Research on the infiltration processes of lawn soils of the Babao River in the Qilian Mountain

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ABSTRACT

Using a Guelph Permeameter, the soil water infiltration processes were analyzed in the Babao River of the Qilian Mountain in China. The results showed that the average soil initial infiltration and the steady infiltration rates in the upstream reaches of the Babao River are 1.93 and 0.99 cm/min, whereas those of the middle area are 0.48 cm/min and 0.21 cm/min, respectively. The infiltration processes can be divided into three stages: the rapidly changing stage (0–10 min), the slowly changing stage (10–30 min) and the stabilization stage (after 30 min). We used field data collected from lawn soils and evaluated the performances of the infiltration models of Philip, Kostiakov and Horton with the sum of squared error, the root mean square error, the coefficient of determination, the mean error, the model efficiency and Willmott's index of agreement. The results indicated that the Kostiakov model was most suitable for studying the infiltration process in the alpine lawn soils.

Key words | Babao River, infiltration model, Qilian Mountain in China, soil infiltration process

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INTRODUCTION

Soil infiltration refers to the process of rainwater seepage from soil surface to form soil water. It is an important link between the precipitation, surface and soil water and groundwater mutual conversion processes.

Soil infiltration controls soil moisture (Braud *et al.* 1999) and influences the evaporation processes (Rana & Katerjin 2000; Wang 2005). Studies on soil infiltration process have important significance for understanding regional runoff and water relationships. The numerical simulation of the soil infiltration process is helpful in improving the model accuracy of the land water cycle and can evaluate the influence of different soil types and land use on soil infiltration (Liu *et al.* 2003). There are different infiltration models: the Green-Ampt equation (Green & Ampt 1911), the Kostiakov experience formula (Kostiakov 1932), the Horton formula (Horton 1940), the Philip equation (Philip 1957), the Fang-zhengsan general empirical formula and the Jiang Dingsheng empirical formula (Fang 1958; Jiang & Huang 1986). These models enhance the understanding of soil infiltration processes and provide numerical calculation methods and a theoretical basis for the hydrological models.

The Qilian Mountain controls the water resources balance of the Heihe River basin in China. The Babao River is a major water source in the Heihe basin, which affects not only the economic and social sustainable development of the local area but also that of the middle and lower reaches in the basin. Because the soil water infiltration process controls underground runoff and water storage of rainfall, infiltration research has important practical significance to models of the soil water storage, soil moisture optimization control and reasonable use of soil 'reservoir' regulating function, among other factors.

There is little study of infiltration models in alpine lawn soils, specifically in the region of the Babao River basin. Therefore, the study of infiltration in this area is necessary.

Using *in situ* field tests and laboratory analyses, the typical grassland soil water infiltration processes of the Babao River basin were studied, the change law of soil infiltration was discussed and a suitable infiltration model was established. This will shed some light on the mechanisms of regional runoff and regularity, as well as their relationships, for further studies. Meanwhile, it will provide a scientific basis for the choice of related hydrologic model parameters and rational utilization of water resources of the Qilian Mountain.

MATERIALS AND METHODS

Research sites and measurement

The study area is located in the upstream area of the Heihe River basin, with an average rainfall of 400 mm. The dominant species are *Kobresia parva*, *Kobresia humilis*, *Kobresia capillifolia*, *Elymus dahuricus*, *Carex*, etc.

The vegetation coverage is above 80%. The test site was chosen by the height of the Babao River. The infiltration process was conducted in a relatively flat place of the grassland. The same site test was repeated three times. The averaged result is the sample test data. The position and characteristics of the test sites are shown in Table 1.

The soil infiltration process was measured with a Guelph Permeameter. The device was developed by a professor in Canada, D. E. Elrick, and his companion. It is used to measure the soil permeability in the field based on the principle of communicating vessels (Zhang *et al.* 2003).

The experiment was performed at 20 cm depth with a 5 cm pressure head. The height of the water level was recorded every 2 min after the start of the test. The tests were stopped when the infiltration water amount was the same during three consecutive phases within the same time (2 min). The beginning permeability coefficient (cm/min), stability permeability coefficient (cm/min) and the time of infiltration are used to describe the test. The infiltration coefficient within 1 min after the start of the test is considered to be the beginning permeability coefficient.

The main soil physical properties were determined, including soil water content, particle size, organic matter and soil bulk density. A 40 cm deep soil profile was dug near each infiltration test sample site. Two samples were collected from 20 cm depth. One was used to test the soil water content. This sample needed to be weighed immediately.

