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A Review on Methodology Regarding the Measurement of Soil Infiltration.

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Abstract: The infiltrability of soil is referred to as the infiltration flux of water at the soil surface per unit area at a unit time. The Infiltration dynamics need careful monitoring and assessesment as data of infiltrability is fundamental prerequisite for designing, evaluating and managing hydrological processes, crop water availabilities, irrigation system management, soil erosion, soil water and solute transport processes. In this regard present paper highlights the commonly used methods for soil infiltration rate measurement along with their principles, application, advantages and disadvantage. Three new methods namely run off-on-ponding, run off-on-out and linear source method together with the corresponding algorithm models, experimental set up and procedures are described in detail. Measurement of soil infiltration using these three new methodology variations in soil infiltration capability as influenced by slop, rainfall intensities and surface sealing caused by erosion can be investigated in more detail than earlier. The linear source method provides a new way for measuring intrinsic soil infiltrability. So these analyses offers alternatives to aid the choice of method used for estimating soil infiltrability.

Keywords: infiltrability, soil, run off-on-ponding, run off-on-out, linear source method.

Introduction

In present scenario due to extensive cultivation and urbanization, theagricultural land may results insignificant changes in the infiltration behaviour of the soil. Because of these changes in the infiltration characteristics of the soil,may lead toalteration in the soil waterbalance, low infiltration, high surface runoff and soil erosion[1].Due to constrained infiltration and ponding of water on the soil surface results in poor soil aeration, which may cause to poor root function and plant growth, as well as reduced nutrient availability and cycling by soil organisms where as Runoff carries away nutrients, chemicals, and soil, resulting in decreased soil productivity, offsite sedimentation of water bodies, and diminished water quality.Besides this,being a key component of the hydrologic cycle it also plays a major role in the hydrological functioning of landscapes[2].The total infiltrated water to the soil surface directly affects the quantity of surface runoff erosion, and the ground water recharge,It is due to this reason estimating the infiltration processcorrectlyover time has great deal ofattention in hydrologic budget determinations, watershed management, and irrigation system design [3]. It plays a fundamental role in the determination of techniques for soil conservation, planning and scale of irrigation drainage systems, and assist in the identification of a real picture of water retention and aeration in the soil [4].A robust infiltration rate data is also quite effective to supplement other soil information which helps to soil scientist, engineers, hydrologist and others to deal with a broad spectrum of water and soil resource management and conservation.

Soil infiltration is the process by which water enters the immediate Soilsurface[5,6,7,8,9].Infiltration can be quantified by cumulative infiltration and/or infiltration rate[7]. The rate at which it occurs is known as the infiltration rate, which decreases exponentially and eventuallyreaches to a constant value called steady or final infiltration rate which is very close to the saturated hydraulic conductivity[10].Cumulative infiltration is the total quantity of water infiltrated in the soil within a certain period of time[1]. During an infiltration event, initial infiltration rate is very high and decreases exponentially and eventually.

Theory of infiltration

The theory of infiltration based on some fundamental laws and equation viz.,continuity equation, modified darcy's law called Buckingham-Darcy law and Richards equation.

The equation which explain the movement of water through porous media was first conceptually illustrated by Henry Darcy in 1856. The Law, Q = KsAi, describes the relationship between discharge, Q, the saturated hydraulic conductivity, K, the cross sectional area through which fluid is moving, A, and the hydraulic gradient, i (i = ΔH/L), where ΔH is the change in head between a distance L .[11]

In the flux form this can be expressed as -

$$q = -K\frac{\Delta \mathbf{H}}{\mathbf{L}}$$

Here ,

q = Q/A = (the volume of water flowing through a unit cross-sectional area per unit time t) is called the flux density or, the flux.

K = saturated hydraulic conductivity.

Δ*H*/L = hydraulic gradient,

Darcy's law, is sufficient only to describe steady flow processes, in which the flux remains constant and equal along the conducting system i.eunder saturated conditions of soil [12]. However in unsteady or transient flow processes, in which the magnitude and the direction of the flux and potential gradient vary with time, require the additional law namely law of conservation of matterexpressedas continuity equation and states that if the rate of inflow into the volume element is greater than the rate of outflow, then the volume element must be storing the excess and increasing its water content[12].

Mathematically-

$$\frac{\partial \theta}{\partial t} = -\frac{\partial \mathbf{q}}{\partial \mathbf{z}}$$

where

z = vertical distance from the soil surface downward

q = flux .

