1 Infiltration measurement techniques

According to the objectives and accessibility, several techniques have been used to measure soil infiltration. In this section we will briefly describe the various measurement techniques. These include single-and double-rings infiltrometers (equipped or not by Marriotte bottle), tension or ponded disc infiltrometer (common, mini and micro-disc infiltrometer), Guelph infiltrometer, rainfall simulator (run off-on-ponding or run off-on-out methods), and linear source method (Mao et al., 2008b). For a more detailed discussion and evaluation of various methods the reader referred to the pertinent literature, e.g. Mao et al. (2008a).

1.1 The single- and double-ring infiltrometers

Single- and double-ring infiltrometers are the most widely used instruments for soil infiltration measurement (Bouwer, 1986).

The single-ring infiltrometer (Fig. 1) consists of a metal or steel ring that is inserted into the soil to a small depth (Bagarello and Sgroi, 2004). To reduce the horizontal leakage in the single-ring infiltrometer, the use of a double-ring infiltrometer (Fig. 1) has become more popular for soil infiltration measurements (Mao et al., 2008a) as it better enforces 1D flow conditions. The double-ring infiltrometer consists of two thin-walled cylindrical steel pipes with an outer and inner diameter of typically 60-and 30-cm, respectively but other diameters may be used (Bouwer, 1986). However, Khodaverdiloo et al. (2017) found that the use of different cylinder diameters (5.5-31.8 cm) did not lead to substantial differences in infiltration.

<<Figure 1 about here>>

Several researchers also reported no significant difference in measured infiltration rates between single and double infiltrometer measurements, for example refer to Lin et al. (1999); Bagarello and Sgroi (2007); Alizadeh et al. (2001); and Razzaghi et al. (2016). Despite the fact that single and double ring infiltrometers are easy to apply, their application has been challenged because of measurement errors caused by insufficient water supply, the formation of surface sealing at initial soil infiltration stages, disturbance of soil structure, and scant efficiency in hillslopes and sandy soils (Verbist et al., 2010).

1.2 BEST algorithm

The Beerkan Estimation of Soil Transfer parameters (BEST) is an algorithm proposed by Lassabatere et al. (2006) to deduce the retention and hydraulic conductivity curves from infiltration measurements. Since the development of the original version (Lassabatere et al., 2006), two alternatives were developed, one for coarse soils (Yilmaz et al., 2010), and the third one to alleviate the errors linked to poor or erroneous descriptions of the transient state of water infiltration (Bagarello et al., 2014). The three BEST methods make use of the so-called Beerkan method (Braud et al., 2005), a single-ring experiment at zero water pressure head. It combines this information with a few basic soil physical determinations including particle size distribution (PSD), bulk density, and initial and final water content to estimate soil hydraulic functions described by e.g. the Mualem van Genuchten model or the Brooks and Corey model (1966). More details of the BEST methods can be found in Angulo-Jaramillo et al. (2016).

1.3 Disc infiltrometer

To address the shortcomings of single and double infiltrometer measurements, Clothier and White (1981) developed the disc infiltrometer (Fig. 2). In this system, the tension setting and the measurement of the infiltrated volume of water are carried out by the bubble tower and the graduated water-supply reservoir, respectively (Latorre et al., 2015). The advantages of the disc infiltrometer are the easy measurement of field saturated hydraulic conductivity (K_{fs}) and $K(\theta)$, its capability to estimate one-dimensional and three-dimensional flow (Smettem et al., 1994) through applying a slightly negative water pressure (tension) at the soil surface (Ma et al., 2017) as well as this capability to characterize macroporous flow (Minasny and George, 1999). The original method was therefore modified by Perroux and White (1988) in order to measure infiltration in macro-pores soils (Fig. 2).

A sand layer is generally added at the soil surface to ensure a better contact between the infiltrometer and the soil surface. However, this layer may have an impact on the infiltration curve shape and must be taken into account in the analysis (Vandervaere et al., 2000b, a). The detailed information about the disc infiltrometer structure and mechanisms has been expressed by Clothier and White (1981); Perroux and White (1988); Mao et al. (2008a).

<<Figure 2 about here>>

Several studies have confirmed the superiority of disc permeameter measurements compared to ring infiltrometers measurement, e.g. Santi et al. (2016). However, it must be kept in mind that the activation of macropores may be less efficient when using disc permeameter, due to the fact that a water pressure head above zero cannot be imposed as compared to ring infiltrometers. Ring experiments, that allow a full saturation of the macropore network, should therefore be preferred for the quantification of water initiation into macroporous soils, e.g. Lassabatere et al. (2014).

