International Conference on Water Resources (ICWR 2009)

"Feasibility to use aero-infiltration in measuring of the infiltration rate and soil moisture content"

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Abstract

Global water scarcity, one of the major threats to humanity, not only in arid or semiarid regions of the world but in overpopulated cities is rising. Population and rapid economic development growth have increase demands for water tremendously. Irrigation activities, mainly in many developing countries, consume most the world useable water as compare to domestic and industrial activities. Improvement to water utilization efficiencies, especially in the agricultural sector, will effectively contribute to lessen the magnitude to this problem. Water seepage rate, or infiltration, into the ground topsoil and the moisture content of soil at particular period in time are important factors in any agricultural farm irrigation operation both in the tropic and temperate regions. Accurate measurements for these factors are not so readily available on the most farmlands since present measuring equipments are not practically suitable. This paper proposes a measuring device that uses a very simple method to measure water infiltration rate into the ground and expansively determine the moisture condition of the soil. Considering that water and air are dynamic vectors, air is possible to diffuse on the similar way as water drips and move from surface to subsurface layer of land during an infiltration process. The mathematical models which formulate the correlations of water infiltration rates into the ground and ground soil moisture contents against air pressure drop rates from the aero-infiltrometer has been empirically developed to define the dynamics and hydraulics phenomena. Parameters in the equations are all physically meaningful and readily from field and laboratory experiments. Experimental validation showed that the equations remained relatively accurate. The aero-infiltrometer is expected to be commonly used to optimize water usage.

Keywords: infiltration rate, soil moisture content, aero-infiltrometer

1 Introduction

Infiltration as part of hydrologic cycle is the entry of waters into ground due to gravity forces and the hydrologists also remarked it as opposite of seepage. Infiltration is the net movement of water into soil (Davis and Masten, 2004). The rate and quantity of water which infiltrates is a function of soil type, soil moisture, soil permeability, ground cover, land surface condition, and depth of water table, as well as intensity and volume of precipitation (Wanielista et al., 1990).

The soil type helps identify the size and number of capillaries through which water may move into the ground, while moisture content helps identify capillary potential and relative conductivity. For soils with low moisture content, capillary potential is high and conductivity is low (Wanielista et al., 1990). Soil moisture will increase soil conductivity. The depth of water table affects the potential amount of water which can infiltrate into the soil. Higher water tables mean that the potential infiltration volume may be limited. Soil type with its water conditions and intensity with volume of precipitation affect the amount of water from precipitation which actually infiltrates into the soil (Wanielista et al., 1990). Water irrigation must be monitored more carefully to reduce losses of water and nutrients through deep percolation in the regions dominated by high and medium infiltration rate zones. Crops with greater water requirement and/or deep rooted annual crops may be grown to decrease volumes of water and nutrients moving beyond the root zone and to increase efficiency of agricultural water use in those regions (Erşahin and Karaman, 2000). Measuring the infiltration rate, which is defined as the depth of water infiltrates into ground per unit of time, is possible to predict the volume of water demands to be irrigated using sprinkler technique or gravity irrigation to optimize the quantity of water used in agricultural lands and to avoid the overland flow. In irrigation, a basic understanding of soil/water/plant interactions will help irrigators efficiently manage their crops, soils, irrigation systems and water supplies, and applying water to assure sufficient soil moisture is available for good plant growth (Scherer et al., 1996).

Infiltrometer is a device used to measure the rate of water infiltration into soil or other porous media and extended to measure the soil moisture content. Commonly used infiltrometers are single-ring or double-ring infiltrometer. Others are the disc permeameter, tension infiltrometer, turf-tec infiltrometer and sprinkler infiltrometer. There are several challenges related to the use of ring infiltrometers: (i) the pounding of the infiltrometer into the ground deforms the soil, compressing it or causing cracks which can affect the measured infiltration capacity; (ii) with single ring infiltrometers, water spreads laterally as well as vertically and the analysis is more difficult; and (iii) ring infiltrometers cannot reliably characterize infiltration of furrow irrigation, of sprinkler irrigation, or of rainfall (Bouwer, 1986). Moreover, this method using water as indispensable fluid is not available anywhere, such as in steep and vertical hill slopes as well as in other critical conditions. This will cause the measurement to face a difficulty in unfortunate conditions. Whereas, at a certain time the water infiltration rate and or the soil moisture content are urgent to measure conscientiously in the difficult places such as in valley and hilly lands.