After it was oven-dried at 105 °C, the sample was weighed again. The following formula is used to calculate the soil moisture content:

$$m(\%) = \frac{(m_1 - m_2)}{m_2} \times 100\% \qquad (1)$$

where m is the soil moisture content, m_1 is the weight of the initial soil and m_2 is the weight of the dry soil.

The other soil sample was dried completely in the natural environment. For this sample, 20 g of the naturally dried soil was sieved with a 2 mm aperture sieve. The soil sample that passed through the sieve was used. The organic matter content was tested on a 2 g subsample with the potassium dichromate method (Li 2011). A 0.5 g subsample was used to test the soil mechanical composition with a laser particle size analyzer. The soil mechanical composition, according to the soil particle classification standard of the USA, is divided into eight levels. These levels are clay (<0.002 mm), silt (0.002–0.05 mm), very fine sand (0.05–0.1 mm), fine sand (0.1–0.25 mm), medium sand (0.25–0.5 mm), coarse sand (0.5–1 mm), very coarse sand (1–2 mm) and gravel (>2 mm). In addition, a sample was taken from 20 cm depth in the soil profile with a 5×5 cm corer and was tested for soil bulk density.

Infiltration models to evaluate

There are many types of mathematical models of soil water infiltration with different operational conditions (Zhao & Wu 2004). Based on the common infiltration model and combining previous research results, the empirical models of Kostiakov, Horton and Philip with clear physical meaning are used to test the infiltration process with what is considered to be complete and reliable experimental infiltration data.

Table 1 | The location and features of the test sites

Serial number	Longitude	Latitude	Elevation (m)	Organic matter (g/kg)	Moisture content (%)	Soil bulk density (g/kg)
1	100°32′34.9″	38°02′08.0″	3073	4.24	22.51	0.89
2	100°21′02.6″	38°05′10.1″	2994	5.76	38.48	1.22
3	100°25′03.5″	38°03′26.8″	2978	7.80	32.26	0.87
4	100°44′32.7″	38°00′19.9″	3176	4.63	38.26	0.96
5	101°02′47.4″	37°52′11.3″	3507	6.56	46.64	0.81
6	100°55′47.2″	37°59′10.6″	3528	4.71	26.18	1.38

The 1, 2 and 3 sites are located in the middle reaches, while the 4, 5 and 6 sites are located in the upper reaches.

Kostiakov model

Kostiakov proposed the following model to describe the infiltration rate (Equation (2)) (Kostiakov 1932):

$$f(t) = at^{-b} \tag{2}$$

where $f(t)$ is the infiltration rate, a ($a > 0$) and b ($0 < b < 1$) are constants without physical meaning and t is the time of infiltration. The Kostiakov model can effectively describe the infiltration process within a small time range but performs poorly at larger time scales (Zhao & Wu 2004).

Horton model

Another empirical infiltration model was proposed by Horton (1940):

$$f(t) = f_c + (f_1 - f_c)e^{-\beta t} \tag{3}$$

where f_c is the stable infiltration rate, f_1 is the initial infiltration rate and β is an empirical constant. The advantage of this model is that the infiltration rate is not infinite when t is zero, like the Kostiakov infiltration model, but equal to the initial infiltration rate. The disadvantage is that it cannot sufficiently describe the infiltration process when t is small and the infiltration rate rapidly decreases (Philip 1957).

Philip model

Philip proposed an infiltration model by taking the first two terms of the series solutions of Richards' equation (Philip 1957). The process-based Philip model is based on an infiltration model. It can be utilized to accurately understand the infiltration of water into soil. This model is as follows:

$$f(t) = f_c + \frac{1}{2}st^{-\frac{1}{2}} \tag{4}$$

where S is the soil hygroscopicity (Shukla *et al.* 2003). From Equation (4), it can be seen that, when t is close to infinite, the infiltration rate will be f_c, which can be replaced by the soil saturated hydraulic conductivity (Ks).

Model parameter estimation

The model parameters were estimated by dynamic curve fitting. In this field study, the parameters of each model introduced above were unknown. Additionally, due to the

violation of the assumptions, such as uniform soil properties and uniform initial water moisture (Dashtaki *et al.* 2009), Dashtaki *et al.* (2009) stated that the parameters of the process-based model selected in this research, the Philip model, should be estimated via the curve-fitting method. This method is similar to that used in the empirical models instead of determining those parameters by field measurements of the soil hygroscopicity and the soil saturated hydraulic conductivity.

