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Review of Infiltration Models/Equations and their Application

Ehiomogue Precious
Department of Agricultural and Bio-Resources Engineering,
Michael Okpara University of Agriculture,
Umudike, Nigeria.

Udoumoh Unwana, & Wilson Udeme
Department of Agricultural and Food Engineering,
University of Uyo, Uyo, Nigeria.

Abstract

Infiltration is the process by which water on the ground surface enters the soil. It is commonly used in both hydrology and soil sciences. Infiltrometers, permeameters and rainfall simulators are all devices that can be used to measure infiltration rates. The knowledge of final steady infiltration rate of soil is important for irrigation water efficiency, designing desirable irrigation systems, and drainage, optimizing the availability of water for plants growth and metabolism, improving the yield of crops and minimizing erosion [1]. Thus, infiltration rate is an important factor in sustainable agriculture, effective watershed management, surface runoff, and retaining water and soil resources. Infiltration characteristics of a given soil are part of the dominant variables influencing irrigation. The total irrigation time or intake opportunity time will have to be estimated from the soil intake rate. In addition, the amount of water applied in a border or furrow irrigation upon which advance and recession expression have been determined will have to be estimated from infiltration expression using the contact time. In sprinkler irrigation, the water application rate must not exceed the soil intake rate and similarly stream sizes for border and furrow systems are governed by the soil infiltration rate. Therefore, the role played by infiltration in irrigation and the hydrologic cycle in general is an exceedingly important one. In this study, ten (10) infiltration models consisting of five (5) empirical (Philip (PH), Kostiakov (KT), Modified Kostiakov (MK), Kostiakov-Lewis (KL) and Natural Resource Conservative Service (NRCS)), Three (3) physically based (Green-Ampt (GA), Smith-Parlange (SP), Talsma-Parlange (TP)) and two semi-empirical (Swartzendruber (SW) and Horton (HT)), were reviewed extensively.

Keywords: *infiltration rate, infiltration models, irrigation systems, soil properties, soil water*

Introduction

Infiltration is an important mechanism in soil science, hydrology, irrigation, agriculture, civil engineering, and environmental engineering and sciences. Infiltration not only controls the division of water into soils, water redistribution within soils, and even deep percolation down to groundwater, but also the occurrence time and amount of runoff [2]. The soils infiltration capacity (i.e its steady state infiltration rate) is also an important factor in planning land disposal of waste water, in selecting and planning irrigation systems, in deciding appropriate water conservation techniques on agricultural lands and in the hydrological modelling of run-off processes.

Infiltration modelling approaches are often separated into three categories: physically based, approximate/semi-empirical (analytical), and empirical models. The physically based approaches use parameters that can be obtained from soil water properties and do not require measured infiltration data. The evaluations of semi-empirical/analytical models are purely mathematical or graphical. It is called semi-empirical, because their evaluation process involves the use of the asymptomatic or steady state infiltration rate unlike the physically based models that depends strictly on soil water characteristics. Empirical models tend to be less restricted by assumptions of soil surface and soil profile conditions, but more restricted by the conditions for which they were evaluated, since their parameters are determined based on actual field-measured infiltration data[3].

All infiltration equations make use of some factors in their characterization. However, the physically based equations rely more heavily on the soil hydraulic and physical properties occurring within the profile, such as saturated hydraulic conductivity, soil moisture gradient, and suction at the wetting front. Empirical models rely more on parameters that are determined by curve fitting or estimated by other means and, thus, may better reflect the effect of differences in surface conditions than the physical models, as long as parameters are calibrated separately for those different conditions. Additionally, sometimes-approximate physically based models are used as empirical models with parameters determined in a similar manner. The assumptions, form and intent of each equation need to be considered in deciding which equation to use for a particular application[4].

Infiltration has received a great deal of attention from soil and water scientists/engineers because of the fundamental role of infiltration characteristics in land-surface and subsurface hydrology, irrigation and agriculture. Water infiltration into soil is a function of the physical properties of soils, primarily the initial soil water content and saturated hydraulic conductivity, soil texture and structure, vegetation, and plant root density [5].

Infiltration characteristics of soils can be quantified by direct measurement on the field and / or when field infiltration data are fitted mathematically to infiltration models [6]. The use of infiltration models becomes necessary because field measurements of soil infiltration are cumbersome, expensive, time-consuming and give only local scale results [7].

[8]Reviewed the commonly used direct methods for measuring soil infiltration which include single ring and double ring infiltrometer, mariotte-double ring infiltrometer, disc permeameter, rainfall simulator, runoff-on-ponding, runoff-on-out and linear source methods. The results obtained from field infiltration tests and soil analysis is used for infiltration modeling.

Many researchers have compared the accuracy of the models by comparing the computed and observed infiltration rates [9]. Under specific conditions, a particular model shows better predictions than others.