1.4 Hood infiltrometer

The Hood Infiltrometer (Fig. 3) is a new type of tension infiltrometer (Schwärzel and Punzel, 2007) used for determination of saturated and unsaturated hydraulic conductivities in-situ (Zhao et al., 2017). The advantages of Hood infiltrometer is that it provides a direct contact between infiltrating water and the infiltration surface that makes unnecessary the use of any contact material. The user only need to cut the vegetation cover to the approximately 5 mm height. In fact, the Hood infiltrometer omits the effects of contact material, as an additional layer, on infiltration process and makes the subsequent data analysis easier than for the disc infiltrometer (Schwärzel and Punzel, 2007).

<<Figure 3 about here>>

1.5 Guelph permeameter

The Guelph permeameter (Fig.4) is an in-hole constant-head permeameter based on Marriotte principle (Zhang et al., 1998). A constant pressure head is created in a cylindrical hole and the steady-state rate of water recharge into unsaturated soil is recorded and used to calculate the infiltration components. Measurements can be made in the range of 15 to 75-cm below the soil surface (additional depths can be achieved with additional parts) for 1/2 to 2 hours and may require only about 2.5 liters of water depending on soil type. The Guelph permeameter is efficient in laboratory conditions (Gupta et al., 1993), it might be much more labor-intensive and time-consuming to measure infiltration in the field (Xu et al., 2017). Guelph permeameter has also the disadvantage of disturbing the soil for installation. Details about the use of the Guelph permeameter to estimated soil hydraulic parameters can be found in Reynolds and Elrick (1986) and Jačka et al. (2014).

<<Figure 4 about here>>

1.6 Aardvark permeameter

The Aardvark permeameter is based on the constant head principle and is similar to other constant head permemeters. The main feature of the Aardvark permeameter is that it provides a constant head at some depth on borehole during the measurement period (Fig. 5). Soil infiltration rate from the bottom and side surfaces of the testing borehole corresponds to the rate of water supplied. The amount of supplied water measured at equal time intervals (the amount of water that was infiltrated by soil) is used to estimates soil hydraulic conductivity. The reservoir water release rate is equivalent to the rate of infiltration rate[1]. The recent application of the Aardvark permeameter over the Tibetan Plateau shows its satisfactory performance in determining saturated hydraulic conductivity at different depths (Zhao et al., 2017; Zhao et al., 2018).

<<Figure 5 about here>>

1.7 Infiltration measuring under rainfall conditions

Soil infiltration rate measurements using natural and/or simulated rainfall was firstly introduced by Amerman et al. (1970) and further developed and modified by e.g., Ogden et al. (1997), Zegelin and White (1982), and Peterson and Bubenzer (1986). Unlike natural rainfall, the simulated rainfall is applied onto the soil surface at a controlled rate (Huang et al., 2015). Overland flow is collected and recorded as a function of time. Soil infiltration rate is then calculated from the difference between simulated rainfall and runoff rates.

1.8 The linear source method

Mao et al. (2008b) introduced the linear source method to measure the soil infiltration process. The linear source method is composed of one or some soil flume along measuring tapes are attached (Fig. 6), a linear water distributor, and a Marriotte bottle to provide a water supply at a constant flow rate. A digital camera is situated at the front section to record the advance of the wetting along the flume. However, in field applications, the soil box is not needed and the measurement tape will by laid out directly on the soil surface. A detailed description of linear source method mechanism is presented in Mao et al. (2008b).

<<Figure 6 about here>>

Measuring original soil infiltrability without inducing any soil surface sealing, blockage, aggregate breakdown, and erosion and related effects on infiltration measuring is the advantage of the linear source method compared to others (Mao et al., 2008a). Measuring the very high initial soil infiltrability and soil structure stability during the experiment, are major advantages of the technique. Additionally, the influence of other soil factors and effects (i.e. raindrop impact,

[1] - http://www.soilmoisture.com/AARDVARK-PERMEAMETER-KIT-IN-CASE-UP-TO-10-FT.-MANUAL-READING/

soil surface slopes, surface sealing processes) on the soil infiltrability can be studied by the use of the linear source method (Singer and Blackard, 1982; Poesen, 1986; Mah et al., 1992; Chaplot and Le Bissonnais, 2000; Janeau et al., 2003; Bobe, 2004).

1.9 The point source method

The point source method (Fig. 7) was introduced by Mao et al. (2016) for soil infiltrability measurement. The soil infiltrability can be estimated from the relationship between the wetted radius on the soil surface and the amount of water infiltrated. Both, the actual and integrated soil infiltrability can be estimated with a very high accuracy using the point source method. A detailed description of the point source method is given by Mao et al. (2016).