Measuring the water infiltration rate and soil content moisture are important for hydrologists, water engineers, farmers and irrigators to optimize water uses in agriculture, water resource conservation and management, storm water management as well as soil erosion and sediment control. The data are necessary to collect from certain places with different morphologies from mountains to estuary of a river basin catchment area. Unfortunately, the double-ring infiltrometer that is commonly used has several difficulties such as miserly and bulky equipment as well the needs to have available water resources. The previous study focuses on two-phase flow infiltration related to water and soil air, confirmed that air compression ahead of the wetting front is a major cause of wetting front instability followed by fingering. These processes may substantially affect the rate of water infiltration (Wang et al., 1997). Although the models derived on the basis of the *Green - Ampt* assumptions were extended to include the potential effects of air compression and air counter-flow during water infiltration into a porous medium (Wang et al., 1997), mathematical models which formulate correlations of water infiltration rates into the ground and soil moisture contents against air pressure drop rates are still not fully understood. The idea to replace dynamic vector from water to air measurement is still not focused.

The objectives of this study are (1) to promote a new methodology that is practically feasible to measure water infiltration rate and soil moisture content,

(2) to empirically derive mathematical expressions based on data monitoring through the physical model of aero-infiltrometer accounting for water infiltration rate and soil moisture content theoretically.

2 Design equipment and operational procedure

The aero-infiltromer's components consist of air tank, air valve, air injection nozzle, air input nozzle, and pressure meter as presented in Figure 1 (Lai and Ibrahim, 2006; Jalali, 2007). The different diameters of a PVC pipe are selected to fabricate this equipment conical from air tank to air injection nozzle. A PVC pipe is used to invent aero-infiltrometer due to its low price of such material compared to glass and steel. The advantages of a PVC pipe are easy to fabricate manually and simple to stick the air injection nozzle (see Figure 1) into the soil.

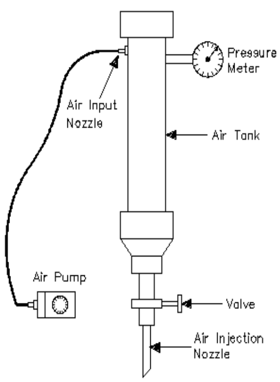

Figure 1 Schematic of aero-infiltrometer

A simple procedure of using the aero-infiltrometer as follows:
- select the target's land and clean it from plants and rubbish;
- stick in the air injection nozzle into the soil at 6 cm of depth;
- close the valve and using the air pump to inject air through the air input nozzle;
- stop air injection when air pressure is indicating at the pressure meter up to 17 psi;
- open the valve and read cumulative air pressure drop until air pressure in the air tank is equal to standard atmospheric pressure (≈14.696 psi);
- record the cumulative time and cumulative air pressure drop in the formatted table as raw data collection; and
- repeat the measurement until the reading of air pressure drop is stable.

3 Model development

3.1 Postulate

The concept of this methodology is based on the postulate that water and air are dynamic matters and air is possible to diffuse in the soil in a similar way generally as water drips and to move from surface to subsurface land when it infiltrates. With the pressure of the same type of soil it is assumed that air moves properly to subsurface land as the movement of water. The air-confining vadose zone such as the effects of air pressure fluctuation, air eruptions from the surface, hysteresis in capillary pressure, and macro-pores on infiltration have been analyzed in the previous study (Wang et al., 1997). All the phenomena can be generally represented to the parameters in Equations to analyze the correlation between air infiltration and water infiltration in this study. Therefore, it is possible to summarize the global phenomena into the mathematical expressions. The parameters in the equations will examine the physical meaningful to explain the water infiltration rate and soil moisture content. Apparently, it is possible to use the data measured from the physical model to empirically develop mathematical models that correlate water infiltration rate and air pressure drop rate as well as soil moisture content and air pressure drop rate based on the data monitoring recorded via the double-ring infiltrometer and the aero-infiltrometer.