Model evaluation

The evaluation of the infiltration models was performed by comparing the difference between predicted cumulative infiltration values and the measured values and analyzing the residual errors. Those model performance indices are addressed below.

The sum of squared error (SSE) is the difference between the measured and the predicted cumulative infiltration for a specific model. Dashtaki *et al.* used the SSE to evaluate soil infiltration models (Shukla *et al.* 2003; Dashtaki *et al.* 2009). The SSE is given below:

$$SSE_i = \sum_{j=1}^{n} (I(m)_j - I(p)_j)^2 \tag{5}$$

where $I(m)j$ is the measured cumulative infiltration for soil (i), $I(p)j$ is the predicted cumulative infiltration by the soil infiltration model (i), and j is the number of the jth infiltration measurement in one set of soil infiltration measurements (i) with a total of n cumulative infiltration measurements. Usually, a good model has a low SSE value. Therefore, SSE is employed to evaluate the performance of those researched models.

In this research, the number of observations is different for each set of infiltration measurements, which caused differences between the R^2 values. The range of R^2 is from 0 to 1. When the value is equal to 1, the model performance is perfect.

Model efficiency (EF, %) is another index to evaluate the goodness of fit (Mishra & Singh 1999; Shukla *et al.* 2003; Duan *et al.* 2011). It can be calculated by the following equations:

$$EF = (1 - D_1/D_0) \times 100 \tag{6}$$

$$D_1 = \sum_{j=1}^{n} (I(m)_j - I(p)_j)^2 = SSE_i \tag{7}$$

$$D_0 = \sum_{j=1}^{n} (I(m)_j - \overline{I(m)_j})^2 \qquad (8)$$

where $\overline{I(m)_j}$ is the mean of the observed data. There may be a case when D_1 is larger than D_0 and thus EF will be negative. Therefore, EF will be set as zero in such a case, resulting in the range of EF from 0 to 100. When EF is 100, the predicted cumulative infiltration values are in perfect agreement with the measured cumulative infiltration values (Mishra et al. 2003). For each type of lawn soil tested, the average EF for the three different sets of measurements will be used to evaluate the model performance.

Willmott's index of agreement (W), first proposed by Willmott in 1981, was also used to evaluate the model performance. It is regarded by Willmott et al. (1985) to be a specific member of the relative average error family for evaluating complex geophysical models (Willmott et al. 1985). The range of W is from 0 to 1. A W value of 1 indicates perfect agreement between the predicted and the measured infiltration rates at the same time, and, at the other extreme, a W value of 0 implies a complete disagreement. W illustrates the degree of agreement between predicted values and observed values and can be simplified as follows:

$$W = 1 - \frac{\sum_{j=1}^{n} \left[I(p)_j - I(m)_j \right]^2}{\sum_{j=1}^{n} \left[\left| I(p)_j - \overline{I(m)_j} \right| + \left| I(m)_j - \overline{I(m)_j} \right| \right]^2} \qquad (9)$$

The analysis of residual errors in this study includes the mean error (ME) and the root of the mean square error (RMSE) (Dashtaki et al. 2009). The ME is given below:

$$ME_i = \sum_{j=1}^{n} \frac{I(p)_j - I(m)_j}{n} \qquad (10)$$

The ME statistic can show whether the evaluated model over- or underestimates the observed values of cumulative infiltration (Dashtaki et al. 2009). The RMSE is shown below:

$$RMSE_i = \sqrt{\frac{\sum_{j=1}^{n} (I(p)_j - I(m)_j)^2}{n}} \qquad (11)$$

In most cases, the RMSE is larger than zero, but for perfect goodness of fit of a model, RMSE is close to zero or even equal to zero. The smaller the RMSE, the higher the calculation precision of the model (Liu et al. 2010). This means that all observed cumulative infiltration values should be close to or identical to the model-predicted cumulative infiltration values.

Finally, the mean values of ME, RMSE, EF, W, and SSE have been calculated to compare the models' performances for all the different lawn soils tested. Lower values of mean ME, RMSE, and SSE and higher values of the mean of EF and W are expected for the better infiltration models of the lawn soils in this research.

RESULTS AND DISCUSSION

Soil physical properties

In the study area, the soil organic matter content at 20 cm depth is between 4.24 and 7.80 g/kg, with an average of 5.61 g/kg. The soil moisture content varies from 22.51 to 46.64%. The values of soil bulk density are 0.81 to 1.38 (Table 1). Soil particle size is primarily silt, followed by sand (Table 2). The typical soil belongs to silt loam, based on the soil mechanical composition.