<<Figure 7 about here>>

As shown in Fig. 7, the original experimental apparatus of the point source method includes a rectangular soil box made of synthetic glass, a Marriotte bottle for water supply, and a point source distributor made of the combination of a needle with a small circular shaped sponge slice (Mao et al., 2016). The inflow rate and the advancing process of the wetted area are recorded during the experiment. The point source distributor was made of a needle-1mm in diameter and a small circular sponge slice-1 cm in diameter as shown in Fig. 7. The sponge was placed on the soil surface under the needle directly. Water flowed from the outlet of the Marriotte bottle to the sponge first and then to the soil surface. This device prevented the direct hit of water drop onto the soil surface in order to preserve the original structure of the soil surface during the course of the experimentation.

References

Alizadeh, A., Bazari, M. E., Velayati, S., Hasheminia, M., and Yaghmai, A.: Using reclaimed municipal wastewater for irrigation of corn, International Workshop on Wastewater Reuse Management. ICID- CIID. , Seoul, Korea, 2001, 147–154,

Amerman, C., Hillel, D., and Peterson, A.: A variable-intensity sprinkling infiltrometer, Soil Science Society of America Journal, 34, 830-832, 1970.

Angulo-Jaramillo, R., Bagarello, V., Iovino, M., and Lassabatere, L.: Saturated Soil Hydraulic Conductivity, in: Infiltration Measurements for Soil Hydraulic Characterization, Springer, 43-180, 2016.

Bagarello, V., and Sgroi, A.: Using the single-ring infiltrometer method to detect temporal changes in surface soil field-saturated hydraulic conductivity, Soil and Tillage research, 76, 13-24, 2004.

Bagarello, V., and Sgroi, A.: Using the simplified falling head technique to detect temporal changes in field-saturated hydraulic conductivity at the surface of a sandy loam soil, Soil and Tillage Research, 94, 283-294, 2007.

Bagarello, V., Di Prima, S., and Iovino, M.: Comparing alternative algorithms to analyze the Beerkan infiltration experiment, Soil Science Society of America Journal, 78, 724-736, 2014.

Bobe, B.: Evaluation of Erosion in Harerge Region of Ethiopia Using Soil Loss Models, Rainfall Simulation and Field Trials, Ph. D. Dissertation, University of Pretoria, South Africa, 2004.

Bouwer, H.: Intake rate: cylinder infiltrometer, Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods, 825-844, 1986.

Braud, I., De Condappa, D., Soria, J. M., Haverkamp, R., Angulo-Jaramillo, R., Galle, S., and Vauclin, M.: Use of scaled forms of the infiltration equation for the estimation of unsaturated soil hydraulic properties (the Beerkan method), European Journal of Soil Science, 56, 361-374, 2005.

Chaplot, V., and Le Bissonnais, Y.: Field measurements of interrill erosion under- different slopes and plot sizes, Earth Surface Processes and Landforms, 25, 145-153, 2000.

Clothier, B., and White, I.: Measurement of sorptivity and soil water diffusivity in the field, Soil Science Society of America Journal, 45, 241-245, 1981.

Gupta, R., Rudra, R., Dickinson, W., Patni, N., and Wall, G.: Comparison of saturated hydraulic conductivity measured by various field methods, Transactions of the ASAE, 36, 51-55, 1993.

Huang, L., Zhang, P., Hu, Y., and Zhao, Y.: Vegetation succession and soil infiltration characteristics under different aged refuse dumps at the Heidaigou opencast coal mine, Global Ecology and Conservation, 4, 255-263, 2015.

Jačka, L., Pavlásek, J., Kuráž, V., and Pech, P.: A comparison of three measuring methods for estimating the saturated hydraulic conductivity in the shallow subsurface layer of mountain podzols, Geoderma, 219, 82-88, 2014.

Janeau, J.-L., Bricquet, J.-P., Planchon, O., and Valentin, C.: Soil crusting and infiltration on steep slopes in northern Thailand, European Journal of Soil Science, 54, 543-554, 2003.

Khodaverdiloo, H., Cheraghabdal, H. K., Bagarello, V., Iovino, M., Asgarzadeh, H., and Dashtaki, S. G.: Ring diameter effects on determination of field-saturated hydraulic conductivity of different loam soils, Geoderma, 303, 60-69, 2017.

Lassabatere, L., Angulo-Jaramillo, R., Soria Ugalde, J., Cuenca, R., Braud, I., and Haverkamp, R.: Beerkan estimation of soil transfer parameters through infiltration experiments—BEST, Soil Science Society of America Journal, 70, 521-532, 2006.

Lassabatere, L., Yilmaz, D., Peyrard, X., Peyneau, P. E., Lenoir, T., Šimůnek, J., and Angulo-Jaramillo, R.: New analytical model for cumulative infiltration into dual-permeability soils, Vadose Zone Journal, 13, 2014.

Latorre, B., Peña, C., Lassabatere, L., Angulo-Jaramillo, R., and Moret-Fernández, D.: Estimate of soil hydraulic properties from disc infiltrometer three-dimensional infiltration curve. Numerical analysis and field application, Journal of Hydrology, 527, 1-12, 2015.

