Methods for measuring soil infiltration: State of the art

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Abstract: Soil infiltration is the process by which water on the soil surface penetrates the soil. Quantifying the soil infiltration capacity (soil infiltrability) is very important for determining components of the hydrological modeling, irrigation design and many other natural or man made processes. In this paper, commonly used methods for soil infiltration rate measurement with their principles and application conditions are introduced. The advantages and disadvantages of each method under various application conditions are discussed for comparison. Three new methods for soil infiltrability measurement, including the corresponding algorithm models, and the experimental apparatus and procedures are introduced. These analyses should facilitate the choice of method used for soil infiltrability measurement.
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1   Introduction

Infiltration is the process by which water on the soil surface penetrates the soil. It is related to overland flow and groundwater, determining the fraction of the irrigation or rain water entering the soil and, thus, affecting the amount of runoff responsible for subsequent soil erosion[1]. Quantifying the soil infiltration capacity, or soil infiltrability, is of great importance to understanding and describing the hydrologic analysis and modeling.

Infiltration can be quantified by the soil infiltrability, and/or cumulative infiltration. The units for these two parameters are usually given in mm/min or mm/h, and mm or cm, respectively[2].

Soil infiltration rate and the cumulative infiltration are related by Eq. (1):

$$i = \frac{dI}{dt} \tag{1}$$

Where i is the infiltration rate, mm/h; t is time, h; I is the cumulative infiltration, mm[3,4].

Generally, during an infiltration event, the comparatively very high initial soil infiltrability decreases rapidly with time. The rate of decrease slows down exponentially and the infiltration rate gradually reaches a steady state, i.e., the steady or final infiltration rate. The final soil infiltration rate is equal to, or very close to, the saturated hydraulic conductivity. It usually takes two to three hours for the soil infiltration process to reach the final infiltration rate[5].

Soil infiltrability is determined by the matric potential gradient at the soil surface. The high initial soil infiltration rate is related to the relatively high matric potential gradient of an initially dry soil. The soil suction gradient decreases with the increase of wetted soil depth. The soil infiltrability is affected by time, soil texture and structure, initial soil moisture content, topography, soil surface cover conditions, rainfall intensity, etc.

The soil infiltration rate is closely related to soil conditions, including soil texture, aggregate stability, cracks and crusts at the soil surface. Sandy soils and soils

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with stable aggregates have much higher infiltrabilities than the silty soil. The swelling in clay soils can further reduce the soil infiltrability. The presence of macro pores and the consequent high soil porosity promotes the infiltration process.

Soil moisture content may affect soil infiltration as follows. Generally, the lower the initial soil moisture content is, the higher the initial soil infiltration rate will be. The wetting front clearly separates the wetted and the initially dryer soil during the infiltration process. At the wetting front, the suction gradient decreases with an increase in initial soil moisture content thus lowering the soil infiltration rate.

The soil infiltration process is also influenced by the water supply at the soil surface. When the inflow rate of the water supply is lower than the soil infiltrability, the soil infiltration process is controlled by the inflow rate, i.e., the infiltration rate is equal to the inflow rate. When the inflow rate is higher than the soil infiltrability, water cannot be totally absorbed by the soil. Overland flow or runoff occurs in this situation. The soil infiltration process is then controlled by the soil infiltrability, which is called as the profile control stage.

Plants and vegetative residues upon the soil surface can maintain soil structure, reduce raindrop impact-induced surface sealing, promote soil infiltration and minimize runoff and soil erosion. The infiltration rates of soil under plant cover are, therefore, usually higher than those of a bare surface.

The topography of a watershed or a hill-slope refers to generally as slopes, and the combinations of soil surface properties, the orientation of the slopes and the micro-topography of the soil surface, also affect soil infiltration processes [6,7].

The preceding descriptions are based on the assumption that the soil structure is stable whereas, in fact, the structure of the soil, especially that on the soil surface, is often unstable. The soil infiltration rate changes greatly with time because of the changes in the soil surface conditions affected by the disintegration of soil aggregates, surface seal formation and formation of air pockets inside the soil.