Soil infiltration process

The in situ tests show that the averaged soil initial and stable infiltration rates are 0.48 and 0.21 cm/min in the middle

Table 2 | Soil mechanical composition (%)

	< 0.002 mm	0.002–0.05 mm	0.05–0.1 mm	0.1–0.25 mm	0.25–0.5 mm	0.5–1 mm	1–2 mm
1	9.07	74.39	9.62	3.46	2.29	1.07	0.09
2	8.18	63.17	8.05	6.66	8.42	5.41	0.11
3	12.26	78.58	7.81	1.30	0.05	0.00	0.00
4	6.52	71.64	9.79	4.93	2.90	2.81	1.40
5	9.28	80.34	6.54	2.09	1.03	0.73	0.00
6	8.48	68.02	11.65	5.36	2.26	2.06	2.18

reaches of the Babao River, while those in the upper reaches are 1.93 and 0.99 cm/min, respectively (Table 3).

The infiltration processes can be divided into three stages: the rapidly changing stage (0–10 min), the slowly changing stage (10–30 min) and the stabilization stage (after 30 min). For example, in the upper reaches of the Babao River, the soil infiltration rate is obviously reduced from 1.93 to 1.14 cm/min during 0 to 10 min, and the infiltration rate variation is 0.79 units. During 10 to 30 min, the soil infiltration rate decreased slowly from 1.14 to 1.0 cm/min, with an infiltration rate variation of 0.14 units. The infiltration rates gradually achieve stability after 30 min. The soil infiltration processes in the middle reaches of the Babao River are basically the same as those in the upper reaches. During 0 to 10 min, soil infiltration rate is obviously reduced, from 0.48 to 0.27 cm/min, and the change quantity of the infiltration rate variation is 0.21 units. During 10 to 30 min, the former decreased slowly, from 0.27 to 0.22 cm/min, and the latter is 0.05 units. The infiltration rates gradually achieve stability after 30 min.

In contrast, the initial and the steady infiltration rates of the upper reaches were not only higher than those of the middle reaches, but the variation between the initial and the steady states was also larger. The infiltration rate during the early infiltration stage changed significantly as the test progressed. As the soil gradually became saturated, the rate changes became smaller.

The initial infiltration rate and the stable rate of upper reaches are larger than those of the middle reaches area. There are many factors that affect them, such as unit weight, organic matter, etc. (Bodman & Colman 1994; Li & Fan 2006). The soil bulk density of the upper reaches area is slightly lower than that of the middle reaches area.

The organic matter content, on average, is also slightly greater than that of the middle reaches area, but the difference between them is small. When the bulk densities and organic matter contents are similar, the soil's initial and stable infiltration rates are mainly affected by the soil particle size and moisture content. A soil's clay content has a large effect on the soil water infiltration capacity, whereby higher clay contents diminish the water infiltration capacity of the soil (Xie & Fan 2004; Li et al. 2009). The soil clay content of the upper reaches area is on average 8.1%, whereas that of the middle reaches area is 9.8%. Therefore, the initial and stable infiltration rates of the upper reaches are larger than those of the middle reaches. Some studies have indicated that the soil initial infiltration rate decreased along with increases in the soil moisture content (Tian et al. 2006; Xi et al. 2008; Zeng et al. 2010). However, other studies have come to the opposite conclusion. For instance, Liu et al. (2009) showed that the soil initial infiltration rate increased with increases in the soil moisture content during the initial stage of the test using the double ring infiltration method. This is consistent with the results of our tests. The results of studies on the influence of soil water content on the steady infiltration rate are also dissimilar. Some studies have shown that the stable infiltration rate decreases with increases in the soil moisture content (Wu et al. 2003; Liu et al. 2009), and others have found that the soil stability infiltration rate is completely unrelated to the natural water content (Tian et al. 2006). Still other studies have shown that the stable infiltration rate increased with increases in the soil moisture content (Liu et al. 2012). Our results agree with the latter; the steady infiltration rates were higher in areas with higher soil moisture contents in this test. For further comparative study results, the experimental conditions were listed (Table 4). The soil layer and soil particle size of Liu et al. (2009) are similar to ours. However, unlike those authors' experimental methods, no fixed waterhead pressure was used in the present study. The methods of Liu et al. (2012) were similar to ours, but the soil layer and the particle sizes were different. On the basis of earlier research, the following conclusion is put forward. Due to soil aggregate expansion and rapid disintegration, together with the blockage of the wetting of the surface of the undisturbed soil with lower moisture content, soil porosity and the pore connectivity are poor. The decrease of physical porosity, which can be permeable, makes the initial and stable infiltration rates decrease. On the contrary, when the moisture content is higher, these phenomena will not occur, and the initial and steady infiltration rates increase with increases in the water content.