Lin, H., McInnes, K., Wilding, L., and Hallmark, C.: Effects of soil morphology on hydraulic properties II. Hydraulic pedotransfer functions, Soil Science Society of America Journal, 63, 955-961, 1999.

Ma, D., Zhang, J., Horton, R., Wang, Q., and Lai, J.: Analytical method to determine soil hydraulic properties from vertical infiltration experiments, Soil Science Society of America Journal, 2017.

Mah, M., Douglas, L., and Ringrose-Voase, A.: Effects of crust development and surface slope on erosion by rainfall, Soil Science, 154, 37-43, 1992.

Mao, L., Bralts, V. F., Pan, Y., Liu, H., and Lei, T.: Methods for measuring soil infiltration: State of the art, International Journal of Agricultural and Biological Engineering, 1, 22-30, 2008a.

Mao, L., Lei, T., Li, X., Liu, H., Huang, X., and Zhang, Y.: A linear source method for soil infiltrability measurement and model representations, Journal of Hydrology, 353, 49-58, 2008b.

Mao, L., Li, Y., Hao, W., Mei, X., Bralts, V. F., Li, H., Guo, R., and Lei, T.: An approximate point source method for soil infiltration process measurement, Geoderma, 264, 10-16, 2016.

Minasny, B., and George, B.: . The measurement of soil hydraulic properties in the field, Science, 22, 26th, 1999.

Ogden, C., Van Es, H., and Schindelbeck, R.: Miniature rain simulator for field measurement of soil infiltration, Soil Science Society of America Journal, 61, 1041-1043, 1997.

Perroux, K., and White, I.: Designs for disc permeameters, Soil Science Society of America Journal, 52, 1205-1215, 1988.

Peterson, A. E., and Bubenzer, G. D.: Intake rate: sprinkler infiltrometer, Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods, 845-870, 1986.

Poesen, J.: Field measurements of splash erosion to validate a splash transport model, Zeitschrift für Geomorpholgie, Supplement Band, 58, 81-91, 1986.

Razzaghi, S., Khodaverdiloo, H., and Ghorbani Dashtaki, S.: Effects of long-term wastewater irrigation on soil physical properties and performance of selected infiltration models in a semi-arid region, Hydrological Sciences Journal, 61, 1778-1790, 2016.

Reynolds, W. D., and Elrick, D. E.: A Method for Simultaneous In Situ Measurement in the Vadose Zone of Field-Saturated Hydraulic Conductivity, Sorptivity and the Conductivity-Pressure Head Relationship, Groundwater Monitoring & Remediation, 6, 84-95, 1986.

Santi, A. L., Damian, J., Melo, u., Cherubin, M., Roberto, i., Amado, T. J. C., Eitelwein, M. T., Vian, A., Luis, e., and Herrera, W. F. B.: Soil physical and hydraulic changes in different yielding zones under no-tillage in Brazil, African Journal of Agricultural Research, 11, 1326-1335, 2016.

Schwärzel, K., and Punzel, J.: Hood infiltrometer-A new type of tension infiltrometer, Soil Science Society of America Journal, 71, 1438, 2007.

Singer, M. J., and Blackard, J.: Slope angle-interrill soil loss relationships for slopes up to 50%, Soil Science Society of America Journal, 46, 1270-1273, 1982.

Smettem, K., Parlange, J., Ross, P., and Haverkamp, R.: Three-dimensional analysis of infiltration from the disc infiltrometer: 1. A capillary-based theory, Water Resources Research, 30, 2925-2929, 1994.

Vandervaere, J.-P., Vauclin, M., and Elrick, D. E.: Transient flow from tension infiltrometers II. Four methods to determine sorptivity and conductivity, Soil Science Society of America Journal, 64, 1272-1284, 2000a.

Vandervaere, J.-P., Vauclin, M., and Elrick, D. E.: Transient flow from tension infiltrometers I. The two-parameter equation, Soil Science Society of America Journal, 64, 1263-1272, 2000b.

Verbist, K., Torfs, S., Cornelis, W., Oyarzún, R., Soto, G., and Gabriels, D.: Comparison of single-and double-ring infiltrometer methods on stony soils, Vadose Zone Journal, 9, 462-475, 2010.

Xu, C., Xu, X., Liu, M., Liu, W., Yang, J., Luo, W., Zhang, R., and Kiely, G.: Enhancing pedotransfer functions (PTFs) using soil spectral reflectance data for estimating saturated hydraulic conductivity in southwestern China, Catena, 158, 350-356, 2017.

Yilmaz, D., Lassabatere, L., Angulo-Jaramillo, R., Deneele, D., and Legret, M.: Hydrodynamic characterization of basic oxygen furnace slag through an adapted BEST method, Vadose Zone Journal, 9, 107-116, 2010.