The soil infiltration process was conceptually illustrated by Darcy in Eq. (2).

$$i = -K_s \frac{\Delta H}{\Delta z} \qquad (2)$$

Where K_s is the saturated hydraulic conductivity, mm/h; $\Delta H/\Delta z$ is the hydraulic gradient, mm/mm, as determined by an increase or decrease in hydraulic pressure at the soil surface (ΔH) with soil depth (Δz).

The hydraulic pressure is controlled by the soil suction and gravity at the wetting front. The infiltration driving force, $\Delta H/\Delta z$, depends on the matric suction and elevation potential at the wetting front. The suction gradient is initially very high, which results in high soil infiltrability. Increase in the wetted soil depth causes decrease in the suction gradient until soil infiltrability reaches the steady stage, when it is controlled by the elevation potential at the soil surface and the suction gradient is negligible.

The initial soil infiltrability is high because of the large adsorption force of the dry soil particles. The second stage of the infiltration process starts once the soil water content is higher than the maximum molecular water holding capacity. The water movement among the soil particles in this stage is controlled mainly by capillary forces and gravity. Under these forces, the air inside the soil is replaced by water. However, some air usually remains trapped within the soil profile as air bubbles that may subsequently restrict the movement of infiltrating water. The soil infiltrability decreases sharply during this period until the soil is totally saturated. The fast decrease in soil infiltrability is due to the short period during which the capillary forces act within the soil since these cease as the pores fill with water. Sometimes the first two stages are combined as a leakage stage because the soil is unsaturated until the end of the second stage.

Water infiltration is controlled by gravity alone when the soil is totally saturated in the third stage, which is the steady infiltration period. Water movement during this period maintains a steady flow rate inside the saturated soil.

The two main stages of the soil infiltration process introduced above may occur simultaneously and cannot be distinguished clearly, especially when the soil infiltration process takes place in thicker soil layers.

The wetted soil profile can be divided into several zones vertically. Under sufficient water supply, there is a very thin layer of ponded water upon the soil surface. The soil under this water layer is totally saturated and referred to as the saturated zone. Below the saturated zone, the soil water content decreases to form the transitional zone. The soil water content of this layer is about 60%～80% of the saturated soil moisture content. The water movement is controlled mainly by gravity within the zone. Below this zone is the wetting front that separates the wetted soil from the dry soil[5].

Different methods have been used to measure soil infiltrability such as direct measurement and watershed methods. The direct measurement methods are usually

conducted on a small area where the infiltration curve at a particular location can be determined directly. The watershed method is applied to an entire watershed as indicated by its name. The rainfall intensity and total runoff during a rainfall event are measured to estimate the infiltration rate and/or cumulative infiltration. The soil infiltration rate measured by this method is thus an average value for the whole watershed [8].

A number of methods have been developed for soil infiltrability measurement, such as the double ring infiltrometer method[9], the modified double-ring or Mariotte-double ring method[10], rainfall simulation[11,12], modified rainfall simulation[13,,14], the run off-on-ponding method[15], the run off-on-out method[16], the disc permea-meter method[17,18]; and the linear source method[8].

2   Infiltration under unlimited water supply conditions

2.1   Ring infiltrometer

The single ring and double-ring methods are the most commonly used soil infiltration rate measurement methods. The principles of these two methods are very similar. The experimental apparatus, limitations, advent-ages and disadvantages of these two methods are discussed below.

The single ring method usually uses one ring of 30 cm or a little larger in diameter and 20 cm in height. The double ring method uses an outer ring of about 60 cm in diameter and the same height as an inner ring positioned in its center that is the same as that used in the single ring method. These two rings need to be strong enough to withstand being forced into the soil without any distortion. Figures 1a and 1b show the single ring and double-ring devices, respectively.
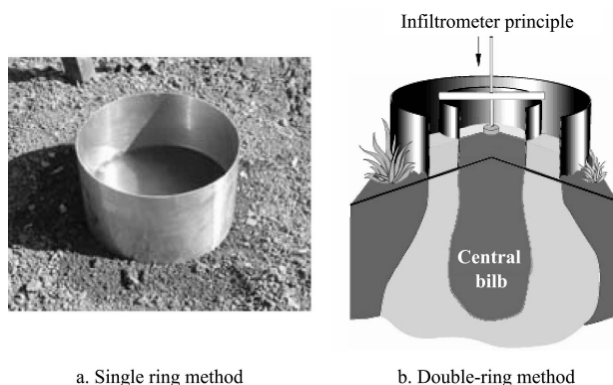

a. Single ring method   b. Double-ring method

Figure 1   Single ring and double-ring method device[11]

The main experimental procedures associated with those two methods are detailed below.