3.2 Data calibration and mathematical models

Aero-infiltrometer and double-ring infiltrometer were used to collect the raw data i.e., the decreasing of water level reading from the double-ring infiltrometer and the cumulative air pressure drop reading from the aero-infiltrometer pursuant to the time. Soil is generally classified by five factors i.e., climate, slope, biological activity, parent material, and age. These factors determine the soil drainage characteristics and more than 3,000 specially named soil types were recorded (Wanielista et al., 1990). Based on the data from the previous study collected from three sites around the campus of Universiti Tun Hussein Onn Malaysia at Parit Raja, Batu Pahat in Johor state, Malaysia (Lai and Ibrahim, 2006) it is possible to develop mathematical expressions to evaluate the dynamic and hydraulic phenomena related to movement of water and air into the soil.

As a starting point for modeling of the infiltration rate, this paper considers the data monitoring of air pressure drop and water infiltration. Cumulative times recorded from the aero-infiltrometer and double-ring infiltrometer are inserted into the same column of data recorded table, considering that the water in the vadose zone has a pressure head less than atmospheric pressure (Kresic, 2007). Calibrations of aero-infiltrometer and double-ring infiltrometer to have the same scale of cumulative times against the cumulative air pressure drops and the cumulative water infiltrations are reasonable performed via extrapolation and/or interpolation (see Figure 2).

Air pressure drop rate is defined as the decreasing of air pressure drop per unit of time. If we recognize that air pressure drop rate is

$$\mathbf{P} = \frac{\int \partial L_p}{\int \partial t} \qquad (1)$$

where,

P is air pressure drop rate (in psi/hr);
∂L_p is air pressure drop during ∂t (in psi);
∂t is time period (in hr),

it is experimentally possible using Equation 1 to calculate the air pressure drop rates of tested soils obtained vary from 8.6 to 45 psi/hr for site-1, from 66.9 to 180 psi/hr for site-2 and from 6.1 to 45 psi/hr for site-3.

One of the oldest and most widely used infiltration equations was developed in 1939 (Horton, 1939). This equation assumes that the rainfall intensity is greater than the infiltration capacity at all times and that infiltration rate decreases with time (Bedient and Huber, 1992). The Horton equation's major drawback is that it does not consider storage available in the soil after varying amounts of infiltration have occurred, but only consider infiltration as function of time (Akan, 1993). The equation used in this study to measure the experimental water infiltration rate is defined as (Fulazzaky et al., 2008)

$$\mathbf{f_{exp}} = \frac{\int \partial L_w}{\int \partial t} \qquad (2)$$

where,

f_{exp} is experimental water infiltration rate (cm/hr);
∂L_w is decreasing of water level during ∂t (in cm);
∂t is time period (in hr).

Using Equation 2 we obtained the water infiltration rates of tested soils ranging from 4 to 50 cm/hr for site-1, from 1 to 5 cm/hr for site-2 which may be categorized as sandy loam according to the previous classification (Kopec, 1995) and from 11 to 30 cm/hr for site-3 (see Figure 5).

The calibration of time affects a mathematically intractable air infiltration movement model that is obtained via tracing a curve of correlation between air drop pressure rate and experimental water infiltration rate. The properties of the models were selected from the best correlation coefficient, R^2, from trial of linear, logarithmic, exponential or power curve expressions. We then tried to obtain reasonable explanations for the values of infiltration rate and examine the dynamic properties of the model over this part of the moisture content coefficient, α, related to capillary potential and relative conductivity as well as the soil type index, β, related to size and number of capillaries hypothetically. Power curves analysis are found as in Figure 3 to give excellent insight into dynamic matters movement i.e., air and water and also give a forum for understanding and verifying the two differently used air infiltrating and water infiltration analyses. The mathematical expression is (Fulazzaky et al., 2008)

$$f_{th} = \alpha \cdot (P)^{\beta} \qquad (3)$$

where,

f_{th} is theoretical water infiltration rate (in cm/hr);
P is air pressure drop rate (in psi/hr);
α is moisture content coefficient related to capillary potential and relative conductivity (in cm/psi);
β is soil type index related to size and number of capillaries (dimensionless).