Zegelin, S., and White, I.: Design for a field sprinkler infiltrometer, Soil Science Society of America Journal, 46, 1129-1133, 1982.

Zhang, Z. F., Groenevelt, P. H., and Parkin, G. W.: The well-shape factor for the measurement of soil hydraulic properties using the Guelph Permeameter, Soil and Tillage Research, 49, 219-221, 1998.

Zhao, H., Zeng, Y., Lv, S., and Su, Z.: Analysis of Soil Hydraulic and Thermal Properties for Land Surface Modelling over the Tibetan Plateau, Earth Syst. Sci. Data Discuss., 2018, 1-40, 10.5194/essd-2017-122, 2018.

Zhao, H. H., Zeng, Y. Y., and Su, Z. B.: Soil Hydraulic and Thermal Properties for Land Surface Modelling over the Tibetan Plateau, Dataset, https://doi.org/10.4121/uuid:61db65b1-b2aa-4ada-b41e-61ef70e57e4a, 2017.

Figures captions:

Figure 1. Single ring (left) and double-ring (right) infiltrometer. Images are taken by Andreas Panagopoulos (left) and Artemi Cerdà (right)

Figure 2. Experimental apparatus of disc (left[†]) and mini disc (right, taken by Artemi Cerdà) infiltrometer.

Figure 3. Schematic setup of the Hood Infiltrometer. Image is taken from the guide "Operating instructions for Hood Infiltrometer IL-2700"

Figure 4. Guelph permeameter setup. Image is taken by Jesús Rodrigo-Comino

Figure 5. Schematic of a standard setup of an Aardvark permeameter.[‡]

Figure 6. Linear source method apparatus for studying infiltration process (Mao et al., 2008b)

[†] - https://en.wikipedia.org/wiki/Disc_permeameter

[‡] - http://www.soilmoisture.com/AARDVARK-PERMEAMETER-KIT-IN-CASE-UP-TO-10-FT.-MANUAL-READING/