The single ring method is carried out in exactly the same manner as the double ring method but lacks the outer ring that is used to ensure the vertical movement of the water from the inner ring thus greatly reducing the horizontal leakage that occurs in the single ring method.

In the double ring method, the rings are carefully forced 10 cm deep into the soil, concentrically, avoiding undue disturbance of the soil surface. The heights of the two rings above the soil surface should be kept approximately at the same level. Water is added within the two rings simultaneously and 5-cm depth of water in both of them is then maintained throughout the experiment. The water volume supplied to the inner ring, in order to maintain a constant head of water, is recorded as a function of time and then used for infiltrability computation. The average soil infiltration rate for a given time period is estimated from the volume of the water supplied to the inner ring divided by the area of the inner ring.

These methods can both be conveniently applied to the field conditions because of the simple experimental apparatus and straightforward mathematical model.

There are several problems with the ring method. The initial soil infiltration process is likely to be limited by insufficient water supply. As described above, under these conditions the soil infiltration process is controlled by the inflow rate instead of the actual initial soil infiltrability. To maintain the depth of water inside the rings, a very high flow rate of water should be added within a short period of time when the infiltration process starts. Furthermore, when using these high flow rates, rapid wetting of the soil surface occurs that probably causes disintegration of surface soil aggregates due to slaking, which can enhance surface seal formation that lowers soil infiltrability dramatically. The soil structure is also inevitably disturbed when the double rings are forced into the soil. It is very difficult to measure the original soil infiltrability with either the double-ring or single ring method. Finally, the ring methods cannot be used on a sloping soil surface.

2.2   Mariotte-double ring method

The device used in the Mariotte-double ring method consists of two major parts: the cumulative infiltration measurement device comprising a Mariotte bottle and modified double rings, and the device for soil water content measurement by the gamma ray detection method consisting of a radioactive source, detector and access tube.

The major principles of the Mariotte double-ring method are described below. The Mariotte bottle and the

double-ring method are combined to control the water supply to the inner ring. This improves the accuracy of the water supply during the experiments. The gamma ray detector is used to monitor soil water content changes over time within the soil profile. The relative error is estimated by comparing the cumulative infiltration and the water content distribution using the mass balance principle.

The Mariotte double-ring method improved the accuracy of the double-ring method. Furthermore, the real-time distribution of the water contents during the experiment can be observed to estimate the relative error of the experiment. However, the defects of the Mariotte double-ring method are that the experimental apparatus is relatively complicated and expensive for use in field experiments. This method does not address the problems

associated with the double-ring method such as being limited to level soil surfaces and the disturbance of the initial soil structure. Additionally, the potential hazard incurred when using the radioactive gamma ray source is a major concern regarding the health and safety of the operator.