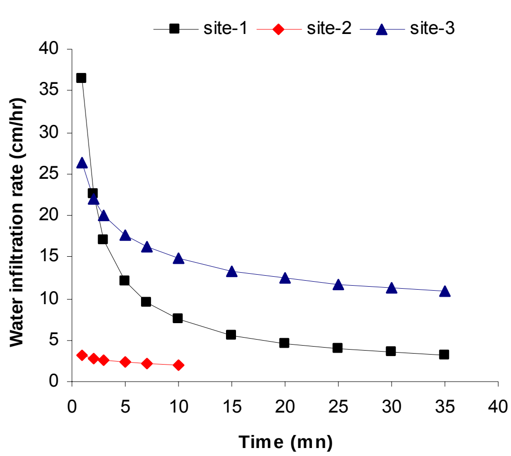

Figure 5 Evolution of infiltration rate

The main hydraulic characteristic of the unsaturated zone is the negative fluid pressure head, which is lower than the atmospheric pressure (Kresic, 2007). Soil types and degree of soil saturation are the major determining factors in infiltration. Sand, silt, clay and decays are the primary particles in soil. Moisture content coefficient, α, is an important parameter which depends on capillary potential and relative conductivity affecting on mobility of air and water during movement in the soil. While soil type index, β, is a parameter that lies to size and number of capillaries influencing whether air movement or water movement to infiltrate from surface to subsurface land. Table 1 shows the values of α and β for different sites of measurement. The analysis of these parameters using the data from the previous study (Jalali, 2007) to examine the artificial sandy clay (sandy 50%, clay 50%) is verified that increasing the initial moisture content in the soil will increase the soil moisture content coefficient, α, which is susceptibility related to capillary potential and relative conductivity. While the soil type index, β, will decrease with moisture which is supposedly related to deduction of size and number of capillaries due to water adsorption onto the soil, as shows in Table 1.

Table 1 Values of α and β

	α (cm/psi)	β	R^2
For different site of tested soils			
Site-1	0.1683	1.4708	0.9963
Site-2	0.0803	0.7703	0.9371
Site-3	4.2691	0.5051	0.8739
For different initial moisture content			
10%	2.9947	0.5842	0.9992
15%	3.4935	0.5812	0.9939
25%	5.7551	0.3963	0.9767

If the vadose zone envelops the soil, the water contained therein is termed soil moisture. The movement of water within the vadose zone is studied within soil physics and hydrology, particularly hydrogeology, and is of importance to agriculture, contaminant transport, and flood control. The Richard's equation is often used to mathematically describe the flow of water, which is based partially on Darcy's law (Kumar, 2004). Recharge, which is an important process that refills aquifers, generally occurs through the vadose zone from precipitation. Soil moisture content is defined as the quantity of water contained in soil on gravimetric basis. The property is used in a wide range of scientific and technical areas, and is expressed as a ratio, which can range from 0 (completely dry) to the value of the soil's porosity at saturation (van Genuchten, 1980; Dingman, 2002; Lawrence and Hornberger, 2007). In calculus this may be written as

$$\theta_{exp} = \frac{\Delta I}{\Delta I_o} . 100\ \% \qquad (4)$$

where,

θ_{exp} is experimental soil moisture content (in %);
ΔI is water infiltration rate during Δt (in cm/hr);
ΔI_o is water infiltration rate after soil saturation (in cm/hr).