Fig01

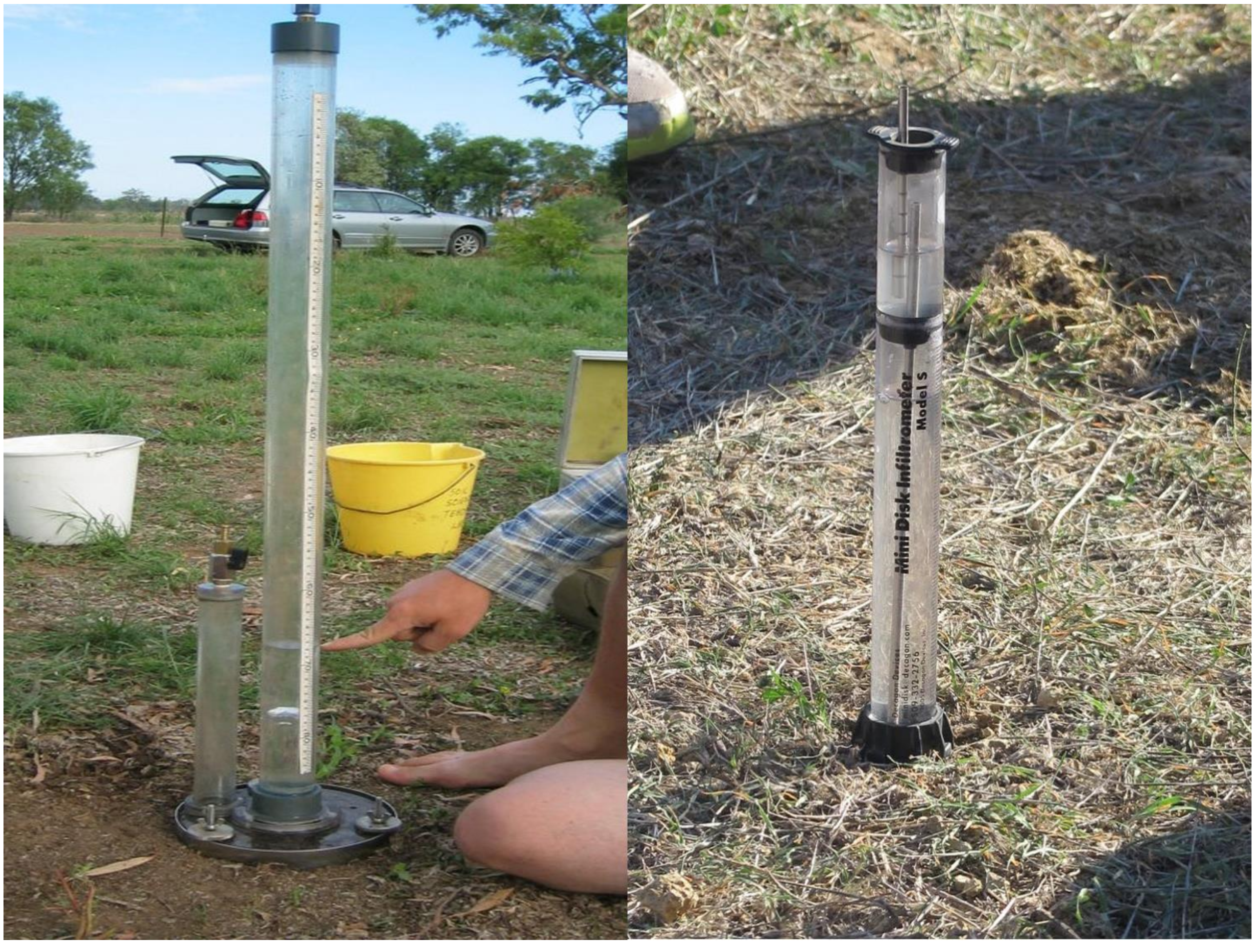


Fig02