3 Disc permeameter

Brent Clothier and Ian White developed the sorptivity tube which provides a constant negative potential (tension) at the soil surface. Modifications to the design led to the development of the disc permeameter, which is also known as the tension infiltrometer, by Perroux and White[22] of CSIRO. The experimental apparatus is shown in Figure 2.
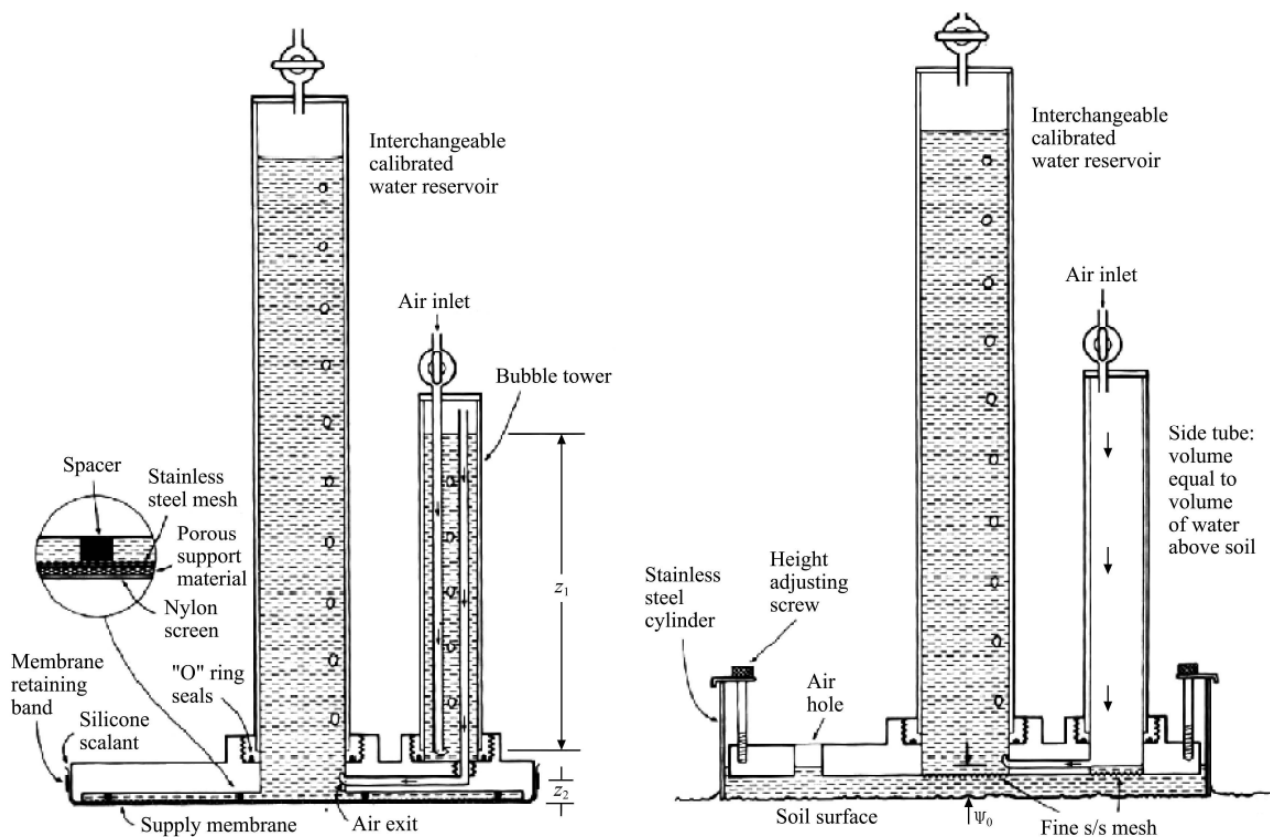
Note: z_1, z_2 are evaluation differences inside the Mariotte bottle. ψ_0 is matric potential

Figure 2 Experimental apparatus of the CSIRO disc permeameter for tension (left) and ponded (right) infiltration

The disc permeameter comprises a nylon mesh supply membrane (around $10\sim40$ mm in diameter), a water reservoir and a bubbling tower. The bubbling tower is connected to the reservoir and is open to the air.

The first stage of the infiltration process is controlled by the soil capillaries for a given depth of water on the soil surface. The steady infiltration rate may be attained for a homogenous soil and is determined by the

capillaries, gravity, the ponding area and the water head at the soil surface. The disc permeameter can indicate whether the water flow into the soil is controlled mainly by the capillaries or by gravity. The size of the soil pores can be measured by changing the hydraulic head of the water supply.

Comparisons made between the double-ring and disc permeameter methods are made in Table 1.

	Double-ring	Disc permeameter
Total water needed in an experiment	30 L	2 L
Initial infiltrability	can not be observed	can be estimated
Experiment time	2–6 h	30 min
Water head	5 cm	Adjustable
Infiltrated zone	50 cm in depth and 30 cm in diameter	20–30 cm in depth and 20 cm in diameter
Lateral infiltration	No	Exists
Initial infiltrability	can not be observed	can be estimated