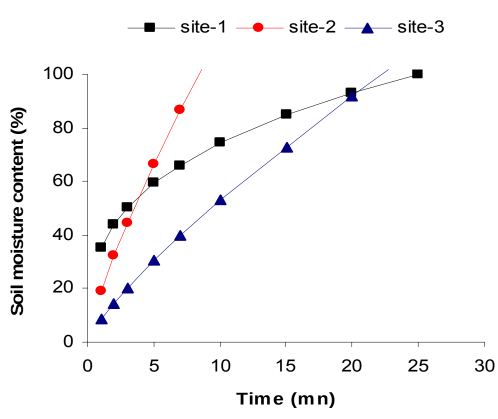

Figure 6 Evolution of soil moisture content

Soil moisture content can be experimentally calculated using Equation 4 that the values of θ_{exp} vary from the value of the soil moisture content at θ_{exp} = 31 % which correlates that the air pressure drop rate, P, is 45 psi/hr to the soil's porosity at saturation (θ_{exp} = 100 %) which correlates the air pressure drop rate, P, is 8.6 psi/hr for site-1; from θ_{exp} = 3.9 % which correlates P = 180 psi/hr to θ_{exp} = 100 % which correlates P = 66.9 psi/hr for site-2; and from θ_{exp} = 6.1 % which correlates P = 45 psi/hr to θ_{exp} = 100 % which correlates P = 7.2 psi/hr for site-3 (see Figure 6). A plot of air pressure drop rate versus experimental soil moisture content takes the shape as shown in Figure 4 therefore gives a mathematical expression (Fulazzaky et al., 2008) of

$$\theta_{th} = \varepsilon . (P)^{\gamma} \qquad (5)$$

where,

θ_{th} is theoretically soil moisture content (in %);
P is air pressure drop rate (in psi/hr);
ε is soil porosity coefficient related to void spaces in the soil (in %.hr/psi);
γ is soil permeability index related to moisture in the soil (dimensionless).

Table 2 Values of ε and γ

	ε (%.hr/psi)	γ	R^2
For different site of tested soils			
Site-1	443.24	-0.6931	0.9956
Site-2	4×10^7	-3.0357	0.9813
Site-3	2380	-1.5567	0.9954
For different initial moisture content			
10%	14,941	-1.6927	0.9874
20%	12,085	-1.6397	0.9814
25%	4,058	-1.3620	0.9895

The soil in which groundwater moves is characterized by many factors, two of which are void spaces, see porosity and resistance, and see permeability (Wanielistaet et al., 1997). It is theoretically possible using Equation 5 to calculate the values of soil moisture content for site-1, site-2 and site-3 in accordance with the air pressure drop rate which can range from completely dry to the value of the soil's porosity at saturation. Table 2 shows that the values of ε and γ are independent for different sites of measurement. The phenomena explains that the artificial sandy clay characterizing low initial moisture content indicates high air mobility potential due to the high scattering of void spaces. The parameters in Equation 5 are physically meaningful where the soil porosity coefficient, ε, is high for dry soil and soil conductivity is low that justifying through the soil permeability index, γ, is low (see Table 2). The values of ε will decrease and the values of γ will increase with moisture which confirms the previous study where initial differences in structure and porosity were transient and related to soil moisture content (Foley et al., 2006). Air pressure drop rate and water infiltration rate will increase with the decreasing soil moisture content that is verified.

4 Conclusion

A new proposed methodology using aero-infiltrometer (Lai and Ibrahim, 2006; Jalai, 2007) is feasible to measure water infiltration rate and soil moisture content. The theoretical infiltration rate and soil moisture content data measured via air pressure drop rate using aero-infiltrometer were found closely similar to the experimental infiltration rate and soil moisture content data measured via double-ring infiltrometer.

Functional infiltration and moisture expressions accounting for capillary potential and conductivity, size and number of capillaries, void spaces, and moisture content in the soil were presented. Parameters in the equations are all physically meaningful and experimental validation showed that the equations remained relatively accurate.

Acknowledgments This paper was used the Short Grant budget from the Universiti Tun Hussein Onn Malaysia (UTHM) and explored the data of Final Year Undergraduate Project reports. The data and financial supported by the UTHM were greatly appreciated.