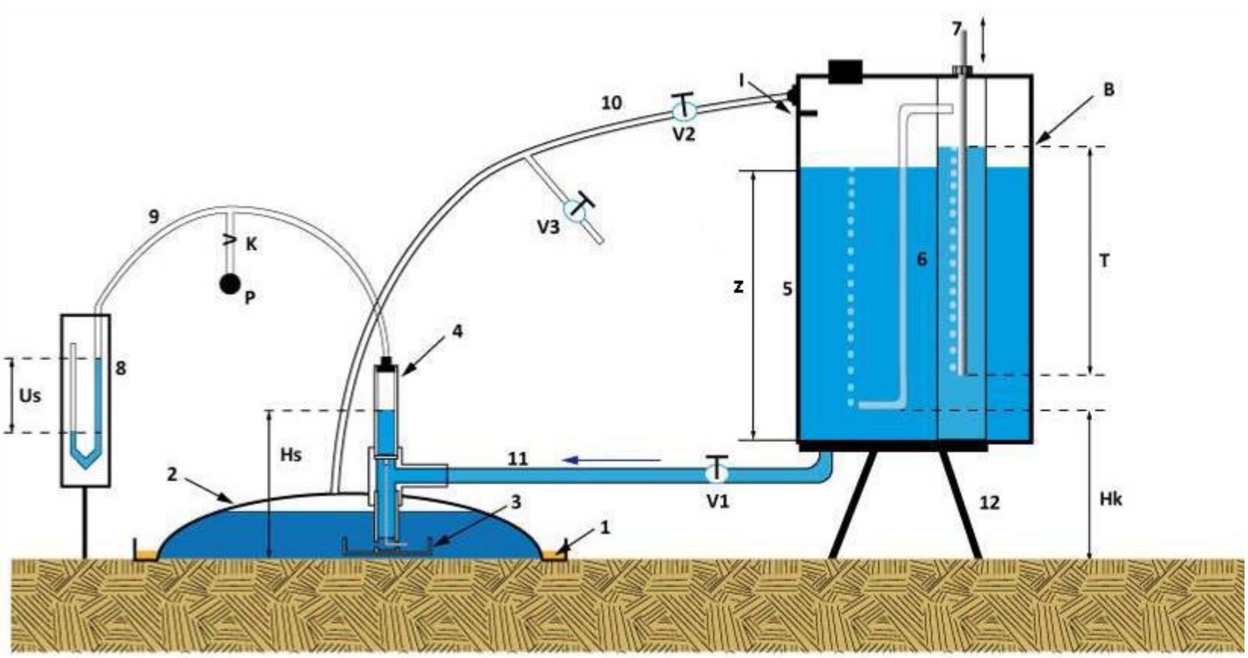
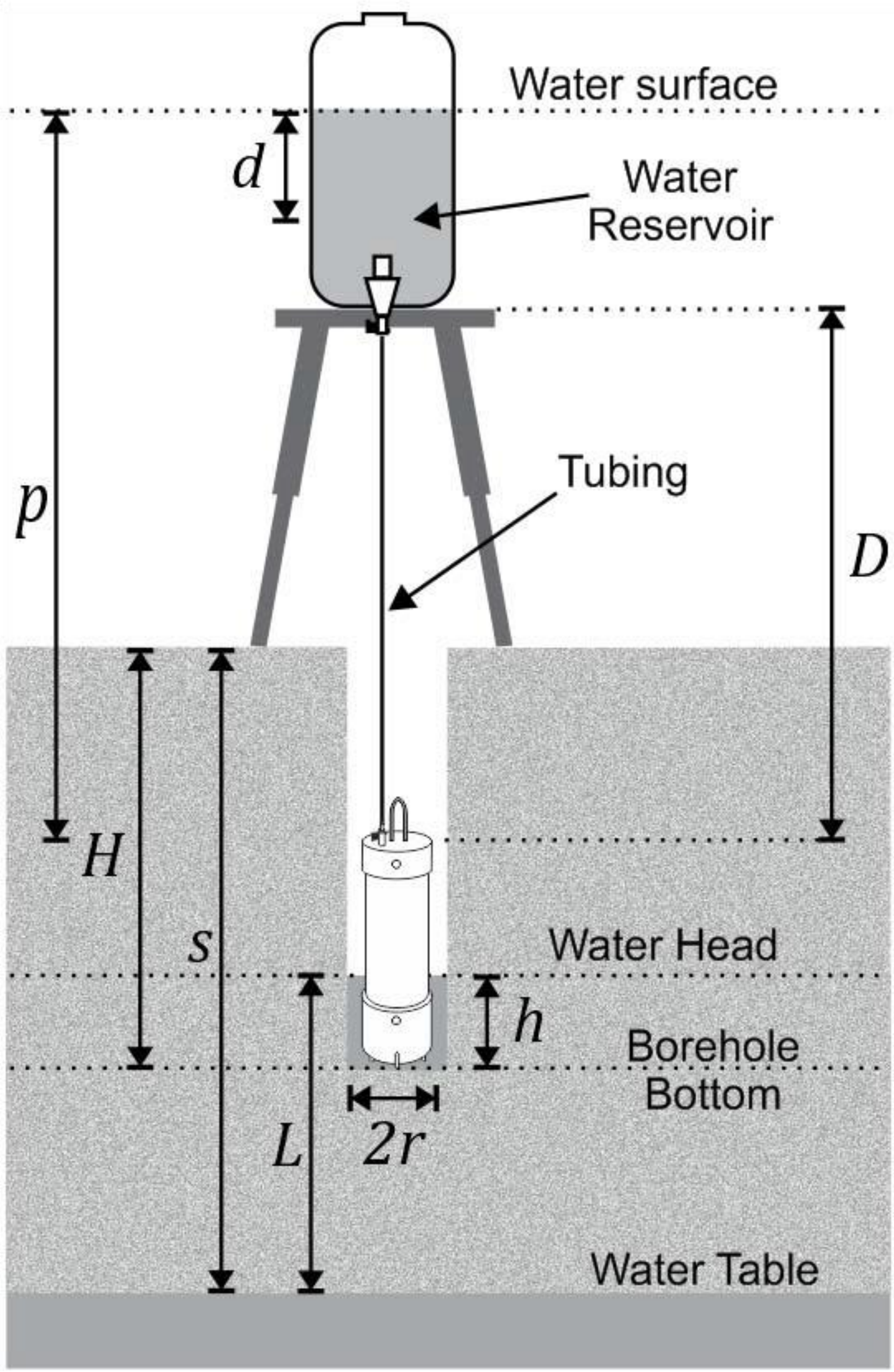