4   Infiltration under rainfall conditions

4.1   Rainfall simulator method

Rainfall simulators can be used for soil infiltration rate measurements as described by Amerman et al.[19], Zegelin and White[20], Peterson et al. [11] and Odgen [,12] among many others. Simulated rainfall, similar to that occurring under natural rainfall conditions, is sprayed at a controlled rate onto the soil surface to be studied. Overland flow is collected and recorded as a function of time for a given rainfall intensity. Soil infiltration is then calculated from the difference between rainfall intensity and runoff rate. The experimental apparatus, used by Odgen, is shown in Figure 3.
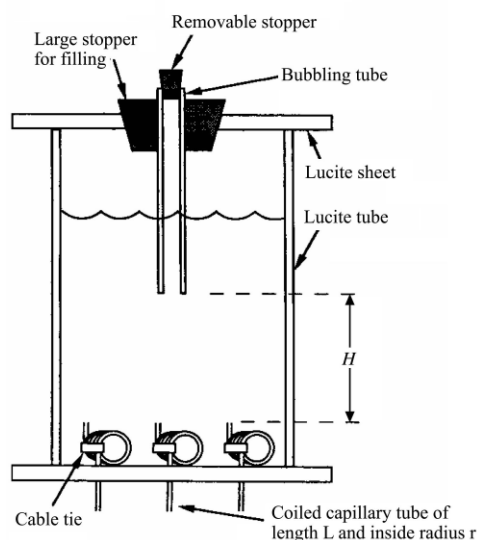
Figure 3   Schematic of a rainfall simulator[12]

The relationship between the rainfall intensity and soil infiltration rate is given by:

$$P - R = I + V_d + D_a + I_s \qquad (3)$$

Where P is the depth of cumulated rainfall, mm; R is the runoff, mm; I is the cumulative infiltration, mm; V_d is the ponded water depth in puddles, mm; D_a is the water stored in the microtopography, mm; and I_s is the water intercepted by plant canopies, mm.

V_d and I_s are neglected if there are no puddles or plants on the experimental site. D_a is usually very small compared with the other parameters. Therefore, the soil infiltration rate can be estimated from the rainfall intensity and runoff rate more simply from:

$$i = p - r \qquad (4)$$

Where i is the infiltration rate, mm/h; p is the rainfall intensity, mm/h; and r is the runoff rate, mm/h.

This method can be applied to study the soil infiltration process with rainfall. The effects of the raindrops can also be analyzed using this method. Usually limited by the sprinkler's rainfall intensity, the relatively high initial soil infiltrability cannot generally be measured[21, 22]. If a sufficiently high rainfall intensity was to be applied in order to measure the initial soil infiltrability, the rapid wetting of the surface soil and the impact of the raindrops would immediately initiate surface seal formation, which greatly lowers the soil infiltration rate[16], and induce soil erosion[23,24] in an unnatural fashion.

The typical results obtained by a rainfall simulator are conceptually shown in Figure 4.
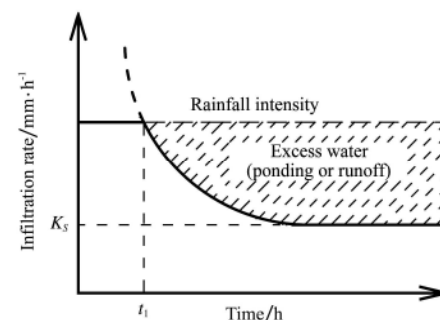
Figure 4   Infiltration curve[11]

As shown in Figure 4, the initial soil infiltration rate equals the rainfall intensity instead of the inherent soil infiltrability. The soil infiltrability at the very beginning of the infiltration process cannot be observed practically with this method.

4.2   Run off-on-ponding method

Lei et al.[15] suggested a method to measure soil infiltrability using a rainfall simulator with part of the upper slope covered by water-impermeable material to generate runoff, which then runs on to the soil surface on the lower slope.

In Figure 5, P is the constant precipitation intensity from a sprinkler or drippers. The section AB on the upper slope of length x_I is covered with an impermeable material such as plastic or metal sheeting and is used for runoff generation to supplement the water supply to the soil in the downslope area. The downslope section, BC, with a length

of x_2, receives both the run-on from the upslope section, AB, and direct precipitation that infiltrates into the soil surface.