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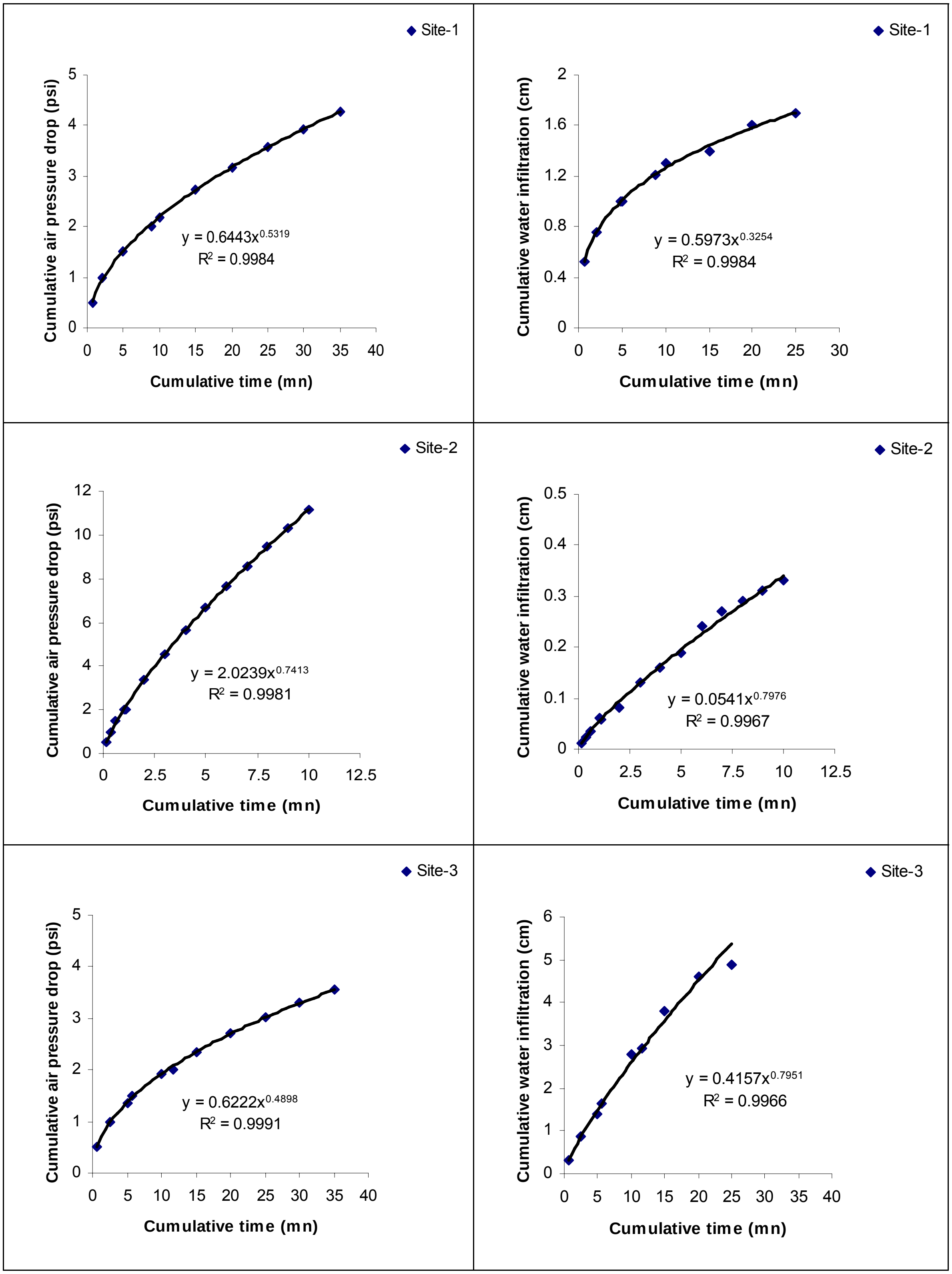