θ = soil wetness

t = time

Since Buckingham (1907) was first to describe hydraulic gradient dependent flow through unsaturated media by modifying the Darcy's Lawcalled Darcy–Buckingham equation[26].

$$q = -\frac{K(\theta)\Delta \mathbf{H}}{L}$$

Where,

q = Q/A = (the volume of water flowing through a unit cross-sectional area per unit time t) is called the flux density or, the flux.

K(θ)= is the unsaturated hydraulic conductivity of the porous medium.

$\Delta H/L$ = hydraulic gradient

This law is based on the assumptions that (a) The driving force for water flow in unsaturated soil is the sum of the matric and gravitational potentials.(b) The hydraulic conductivity of unsaturated soil is a function of the water content or matric potential[11].

When this equation is combined with continuity equation a new equation is produced called the Richards equation (1931) forflow of water through unsaturated soil[12].

$$C\frac{\partial\psi}{\partial z} = \frac{\partial}{\partial z}\left(k\frac{\partial\psi}{\partial z}\right) + \frac{\partial k}{\partial z}$$

Here,

$C = -\frac{\partial\theta}{\partial\psi}$ is defined as the specific or differential water capacity (i.e. the change in water content in a unit volume of soil per unit change in matric potential).

Ψ = Sunction Head

z = Vertical Depth

k = unsaturated hydraulic conductivity.

The whole process of infiltration phenomenon are governed by the matric sunction and gravitational potentials as well as hydraulic conductivity of the soil, At the first stage, infiltration of water into the soil is dominated by a period during which suction gradient is high, which results in high initial soil infiltrability. During the second stage of the infiltration process, the soil water content is higher than the maximum molecular water holding capacity and the entry of water among thesoil particles in this stage is controlled mainly by capillary forces and gravity. By the influence of these forces the air inside the soil is replaced by water. The soil infiltrability decreases sharply during this period until the soil is totally saturated. At the third stage, When the soil is totally saturated water infiltration is controlled by gravity alone as a result of this Water movement during this period maintains a steady flow rate inside the saturated soil which gives an indication of sub soil structure and drainage property of the soil.

The duration to reach a ultimate infiltration rate is dependent upon the physical properties of the soil as the soils having lower hydraulic conductivities will take more time to reach a constant infiltration rate due to slower movement of water which requires more time for the wetting front to reach a depth where gravitational forces predominate[11].

Major factors controlling the soil water characteristic.

A wealth of studies show that the variability and magnitude of water infiltration are mainly controlled by Initial moisture content, Saturated hydraulic conductivity, Soil texture, porosity, swelling degree of soil colloids, soil surface conditions etc [4,11,7,13.]. Besides this infiltration rate is also affected by Duration and intensity rainfall [12,7], Topography[7] soil type[4,12,*7*, 14] and Vegetation cover [7,15,16].

Initial moisture content- Usually, lower the initial soil moisture content is, higher the initial soil infiltration rate will be owing to larger suction gradients. The suction gradient decreases with an increase in initial soil moisture content thus lowering the soil infiltration rate and the quicker will be the attainment of the final (constant) rate.

Saturated hydraulic conductivity- ince hydrullic conductivity is directly proportional to infiltrability. A higher saturated hydraulic conductivity is generally associated with a higher infiltrability and vice versa.

Soil texture, porosity,swelling degree of collides – Sandy soil (coarse-textured) has higher infiltration capacity than silty soil (a fine-textured). Generally higher the porosity higher will be the infiltrabilty[17]. Similarly swelling of collides reduces the process of infiltration.

Bulk Density – Infiltration rate directly depends upon the bulk density i.e higher the bulk density the lower is the infiltration rate and vice versa[17].

Soil surface conditions –

When the soil surface having cracks and crust the initial infiltrability is greater than that of a uniform soil. On the other hand, compaction of the soil surface lowers the infiltration rate. A dense surface zone acts as an hydraulic barrier which lowers the infiltration rate.

Duration and intensity ofrainfall –

When the infiltration rate is lower than the rainfall intensity, water penetrates as fast as it arrives and the supply rate determines the infiltration rate that is, the process of infiltration is supply controlled or limited. When the rainfall intensity is higher than the soil infiltrability, excess rainwater begins to pond on the soil surface and then to run off as overland flow occurs[3]. Here by the soil infiltration process is then controlled by the soil infiltrability, called as the profile control stage and the time at which rainfall intensity and soil infiltrability become equal is known as the time to ponding .

Topography - Water falling on steeply-sloped land runs off more quickly and infiltrates less than water falling on flat land.

Vegetation cover - Vegetation protects the soil surface against raindrop impact and lowers its erosive capacity, which minimizes soil erosion and compaction. It also provides a layer of organic matter which enhances soil aggregation and promotes the activity of burrowing insect and animals.