Fig03

Fig04


Water surface
d
Water
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Bottom
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Water Table

Fig05

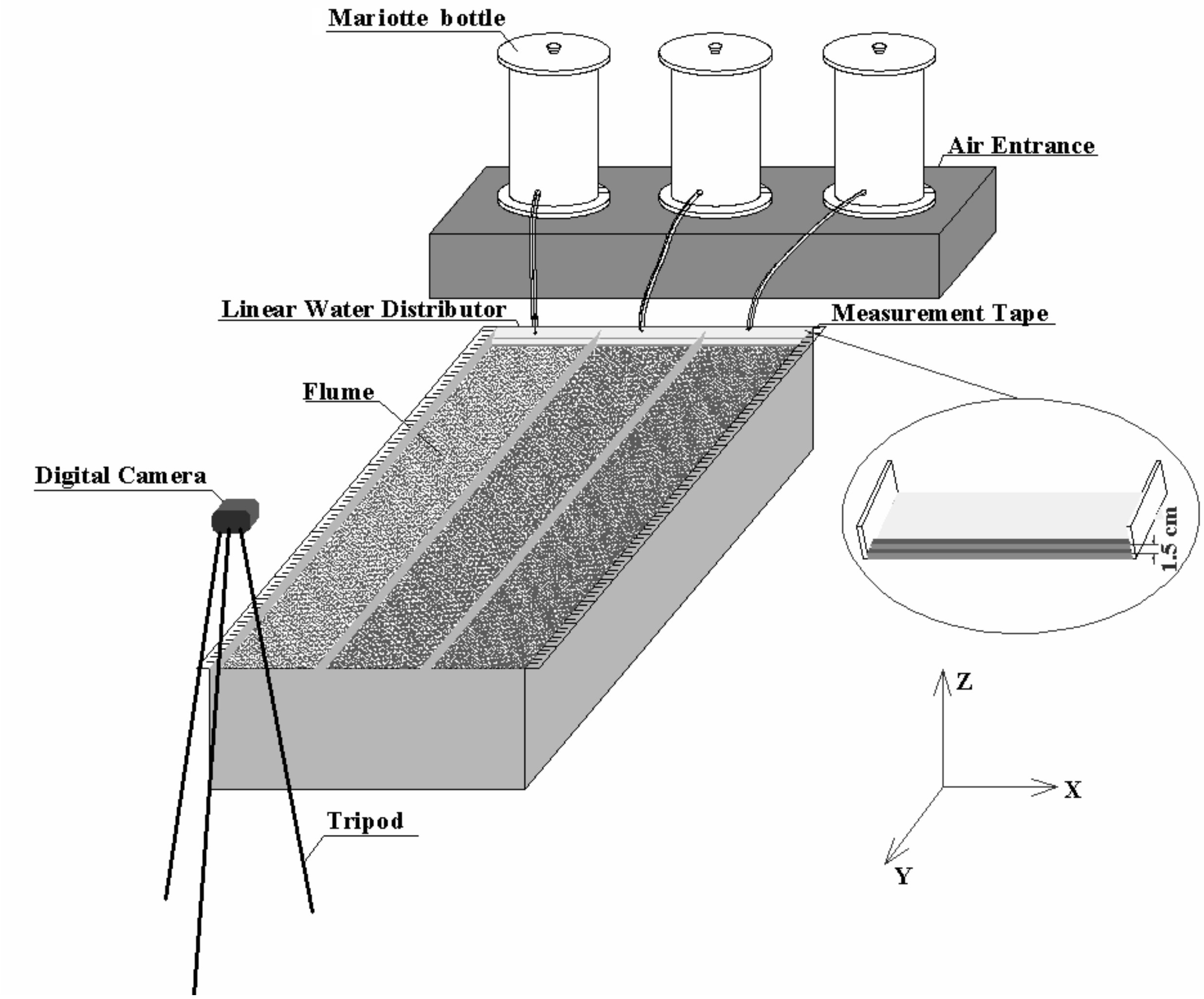
Mariotte bottle
Air Entrance
Linear Water Distributor
Measurement Tape
Flume
Digital Camera
1.5 cm
Z
X
Y
Tripod

Fig06

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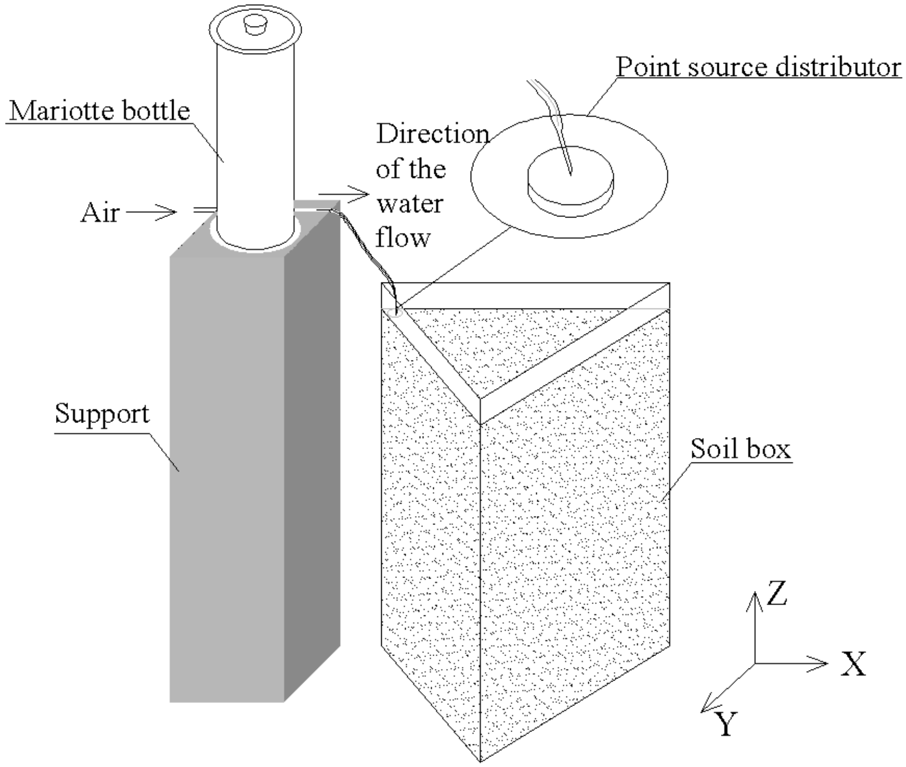

Point source distributor
Mariotte bottle
Direction of the water flow
Air
Support
Soil box
Z
X
Y

Fig07