Figure 2 Time versus air pressure drop and time versus water infiltration

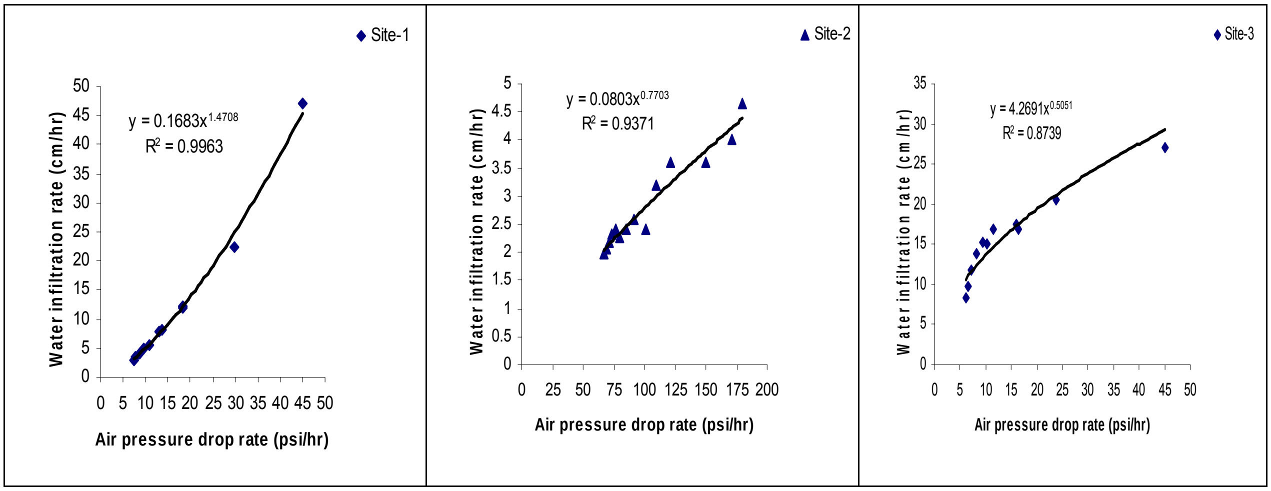

Figure 3 Curve of $f = \alpha \cdot (P)^{\beta}$ for site-1, site-2 and site-3

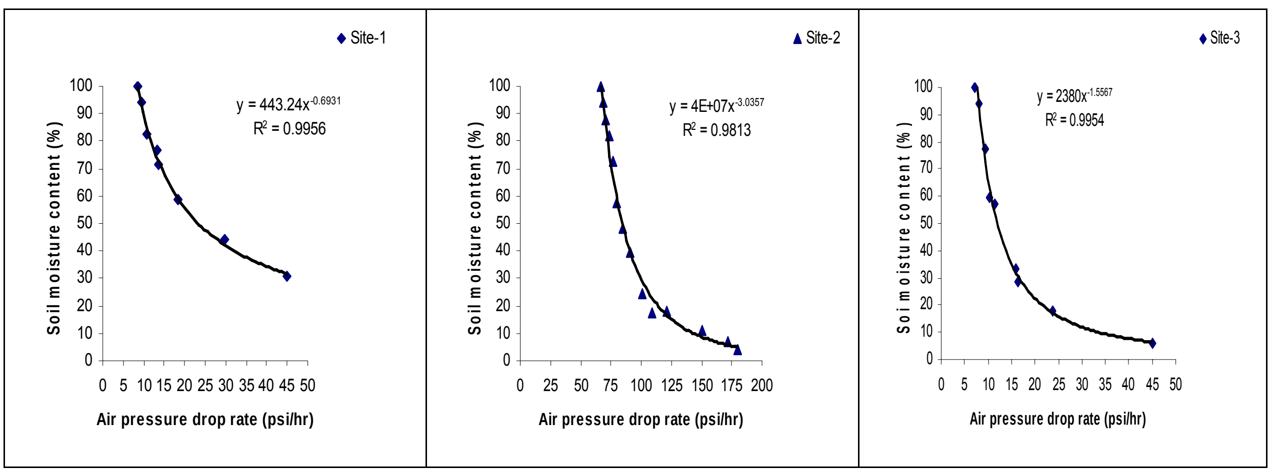

Figure 4 Curve of $\theta = \varepsilon \cdot (P)^{\gamma}$ for site-1, site-2 and site-3