.034                         | 0.46                          | 0.016                | 1.37    | 0.0042               |
| Clay loam        | 0.095                         | 0.41                          | 0.019                | 1.31    | 0.0043               |

The FC of different soil textures was obtained by the prediction model established by RAB et al. [32]. The specific expression was:

$$\text{FC} = 0.0805 + 1.68\theta_p - 1.62\theta_p^2$$

(6)

Where $\theta_p$ is the wilting coefficient, which was expressed by $\theta_r$ (cm$^3$/cm$^3$) in the van Genuchten–Mualem model [16].

2.3. Infiltration Model

With a simple form and clear physical meaning, the Philip equation [33] is suitable for analyzing the three-dimensional infiltration of homogeneous soil with uniformly distributed initial water content [19,34], and was expressed as follows:

$$i = 0.5S \theta_p^{0.5} + A$$

(7)

where $i$ is the infiltration rate (cm$^3$/min), $S$ is the sorptivity (cm$^3$/min$^{0.5}$), and $A$ is the steady infiltration rate (cm$^3$/min).

2.4. Statistical analysis

Four indicators, namely, the mean absolute error (MAE), the root mean square error (RMSE), the percentage bias (PBIAS) and the Nash efficiency coefficient (NSE), were selected to conduct an error analysis of the measured and predicted values of the soil infiltration rate. The indicator parameters were defined as follows:

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |M_i - S_i|$$

(8)

$$\text{RMSE} = \left[ \frac{1}{N} \sum_{i=1}^{N} (M_i - S_i)^2 \right]^{0.5}$$

(9)

$$\text{PBIAS} = \frac{\sum_{i=1}^{N} (M_i - S_i)}{\sum_{i=1}^{N} S_i}$$

(10)
\[ \text{NSE} = 1 - \frac{\sum_{i=1}^{N} (M_i - S_i)^2}{\sum_{i=1}^{N} (M_i - M_{\text{mean}})^2} \]

where \( M_i \) is the \( i \)th measurement value, \( S_i \) is the \( i \)th simulated value, \( M_{\text{mean}} \) is the measured mean value, and \( N \) represents the total number of data points.

The closer the values of MAE and RMSE are to 0, PBIAS is \([-10, 10]\), and the closer NSE is to 1, the smaller the difference between the simulated value and the measurement value, i.e., the better they fit with each other [35].

3. Results and discussion

3.1. Simulation of influential factors of VLSI

3.1.1. Initial water content of soil. When \( D=4 \) cm, \( L=20 \) cm and \( B=40 \) cm, the soil infiltration rate of VLSI under three soil textures, i.e., \( \theta_0=50\% \), 60\% and 70\% FC, was simulated (Figure 3).

As shown in Figure 3, the initial water content mainly affects the soil infiltration rate in the initial stage of infiltration, and the influence decreases with the increase of the initial water content, which has little effect on the stable infiltration rate. In the initial stage of irrigation when the soil is unsaturated, the infiltration rate is affected by the matric potential. The larger the initial water content, the smaller the soil water suction (the larger the matric potential), resulting in a decrease in the initial infiltration rate. In addition, the Genuchten–Mualem model (Equation (2)) was used to calculate the matric potential corresponding to 50\%, 60\% and 70\% FC. It was found that the differences between the three were not significant, especially in the case of sandy soil. Hence, the water content interval has a weak influence on the soil infiltration rate.

3.1.2. Buried depth of the irrigation emitter. When \( D=4 \) cm, \( L=20 \) cm and \( \theta_0=60\% \) FC, the soil infiltration rate of VLSI under three soil textures (\( B=30 \) cm, 40 cm and 50 cm) was simulated (Figure 4).

As shown in Figure 4, the buried depth of the line source has little effect on the soil infiltration rate. Without considering the influence of internal air resistance, a change in the buried depth will not lead to any change in the soil hydraulic gradient \( \nabla h \) and hydraulic conductivity \( K(h) \). Therefore, according to Darcy’s law \( (q=K(h) \nabla h) \), the soil water flux remains unchanged.
3.1.3. Diameter of the irrigation emitter. When $L=20$ cm, $B=40$ cm and $\theta_0=60\%$ FC, the soil infiltration rate of VLSI under three soil textures ($D=2$ cm, 4 cm and 6 cm) was simulated (Figure 5).

As shown in Figure 5, the soil infiltration rate is positively correlated with the diameter of the line source, and the soil infiltration rate increases as the diameter of the line source increases. Thus, the diameter of the line source has a strong influence on the soil infiltration rate. The increase in the diameter of the line source causes an increase in the line source water seepage area, which increases the interfaces (or channels) for water to infiltrate into the soil, resulting in an increase in the soil infiltration rate.

3.1.4. Length of the irrigation emitter. When $D=4$ cm, $B=40$ cm and $\theta_0=60\%$ FC, the soil infiltration rate of VLSI under three soil textures ($L=30$ cm, 40 cm and 50 cm) was simulated (Figure 6).