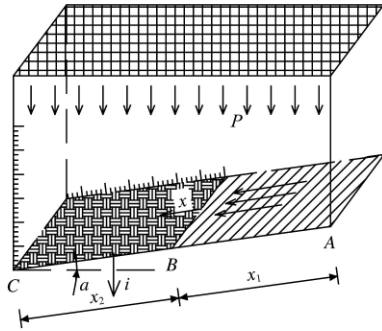

Figure 5　Schematic illustration for the measurement of infiltrability[18]

The main principle of the run off-on-ponding method is described as follows. Initially, the infiltrability is high. The permeable section is penetrated by water supplied to the surface not only as direct rainfall but also as run-on water coming from the impermeable section, AB. Due to the soil's initially high infiltrability, the run-on water advances only a short distance (denoted as x in Figure 5) at first from the boundary between AB and BC. With the continuation of the rainfall-infiltration process, the soil infiltrability decreases with time and a longer slope length is required to completely absorb the same flow rate of run-on water, i.e., x increases with time.

Water either runs off the section, BC, or ponds if stored; note that the infiltration process under ponding conditions starts at the bottom of the slope in this experimental setup. When stored, the ponded water level rises at the bottom of the slope as the infiltrability decreases further with time. The rate of increase of the ponded water level is also an indicator, which can be used to estimate the continuous reduction in infiltrability.

The infiltration process under this method was divided into two stages as: (i) the run-on advance stage; (ii) the ponding stage. Two separate algorithm models were developed for each stage as given in Eq. (5) and (6).

Run-on advance stage:
$$\begin{cases} \text{Cumulative infiltration}=\Delta I(x+\Delta x/2)\cos\alpha W \\ \text{Direct rainfall}=P(x+x/2)\cos\alpha W\Delta t \\ \text{Run-on water}=Px_1\cos\alpha W\Delta t \end{cases}$$
$$(5)$$

Ponding stage:
$$\begin{cases} \text{Cumulative infiltration}=\Delta I\,x_2\cos\alpha W \\ \text{Cumulative rainfall}=P(x_1+x_2)\cos\alpha W\Delta t \end{cases}$$
$$(6)$$

Where I is the cumulative infiltration, mm; x is the distance that water advances upon the run-on section, mm;

W is the width of the soil layer, m; P is the precipitation intensity, mm/h; t is time, h; α is the slope of the soil surface.

The advance of the water flow produced from the impermeable upslope section, which flows on to the soil surface at the lower part of the slope, as a function of time, was thus used to estimate soil infiltrability[15]. This method is capable of measuring the very high initial infiltrability of a sloping soil surface with relatively small amounts of water required. It is based on the assumption that the infiltrability values at all locations along the slope are similar.

4.3　Run off-on-out method

This method is very similar to the run on-off-ponding method introduced by Lei et al.[18]. The major difference between these two methods can be seen in the experimental apparatus shown in Figure 6.
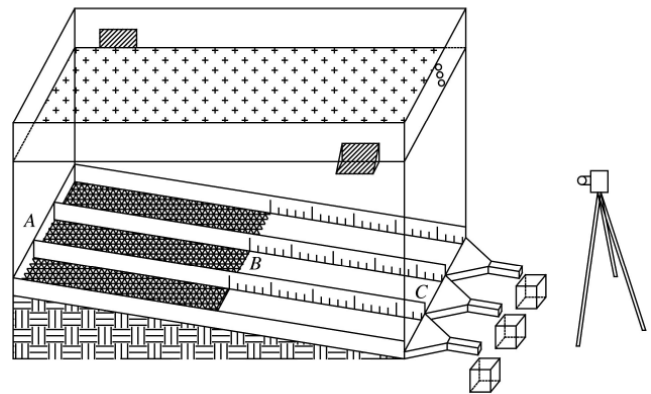

Figure 6　Run off-on-out experimental apparatus[19]

In Figure 6, section AB is for runoff production and is covered with an impermeable material. All the rainfall falling in this section becomes runoff. Section BC is for the water infiltrating into the soil. In this section, the soil absorbs not only the rainwater falling directly onto it but also the water running onto it from section AB. The difference between this and the preceding method is to be found at the end of section BC. Whereas in the run on-off-ponding method the overland flow is allowed to pond at this point, in the run-on-off-out method, overland flow is allowed to run out of the soil section being studied eliminating the effects of water ponding on the soil infiltration rate[25].