Soil infiltrability is also influenced by plant and animal action in the soil. Soil biota and decaying roots which leave channels throughout the root zone increase pore space and create continuous pores linking surface soil layers to subsurface soil layers[18].

Different methodology regarding infiltration

(A) Infiltration under the ponded condition.

Ring infiltrometer method

Single ring and double ring infiltrometer tests are the most desired and documented technique for directly measuring soil infiltration rates [19,7].The single ring infiltrometers consist of a single metal cylinder which is partially inserted into the soil[20].Since, the principles of the single ring methods are very similar to double ring method which has additional outer ring. The water present in the outer ring moistens a large surrounding area, creating a buffer to effectively minimize any flow of water from the inner ring in a horizontal direction i.e. it ensures the movement of water only in the vertical direction[21]. Since in Single-ring infiltrometers the cylinder is notpurely vertical, and diverges laterally and this lateral divergence is due to capillary forces within the soil, and layers of reduced hydraulic conductivity below the cylinder[20].The dimeter of the single ring method usually uses one ring of 30 cm or a little larger having the height 20 cm. Where as in the double ring method the dimeter of the outer and inner rings are 30cm & 60 cm and the height 20cm[7].

After inserting both the ring 10 cm deep into the soil, concentrically and carefully, while maintaining the same height ring is filled with water.After certain known time intervalvolume of water is applied to the inner ring and recorded it while maintaing a constant head in the inner ring while free water level was kept in outer ring.. The soil infiltration rate is then calculated by dividing the volume of the water supplied to the inner ring to the area of the innerring.

Advantage:-

1. Only small area is needed for measurement so conveniently applied to the field conditions.
2. It is inexpensive to construct, simple to run and doesnot require much amount of water and straight forward of mathematical model for its calculation.

Disadvantage : -

1. Since infiltrometer was made up of steel pipe or iron pipe, when it is inserted in to the soil it disturb the soil structure.

2. In ring infiltrometer method infiltration process is also limited by insufficient water supply. Soil infiltration process is controlled in this situation by the inflow rate instead of the actual initial soil infiltration.
3. When the infiltration process starts water is added with very high flow rate, during short period of time as a result of which rapid wetting of the soil surface occurs that lead to breakdown of surface soil aggregates. Due to disintegration of soil aggregates, surface seal formation occurs that lowers soil infiltrability considerably.
4. This method requires the soil surface to be more or less flattened and leveled and not suitable for the sloped soil surface as it inevitably disturb the structure of the surface soil and the continuity of the slope[22].

Based on the above explanation through ring methodology actual soil infiltrability can't measured.

Mariotte-double ring method

This is the some advance form of double ring infiltrometer having the following partMariotte bottle, double rings, radioactive source, detector and access tube. Here the Mariotte bottle and thedouble-ring method are combined to control the watersupply to the inner ring and the gamma raydetector is used to monitor soil water content changesover time within the soil profile. In this method relative error is computed by comparing the cumulative infiltration and the water content allocation by applying the mass balance theory.

Advantage:-

1. This method improves the accuracy ofdouble-ring method.
2. Apart from this Relative error of the experiment is also calculated.

Disadvantage:-

1. The whole system of the Mariotte apparatus is relatively complicated and expensive for use in field experiments.
2. Disturbance of the initial soil structure and requirement of flat soil surfaces for the experiment is the major problem of ring infiltrometer which can,t be solved by this method.

Disc permeameter

The different parts of this instrument consists of three parts made up of disc covered by a nylon mesh connected to a graduated low capacity reservoirthat provides the water-supply, and a bubble tower which is open to air which provide a pressure head at cloth base of the disc. The size and number of the soil pores, sorptivity, hydraulic conductivity can be measured from cumulative infiltration curve measured with this instrument. This instrument is also capable in indicating whether water flow into the soil is controlled mainly by the capillaries or by gravity.

Advantage:-

1. Initial infiltrability can be measured by this and the water head can be adjusted in this.
2. Here very low amount of water is needed and experiment can be completed in 30 minutes as compared to double ring infiltrometer.

Disadvantage :-

1. Lateral infiltration Exists in this.
2. Refilling of the water supply reservoir is needed when long-term infiltration experiments (i.e. infiltration at successive supply pressure heads at the same sampling point) are performedso make it necessary to stop infiltration measurement during refilling[23] .