As shown in Figure 6, the soil infiltration rate is positively correlated with the length of the line source, and the soil infiltration rate increases as the length of the line source increases. Therefore, the length of the line source exerts a strong influence on the soil infiltration rate. The increase in the length of the line source causes an increase in the line source water seepage area, which increases the channels for water to infiltrate into the soil, resulting in an increase in the soil infiltration rate.

3.2. Influential factors of infiltration parameters

Based on the above analysis, the soil infiltration rate of VLSI is mainly affected by soil texture as well as the diameter and length of the line source, whereas the initial water content and buried depth of the line source have little influence on the soil infiltration rate.

To fully reveal the differences in soil textures and the universality of the research results, eight soil textures (Table 1) were selected. Five diameters of the line source (2 cm, 3 cm, 4 cm, 5 cm and 6 cm) and five lengths of the line source (10 cm, 15 cm, 20 cm, 25 cm and 30 cm) were evaluated for each soil texture, totaling 200 simulation scenarios. During the simulations, the initial soil moisture content was 60% FC, the buried depth of the line source was 40 cm and the irrigation water quota was 40 L.

3.2.1. Infiltration parameter $S$. Based on the HYDRUS simulation results, the soil sorptivity $S$ was obtained through numerical fitting conducted according to Equation (7). Figure 7 shows the sorptivity $S$ of three different soil textures under different diameters and lengths of the line source.
Figure 7. Variation of sorptivity $S$ with diameters and lengths of the line source: a Clay loam, b Loam, c Sandy loam.

As shown in Figure 7, sorptivity $S$ is greatly affected by the soil texture, and given the same soil texture, sorptivity $S$ increases with increases in $D$ and $L$. The power function used for fitting was expressed as:

$$S = m_1 D^{m_2} L^{m_3}$$

(12)

Where $m_1, m_2$, and $m_3$ are undetermined parameters.

3.2.2. Infiltration parameter $A$. Based on the HYDRUS simulation results, steady infiltration rate $A$ was obtained through numerical fitting conducted per Equation (7). Figure 8 shows the steady infiltration rate $A$ of three different soil textures under different diameters and lengths of the line source.

Figure 8. Variation of steady infiltration rate $A$ with diameters and lengths of the line source: a Clay loam, b Loam, c Sandy loam.

As shown in Figure 8, steady infiltration rate $A$ is greatly affected by soil texture, and under the same soil texture, steady infiltration rate $A$ increases with increases in $D$ and $L$. The power function used for fitting is expressed as:

$$A = n_1 D^{n_2} L^{n_3}$$

(13)

Where $n_1$, $n_2$, and $n_3$ are undetermined parameters.

Due to the spatial variability of soil texture, the soil textures of farmland in different areas may vary greatly and are unlikely to change. Therefore, in irrigation engineering, parameters should be designed according to the soil textures.
Based on the HYDRUS simulation results, the undetermined parameters $m_1, m_2, m_3, n_1, n_2$ and $n_3$ of sorptivity $S$ and steady infiltration rate $A$ were obtained through numerical fitting conducted per Equations (12) and (13), as shown in Table 2.

| Soil texture          | $S$   | $A$   |
|-----------------------|-------|-------|
|                       | $m_1$ | $m_2$ | $m_3$ | $R^2$ | $n_1$ | $n_2$ | $n_3$ | $R^2$ |
| Sand                  | 1.51  | 0.76  | 1.3   | 0.999 | 16.2  | 0.53  | 0.56  | 0.993 |
| Loamy sand           | 3.44  | 0.76  | 1.07  | 0.999 | 7.49  | 0.5   | 0.56  | 0.994 |
| Sandy loam           | 2.38  | 0.78  | 1.02  | 0.998 | 2.96  | 0.45  | 0.56  | 0.994 |
| Sandy clay loam      | 2.4   | 0.63  | 0.91  | 0.997 | 0.57  | 0.45  | 0.56  | 0.988 |
| Loam                 | 2.56  | 0.65  | 0.93  | 0.999 | 0.86  | 0.43  | 0.57  | 0.989 |
| Silt loam            | 2.51  | 0.66  | 0.89  | 0.987 | 0.51  | 0.37  | 0.56  | 0.988 |
| Silt                 | 2.33  | 0.6   | 0.88  | 0.982 | 0.29  | 0.41  | 0.56  | 0.99  |
| Clay loam            | 1.92  | 0.61  | 0.88  | 0.985 | 0.24  | 0.35  | 0.54  | 0.99  |
| Average value        | 0.69  | 0.99  | 0.994 |       | 0.44  | 0.56  | 0.991 |       |

As shown in Table 2 and based on Equation (12), $R^2 \geq 0.982$ and the average value is 0.994. According to Equation (13), $R^2 \geq 0.988$ and the average value is 0.991. This indicates that parameters $S$ and $A$ of the Philip infiltration model can be determined by fitting the infiltration data by Equations (12) and (13) with high accuracy.