To quantify the soil infiltrability when using this method, the following assumptions are made. Firstly, the evaporation from the soil surface during the rainfall event is neglected, due to the short period of rainfall used. Secondly, the infiltrability is related not to the infiltrated water amount but to the infiltration duration. The infiltration rates in places where cumulative infiltration is

higher or lower follow the same infiltration curve.

The soil infiltration process is divided into two parts as in the run off-on-ponding method. The results measured with the run off-on-out method were compared with those from the double-ring method by Lei et al.[16] as given in Figure 7.

Case I represents the infiltration process under a rainfall intensity of P = 20 mm/h for a slope of S = 0º and a ratio of the runoff/infiltration section lengths, C = 1∶1.

Case II represents the infiltration process under a rainfall intensity of P = 60 mm/h for a slope of S = 20º and a ratio of the runoff/infiltration section lengths, C = 1∶1.
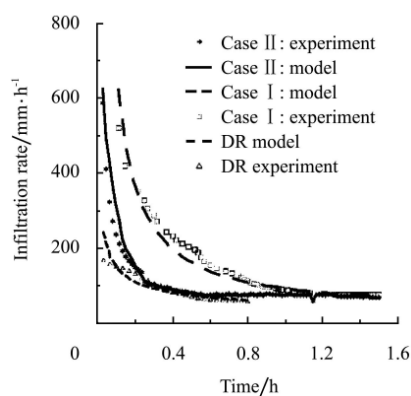

Figure 7   Infiltrabilities of Case I and II, and by the double-ring infiltrometer method[19]

As infiltration is limited by the water supply, the infiltrability curve measured using the double-ring method, denoted as DR, has a flattened section at the beginning of the time line that is significantly below that obtained from the results when using the run off-on-out method. The reasons were identified by Levy et al.[24]; Mamedov et al.[26] and Lei et al.[15] as follows. Surface soil structure is destroyed by fast wetting when a high flow rate of water is poured into the rings in order to measure the high initial infiltration rate. Fast wetting of soil aggregates causes their breakdown due to slaking and results in much lower infiltration rates than the original soil potentially had. Infiltration in the double-ring infiltrometer is a process under a particular hydraulic pressure and is limited by the water supply capacity of the inflow pipe.

The run off-on-out method can also overcome the inability of the traditional sprinkler method to measure very high initial infiltrabilities. The limits due to the water supply on initial infiltrability determinations and the impact of surface aggregate breakdown by fast wetting on lowered initial infiltrability that are associated

with both the double-ring and rainfall simulator methods are resolved in the run off-on-out method. The measurement accuracy is thus reported to be greatly improved[16].

5   Linear source method

The linear source method was introduced by Mao et al.[8] recently. The measurement device includes a soil flume along which two measuring tapes are attached (Figure 8), a specially-designed linear water distributor, a Mariotte bottle to provide a water supply at a constant flow rate, and a digital camera for recording the advance of the wetting front along the flume. In field applications, the soil box is not needed.
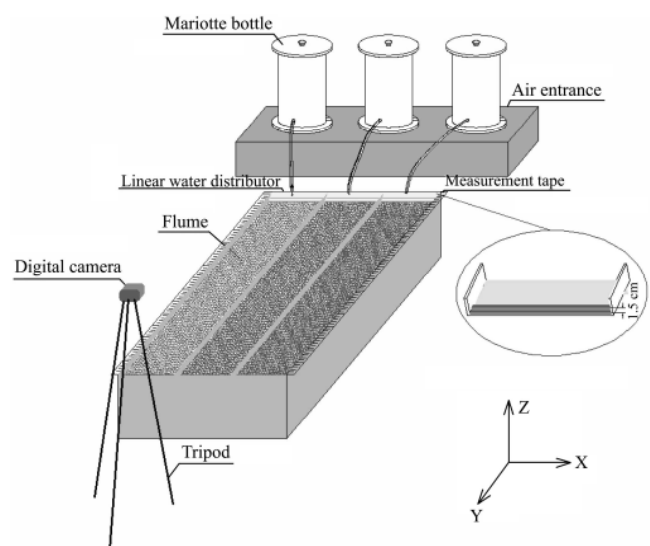