Table 3 │ The estimated parameters of the three evaluated soil infiltration models for lawn soils in the Babao River basin

| Models | Kostiakov | | Horton | | | Philip |
	a	b	f_c	f_1	k	s
1	0.58	0.25	0.21	0.65	0.10	0.32
2	0.49	0.16	0.29	0.50	0.14	0.14
3	0.34	0.25	0.12	0.30	0.08	0.31
Mean	0.47	0.22	0.21	0.48	0.10	0.26
4	1.85	0.27	0.81	1.65	0.18	0.74
5	1.76	0.17	0.92	1.55	0.09	0.70
6	2.17	0.23	1.23	2.60	0.36	0.62
Mean	1.93	0.22	0.99	1.93	0.21	0.68

Table 4 | The experimental conditions

	Liu *et al.* (2012)	Liu *et al.* (2009)
Viewpoint	With increases in the initial water content, the initial infiltration rate decreases and the steady infiltration rate increases	With increases in the initial water content, the initial infiltration rate increases and the steady infiltration rate decreases
Soil layer	0–5 cm	20–30 cm
Experimental method	Fixed waterhead pressure of 5 cm Double-ring method was used to examine soil infiltration	No fixed waterhead pressure Artificial rainfall Double-ring method was used to examine soil infiltration
Particle size	< 0.002 mm, 20–30% 0.05–2 mm, 35–40%	< 0.001 mm, 12%; 0.001–0.005, 22% 0.005–0.01, 13%; 0.01–0.05, 44% 0.05–0.25, 8.6%; 0.25–1, 0.4%

In addition, during the field observations it was found that the vegetation types of the middle and upper reaches are different. The roots of the 3–15 cm high vegetation are primarily near the surface in the upper reaches area. The distribution depths of the root systems are larger and relatively sparse in the middle reaches area, where the vegetation height is 10–30 cm. Due to the blocking effect of plant roots, the infiltration rates were reduced (Cheng 2008). This is one of the reasons that explain why the initial and the steady infiltration rates of the upper reaches area are greater than those of the middle reaches area.

Model parameters

The typical infiltration process was simulated with the Kostiakov, Horton and Philip models. The infiltration simulation parameters are shown in Table 3.

In the Kostiakov model, the 'a' reflects the size of the difference between the initial infiltration rate and the steady infiltration rate. If the 'a' is large, the difference between the initial infiltration rate and the steady infiltration rate is large; if the 'a' is small, the difference between initial infiltration rate and the steady infiltration rate is small. Based on the correlation analysis of the Kostiakov model's simulated values and the measured values, the results show that the parameter 'a' in the model changes between

0.34 and 2.17. The numerical value in the lower elevation region is small, with an average of 0.47. In the higher elevation region, the numerical value is larger, with an average of 1.93. The value of 'a' in the higher elevation region is significantly higher than that in the lower elevation region, which signifies that the difference between the initial infiltration rate and the steady infiltration rate is large in the higher elevation region. Compared with 'a', the value of 'b' ranges between 0.16 and 0.27 and is relatively stable. This indicates that the infiltration rates of all test sample sites are not very large (Liu & Kang 1997).

The parameter 'k' in the Horton model ranges from 0.08 to 0.36. The 'k' reflects the changes in the slope of the infiltration curve. If 'k' is larger, the infiltration rate decreases faster (Zhao & Wu 2004). The results show that the numerical value of 'k' in the lower elevation region is small, with an average of 0.10. In the higher elevation region, the numerical value is larger, with an average of 0.21.

Model performance

The values of the SSE, the RMSE and R^2 values are listed in Table 5 for the three soil infiltration models.

The Kostiakov model had the lowest SEE and RMSE, and the Horton model had the second lowest results, with respect to SSE and RMSE. The theoretically based Philip model was found to be the worst model to describe the infiltration in the studied lawn soils, with respect to SSE and RMSE.

Reviewing the values of R^2 indicates that the Philip model had a better correspondence between measured and predicted infiltration rates. The Horton model had a lower R^2.

Overall, based on the SSE and RMSE results, both the Kostiakov and Horton models were the best at predicting the observed infiltration data for the lawn soils.