(B) Infiltration under the non- ponded condition

Rain fall simulator method

This device duplicates the physical characteristics of natural rainfall as closely and accurately as possible[24].Simulated rainfall is sprayed at a controlled rate with known intensity onto the soil surface to be studied then the generated run off is collected and recorded as a function oftime for a given intensity of rainfall. Finally the infiltration is determined by subtracting the rainfall intensityand the runoff rate. The size of the simulator ranges from simple telephone booth sized installations to ones that require a semi-trailer truck to move. The duration of the test employing a rainfall simulator lies between 30 to 120 minutes with the infiltration rate becoming constant after 20 to 60 minutes. Since universal rainfall simulator applicable to all field situations does not exist as each specific condition requires specific designs for it. Hence, rainfall simulators are usually designed for an individual experiment based on their intended use.

Advantage:-

1. Ability to produce rainfall quickly on demand , wherever it required without having to wait for natural rain at the intensity and duration required, thereby eliminating the erratic and unpredictable variability of natural rain.
2. In addition to this rainfall simulator is relatively inexpensive when compared to the cost of a long-term hydrologic experiment that relies solely on natural rain events.
3. Another advantage of this device includes thatit provide utmost control of an experiment, particularly with respect to data collection and test plot size condition.

Disadvantage:-

1. Initial high soil infiltability of the infiltration process can't be observed practically with this method.
2. For measuring the initial soil infiltrability, If a sufficiently high rainfall intensity is applied, the fast wetting of the surface soil and the impact of the raindrops would immediately initiate surface sealing which lead to lowering of the soil infiltration rate and induce soil erosion.
3. Further it is also incapable in measuring the intrinsic soil infiltrability.

Run off-on-ponding method

This method is developed by [22] which measure soil infiltrability on the sloped surface. The whole experimental setup is shown in the Figure 1, In the figure P represents precipitation intensity which is constant and sprinkle through sprinkler or drippers. The part AB represent the upper slope of length $x1$ which is sheltered with an impermeable material such as plastic or metal sheet having the infiltration zero and is used for runoff generation to supplement the extra water supply to the soil apart from constant precipitation in the down slope area. The part BC, represent the down slope having a length of $x2$ which add on both the run-on from the part AB, and direct precipitation that infiltrates into the soil**.(figure 1-)**

The mechanism for it can be described as follows. As the infiltration starts the permeable section BC is penetrated by water supplied from the impermeable section, $AB$and from direct precipitation .Since initial infiltrability is very high the run-on water moves on only a short distance (Shown as x in Figure 1) starting first from the boundary from the origin of the axis X. As the infiltration process proceed the soil infiltrability decreases with time and a longer slope lengthis needed for complete absorption of the same flow rate ofrun-on water, i.e., x advances with time.This process continue as long as reached a constant value. In BC part runoff occurs or ponded if water is stored, the process of infiltration starts at the bottom of the slope. As the time passess, the ponded water level goes up at the bottom of the slope as the infiltrability goes down further with time. The elevated level of pon ded water is also works as indicator which can be used to estimate the continuous reduction in infiltrability. The whole mechanism for this process is categorized into two stages as: (a) The run-on advance stage; (b) The ponding stage and two separate algorithm models were developed for each stage as given below

(a) Run-on advance stage:

Cumulative infiltration=$\Delta I(x+\Delta x/2)\cos \alpha W$

Direct rainfall=$P(x+x/2)\cos \alpha W\Delta t$

Run-on water=$Px1\cos \alpha W\Delta t$

(b) Ponding stage:

Cumulative infiltration=$\Delta I\, x2 \cos \alpha W$

Cumulative rainfall=$P(x1+x2)\cos\alpha W\Delta t$

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.

Advantage:-

1. This method is capable of measuring the soil infiltration capability under the impacts of raindrop splash and runoff on sloped hill with relatively small amounts of water needed as per the other method.
2. After adopting this method, one can investigate the variations in soil infiltration capabilities as influenced by slope, rainfall intensities and surface sealing caused by erosion.

Disadvantage:-

1. This method is based on assumption that the infiltrability values at all locations along the slope are similar though the differences in run on water arrivals so this assumption needs further clarifications[25].
2. In addition to this, This method is unable to measure the inherit soil infiltration rate of the soil.

Run off-on-out method

This is another method very similar to Run off-on-ponding method again developed by [22].The experimental set up is shown below**. (Figure 2-)**

In the above Figure, section *AB* is runoff production zone covered with an impermeable materialand Section *BC* is forthe water infiltrating zone while receiving the water from direct rainstorm and run off coming from the AB part. Unlike theRun off-on-ponding method, end part of section *BC*, overlandflow is allowed to run out of the soil section being studied while eliminating the effects of water ponding on the soil infiltrability. Further the results obtained by this method were compared by infiltrability curves of the two cases & double ring infiltrometer.(**Figure:- 3)**

Case I Low rainfall intensityand no run out.
Here, rainfall intensity (*P)* = 20 mm/h , slope (*S)* = 0º& ratio of the runoff/infiltration section lengths, *C* = 1∶1.
Case II High rainfall intensityHaving run on advance and run on commutation.
Here, rainfall intensity of *P* = 60 mm/h, slope of *S* = 20º& ratio of the runoff/infiltration section lengths, *C* =1∶1.