Figure 8   Linear source method apparatus[8]

The soil infiltrability is estimated from the rate of advance of the wetting front, separating wet and dry soil, recorded by the digital camera. The relationship between the soil infiltration rate and the progress of the advancing area wetted by water at a constant flow rate is described as follows. Initially, the soil infiltration rate is very high (Figure 9) and a small area of the slope can absorb all of the supplied water. With infiltrability decreasing in the previously wetted soil zone, the same water flow cannot be totally absorbed within the same soil surface area. Thus, the water flow advances over the surface and the wetted area increases gradually (Figure 9). The soil infiltrability keeps decreasing with time until it reaches its steady value (Figure 9) when the area wetted by the constant flow rate no longer expands but also remains constant (Figure 9). The advancing process of the in-flow water over the soil surface indicates that the water supply is sufficient to penetrate the soil in the wetted area.
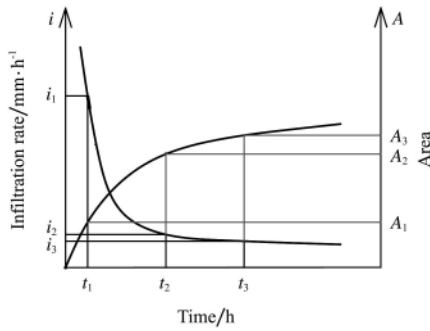
Figure 9   Soil infiltrability and wetted area as a function of time[8]

The algorithm model for the linear source method, based on water-mass balance, is given by:

$$q = K \int_0^A i(A,t)\,dA \qquad (7)$$

Where q is the inflow rate, L/h; i is the infiltration rate, mm/h; A is the wetted area (the horizontal projection area when a slope-α is considered), m^2; $K(=1)$ is the dimensionless transformation coefficient.

Numerical solutions of Eq. (7) for examples shown in Figure 9 are given by the following equations.
The water balance at t_1:

$$q_1 \approx i_1 \Delta A_1 \cos \alpha \qquad (8)$$

The water balance at t_2:

$$q_2 \approx i_2 \Delta A_1 \cos \alpha + i_1 \Delta A_2 \cos \alpha \qquad (9)$$

And the water balance at t_n:

$$q_n \approx i_n \Delta A_1 \cos \alpha + i_{n-1} \Delta A_2 \cos \alpha + \cdots\cdots + i_1 \Delta A_n \cos \alpha \qquad (10)$$

From Eq. (10), the infiltration rates at different times are given as:

$$i_n = \frac{q_n - \sum_{j=1}^{n-1} i_j \Delta A_{n-j+1} \cos \alpha}{\Delta A_1 \cos \alpha} \qquad (n = 1, 2, 3\cdots) \qquad (11)$$

Compared with the other soil infiltration rate measurement methods, the linear source method can measure the intrinsic or the original soil infiltrability. This is the only method to date that is capable of measuring the intrinsic soil infiltrability. The measured soil infiltrability is not affected by soil surface sealing, blockage, aggregate breakdown, and erosion, nor is it limited by an insufficient water supply. The water supply from the linear distributor is sufficient to measure the very high initial soil infiltrability. The soil structure is maintained throughout the experiment. This method makes it possible to analyze the effects of rain drops, soil surface slopes[6-8, 27-28], surface sealing processes, and other factors on soil infiltrability.

6   Conclusions

The soil infiltration rate is an important factor in analysis of the hydrological system that determines the fraction of rain water entering the soil or irrigation and the amount of runoff generated that is responsible for subsequent soil erosion. Seven methods, classified in four categories, for soil infiltrability measurements were introduced. The advantages and disadvantages of each method were analyzed and compared.

Three recently developed soil infiltrability measurement methods are introduced together with corresponding algorithm models. These can be considered as the latest developments in soil infiltrability measurement. These newly-developed methods are all applicable to sloping soil surfaces. The initially high soil infiltration rate can be measured using these methods. The run off-on-ponding and the run off-on-out methods can both be used to analyze the effects of raindrops, soil erosion, surface seal formation, etc., on soil infiltrability. The linear source method is capable of measuring the intrinsic soil infiltrability that can be used to quantify the effects of many factors on soil infiltrability.

Acknowledgments

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