Table 6 lists mean error (ME), model efficiency (EF) and Willmott's index of agreement (W) values of the evaluated soil infiltration models for the individual test point at each research site. On average, the Horton model overestimated the cumulative infiltration in the lawn soils because the ME values were positive, while the other two models underestimated the infiltration and featured negative ME values.

Based on the overall mean values, the Kostiakov and Philip models systematically underestimated the cumulative infiltration in the lawn soils. The absolute value of the mean of the Kostiakov model ME was 0.0019, and that of the Philip model was 0.0296. The Horton model performed best in estimating the infiltration because its absolute value of the average ME is the smallest for the tested lawns.

Table 5 | SSE, RMSE and R^2 of the three evaluated soil infiltration models for lawn soils in the Babao River basin

Models	Kostiakov			Horton			Philip		
	SSE	RMSE	R^2	SSE	RMSE	R^2	SSE	RMSE	R^2
1	0.0328	0.0306	0.8741	0.0508	0.0381	0.8375	0.1386	0.0629	0.9455
2	0.0069	0.0182	0.8728	0.0044	0.0145	0.9246	0.0362	0.0415	0.9519
3	0.0015	0.0109	0.9533	0.0030	0.0152	0.9145	0.0100	0.0277	0.9519
4	0.0410	0.0405	0.9667	0.0945	0.0615	0.9685	0.7363	0.1716	0.9880
5	0.0446	0.0564	0.8841	0.0428	0.0553	0.9046	0.2446	0.1322	0.9527
6	0.2598	0.1274	0.8704	0.2142	0.1157	0.9042	1.3198	0.2872	0.9356
Mean	0.0644	0.0473	0.9036	0.0683	0.0501	0.9090	0.4143	0.1205	0.9543
Model rank	1	1	3	2	2	2	3	3	1

SSE is the sum of the squared error; RMSE is the root mean square error; R^2 is the coefficient of determination.

Table 6 | ME, EF and W of the three evaluated soil infiltration models for lawn soils in the Babao River basin

Models	Kostiakov			Horton			Philip		
	ME	EF	W	ME	EF	W	ME	EF	W
1	− 0.0015	85.3342	0.9528	0.0100	77.2902	0.9482	− 0.0148	37.9995	0.6059
2	− 0.0006	86.6042	0.9542	0.0014	91.4197	0.9749	− 0.0102	29.8732	0.5205
3	− 0.0003	95.2952	0.9876	0.0017	90.7997	0.9772	− 0.0095	69.3896	0.8662
4	− 0.0014	96.3621	0.9901	− 0.0167	91.6044	0.9727	− 0.0434	34.5926	0.5760
5	− 0.0016	87.8183	0.9639	0.0011	88.3169	0.9633	− 0.0319	33.1490	0.5562
6	− 0.0058	85.6698	0.9552	0.0025	88.1879	0.9627	− 0.0676	27.2154	0.4888
Mean	− 0.0019	89.5140	0.9673	0	87.9365	0.9665	− 0.0296	38.7032	0.6023
Model rank	2	1	1	1	2	2	3	3	3

ME is the mean error; EF is the model efficiency; W is Willmott's index of agreement.

The Kostiakov model had the highest EF, while W and the Horton model followed. The model rankings based on the EF and W values were similar to the model rankings based on the SSE and RMSE.

To compare the overall performance of the three evaluated soil infiltration models, the model rankings were summed up as the final score given in Table 7. The scores are the sum of the model ranking numbers with respect to mean SSE, mean RMSE, mean R^2, mean ME, mean EF,

and mean W. Finally, the Kostiakov model was the best at describing and predicting the cumulative infiltration in the studied lawn soils.

CONCLUSIONS

Through *in situ* tests, the soil infiltration processes in the Babao River basin in China were studied. The results showed that the infiltration rate decreases over time. The initial infiltration rate and the steady infiltration rate of the upstream area are larger than those of the middle area. The initial and the steady infiltration rates were higher in areas with higher soil water content. The differences between our results and other research results require further study. The infiltration rate changes rapidly during 0 to 10 min, then the rate of change slows during

Table 7 | Overall ranking of three evaluated soil infiltration models for lawn soils in the Babao River basin

Models	Kostiakov	Horton	Philip
Scores	9	11	16
Final ranking	1	2	3

10 to 30 min and the infiltration after 30 min gradually stabilizes.

The Philip, Kostiakov and Horton models were selected to fit the infiltration data. By evaluating the fitting results, the results indicated that it is best to fit the infiltration process using the Kostiakov model in the alpine lawn soils.

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