Further analysis indicates that under different soil textures, undetermined parameters $m_2, m_3, n_2$ and $n_3$ experience little changes. To simplify the calculation, the average values of the four parameters were taken, i.e., $m_2=0.69$, $m_3=0.99$, $n_2=0.44$ and $n_3=0.56$. By substituting them into Equations (12) and (13), the following equations were obtained:

\[ S = \alpha D^{0.69} L^{0.99} \]  \hspace{1cm} (14)

\[ A = \beta D^{0.44} L^{0.56} \]  \hspace{1cm} (15)

Based on Equations (7), (14) and (15), the simplified estimation model of the soil infiltration rate of VLSI was obtained as follows:

\[ i = 0.5 \alpha D^{0.69} L^{0.99} t^{-0.5} + \beta D^{0.44} L^{0.56} \]  \hspace{1cm} (16)

Equation (16) has only two undetermined parameters, which can be obtained based on only one VLSI experiment.

### 3.3. Model verification and evaluation

The aeolian sand and sandy loam in the Minqin region of the Hexi Corridor, China, were used to conduct the VLSI experiment. One experimental treatment ($D=4$ cm, $L=25$ cm) was adopted to determine the fitting parameters for Equation (16) and obtain the estimation models of the soil infiltration rate of VLSI of two soils, namely,

Minqin aeolian sand:

\[ i = 3.1 D^{0.69} L^{0.99} t^{-0.5} + 10.7 D^{0.44} L^{0.56} \]  \hspace{1cm} (17)

Minqin sandy loam:

\[ i = 1.5 D^{0.69} L^{0.99} t^{-0.5} + 1.4 D^{0.44} L^{0.56} \]  \hspace{1cm} (18)

The vertical line source infiltration experiment with different line source diameters (3 cm and 5 cm) and different line source lengths (20 cm and 30 cm) was carried out indoors. The calculated values were compared with the measurement values, as shown in Figure 9(a) and 9(b).
To more comprehensively evaluate the model established in this study, Cheng compared Minqin aeolian sand and sandy loam with clay loam in the Shanshan region of Turpan, China [36]. One experimental treatment ($D=2$ cm, $L=20$ cm) was adopted to determine the fitting parameters for Equation (16) to obtain the estimation model of the soil infiltration rate of VLSI of Shanshan clay loam:

$$i = 0.14D^{0.69}L^{0.99}t^{-0.5}$$ \hspace{1cm} (19)

Verification was performed based on the measurement values of the other five line source diameters and line source lengths (Figure 9(c)).

The statistical characteristics of the calculated and measurement values were analyzed using Equations (8) ~ (11). The MAE, RMSE, PBIAS and NSE results are shown in Table 3.

**Table 3.** Statistical analysis of calculated and measured values.

| Soil texture      | MAE/(L h$^{-1}$) | RMSE/(L h$^{-1}$) | PBIAS/(%) | NSE/(-) |
|-------------------|------------------|-------------------|-----------|---------|
| Minqin aeolian sand | 0.348            | 0.442             | 2.340     | 0.973   |
| Minqin sandy loam  | 0.058            | 0.073             | 2.893     | 0.996   |
| Shanshan clay loam | 0.118            | 0.137             | 1.642     | 0.983   |

As shown in Table 3, MAE and RMSE are close to zero, PBIAS is 1.642%~2.839%, and NSE is close to 1 (NSE is $\geq 0.973$), indicating that the values calculated by the simplified estimation model are in good agreement with the measured values. Therefore, this model is able to estimate the soil infiltration rate of VLSI under different diameters and lengths of the line source. The simplified estimation model established in this study has only two undetermined parameters that can be obtained based on a single set of experimental data, simplifying the experimental scheme and improving the work efficiency. At a later stage, the quantitative relationship between the coefficient of the power function and the soil texture should be further analyzed to investigate the possibility of estimating the soil infiltration rate of VLSI based on soil physical parameters under different soil textures.

**4. Conclusions**

Numerical simulations carried out in this study show that soil texture has a significant impact on the soil infiltration rate of VLSI. Given the same soil texture, the diameter and length of the line source rather than the initial water content and buried depth of line source are the dominant influential factors of the soil infiltration rate of VLSI. On this basis, the Philip infiltration model was used to analyze the infiltration rate, and it was concluded that both sorptivity ($S$) and steady infiltration rate ($A$) increase as the diameter ($D$) and length ($L$) of line source increase; the relationship between $S$ and $D$ and $L$ and that between $A$ and $D$ and $L$ can be fitted by a power function. The exponential value of the power function,
function was determined based on the HYDRUS simulation results, thereby obtaining a simplified estimation model of the soil infiltration rate of VLSI containing D and L. The effectiveness of the simplified model was verified based on a laboratory experiment and currently available research. The MAE was 0.056–0.348 and the RMSE was 0.073–0.442, i.e., both are close to zero. PBIAS was 1.642–2.893 and NSE was close to 1 (NSE≥0.973), indicating that the model has high calculation accuracy and can be used for estimating and analyzing the soil infiltration rate of VLSI.

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