The infiltrability curve and the steady infiltration rate obtained bythe double-ring method, denoted as DR, has a flattened section at thestarting that is significantly below that obtained from the results when using the new method. Also curve of Case I were significantly different from those of Case II. The reason behind this can be explained as in Case II, due to high rainfall intensity and slope gradient experienced heavier raindrop splash impacts, and more erosion is expected so it produces higher water flow rate and more soilerosion. Eroded soil particles lead to blocking ofsoil pores, or cause surface sealing, to reduce infiltrability. Similarly, for calculating high initial infiltrabilitywith very high flow rate water is poured in the ring infiltrometer, which damages the Surface soil structure and fast wetting of the soil aggregate leads to their breakdown resulting lower infiltrability.

Advantage:-

1. The newly suggested method is capable in measuring very high initial infiltrabilities which was before not possible by traditional sprinkler method.
2. Due to less relative error, It has very high measurement accuracy.
3. Effect ofwater supply limits on initial soil infiltration determinations andthe impact of surface aggregate damage by fastwetting on lowered initial infiltrability which is related with both the double-ring and rainfall simulator methods are resolved in this method.

Disadvantage:-

1. The inadequacy of this method is inability in measuring the intringic soil infiltrability.

Linear source method

The linear source method for measuring soil infiltrability on slopping land was suggested by [25]. The whole experimental apparatus consists of a flume with two measuring tape, a specially-designed linear water distributorMariotte 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.(**Figure 4 –)**

The whole process of soil infiltration rate is estimated by the advancing rate of the wetting front, separating wet and dry soil as recorded by the digital camera. The mechanism of the soil infiltration rate and the progress of the wetting front at a constant flow rate of water is explained as follow. Due to high initial soil infiltrabity a small area of the slope can absorb all ofthe supplied water. As the time passes infiltrability becomes slow down, in thepreviously wetted soil zone, the same amount of water flow Can't be totally absorbed within the same soil surface area as a result of which the water flow advances over the surface and the progressively increment in the wetted area. After attaning a steady value area wetted by the constant flow rate no longer expands and remains constant.

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

$$\mathbf{q} = K\int_0^{\mathbf{A}} \mathbf{i}(\mathbf{A},\mathbf{t})\,\mathbf{dA} \qquad (1)$$

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), m2; *K*(=1) is the dimensionless transformation coefficient. Numerical solutions of Eq. (1) are given by the following equations.

The water balance at t_1:

$$q_1 \approx i_1 \Delta A_1 cos\alpha$$

The water balance at t_2

$$q_2 \approx i_2\, \Delta A_1 cos\alpha + i_1 \Delta A_2 cos\alpha$$

And the water balance at *tn*:

$$q_n = i_n\, \Delta A_1 cos\alpha + i_{n-1}\, \Delta A_2 cos\alpha + \cdots + i_1 \Delta A_n cos\alpha$$

From above equation the infiltration rates at different times are given as:

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

Advantage:

1. This method is capable of measuring the intrinsic soil infiltrability which make it more advance than other method**.**In this method neither soil structure is disturbed nor the initial soil infiltrabilityis limited by insufficient water supply.

Canclusion

Forgreater understanding and insight into hydrologic processes,soil infiltrability ia a key factor which determines fraction of rain water entering the soil and the amount of runoff generated subsequently theprime cause for soil erosion.Through this paper seven methods, broadly categorized into two, for the computation of soil infiltrability measurements weredescribedalong with their advantages and disadvantages.Additionally three latest researchesfor the infiltration rate measurement in the sloppysoil surfaces is also suggested along with their corresponding algorithm models.These researches overcome the problems of conventional methodology (double ring infiltrometer and rain fall simulator method) of soil infiltration such as incapability of measuring the very high initial infiltration rate and the lowered infiltrationrate due to soil aggregates break-down by fast wetting ofsoil surface.The impact of raindrops splashes, surface sealing and crusting, sheet flow erosion can be determined with the help of the run off-on-ponding and the run off-on-out methods.The linear source method supply a new way of measuring transient soil infiltrability of the sloped surface that can be further used to quantify theeffects of many factors on soil infiltrability.

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