Adequate water resource management is essential for stable and efficient crop production especially under irrigated agriculture. Hence, efforts are being directed towards water management and conservation activities such as irrigation and control of flood and erosion. Realistic planning of these water management activities requires sufficient information on the rate at which different soils take up water under different conditions of soil and water. Data on rates of infiltration of water into soils can be used to supplement other soil information which could assist soil scientists, engineers, hydrologists and others to deal more effectively with a wide spectrum of water resource management and conservation problems [10].

Theory and Process of Infiltration

The infiltration rate *is* the soils characteristics, which determines the rate at which water can enter the soil under specific conditions. The accumulated infiltration *(I)* is the total quantity of water that enters the soil at a given time[11]. When water is applied to a soil, the following processes occurs; air is displaced for water to fil the pore spaces, overcoming of metric potential and breaking of soils forces and finally infiltration of water, all these brings about the movement of water from the surface through the soil mass/profile and redistribution or interflow [12].

According to [13], infiltration takes place due to combined influences of gravity and capillary forces. The infiltration of water through a soil surface may be visualized as a flow through a large number of tiny irregular pipes. As the infiltration continues the wet front will be travelling downwards. At any instant of time the resistance to flow is proportional to the thichness of the saturated layer up to the wetting front down beneath the surface while the driving head is proportional to the depth of flow[3].

Water Infiltration

Surface runoff and groundwater recharge are linked to infiltration, soil water movement or percolation is the process of water flow one point to another within the soil. Infiltration and percolation cannot be treated independently, because the rate of infiltration is controlled by the rate of percolation below the soil surface[14]. When rainfall or irrigation infiltrates into the soil, the amount of water retained in the topsoil is affected by the amount of organic matter content, the size, shape and arrangement of mineral particles [15]. Generally, the more the amount of organic matter the soil contains, the more the water it will be able to absorb depending on the soil texture and structure which are known to be modified by organic amendment[16].

For any given soil, the land use pattern plays a vital role in determining the infiltration characteristics and is of particular interest to soil scientists, hydrologists, agronomists, geographers and agricultural engineers. The two essential parameter used in characterizing infiltration of water into the soil profile are the rate and the cumulative amount. Measurement and numerical solutions have shown that the infiltration rate in a uniform, initially dry soil when rainfall does not limit infiltration, decreases with time and approaches an asymptotic minimum rate[10].

Water infiltration is an important process, which controls surface runoff, soil erosions, soil water storage and deep percolation[17]. Information on its magnitude or potential is a key input in the development of sound soil water management and conservation practices. Water infiltration is highly sensitive to soil type, tillage and surface residue[18]. Many of the same factors that control infiltration rate also have an important role in the redistribution of water below the soil surface during and after infiltration. Thus, an understanding of infiltration and the factors that affect it is important not only in the determination of surface runoff, but also in understanding subsurface movement and storage of water within a watershed[19].

Factors Affecting Infiltration Rate

Factors that control infiltration rate include soil properties that are strongly affected by hydraulic conductivity and water holding capacity. These soil properties are related to the characteristics of soil texture, structure, composition, and degree of compaction, which influence soil matric forces and pore space. Additionally, antecedent water content, type of vegetative or other ground cover, slope, rainfall intensity and movement and entrapment of soil air are important factors that also affect infiltration rates. The hydraulic conductivity is of critical importance to infiltration rate since it expresses how easily water flows through soil and is a measure of the soil’s resistance to flow. The unsaturated hydraulic conductivity is a function of pressure head and distribution of water in the soil matrix [20]. The saturated hydraulic conductivity, the hydraulic conductivity at full saturation, is used as a parameter in many of the infiltration equations, since it is easier to determine than either the unsaturated hydraulic conductivity or the diffusivity. Factors affecting water infiltration are discussed briefly.

(i) Water holding capacity

This is the amount of water a soil can hold due to pore size distribution, texture, structure, percentage of organic matter, chemical composition, and current water content. For saturated conditions, the water holding capacity is zero and the hydraulic head is positive [19,21]. Soils with higher sand percentages have larger size particles, larger pores, lower water holding capacity and higher hydraulic conductivity, diffusivity and infiltration rates than clay soils, which have smaller micro-pores and bind water molecules more tightly.

(ii) Soil structure

Soil structure describe the adhesion and aggregation of soil particles and formation of plates, blocks, columns, lumps, and cracks and is affected by chemical composition of soil particles, amount of organic matter present, soil texture, water content, and activity of organisms such as earthworms, insects, fungi, plant roots and microbes. Soil structure affects the path by which water moves through the soil[22].

(iii) Micro-pores

Micro-pores are generally less than a micrometre in width, and occur typically in clayey soils[23]. Water in these pores is referred to as adsorbed, bound or residual water because it is discontinuous and is affected by such phenomena as cation adsorption, hydration, anion exclusion and salt sieving, and therefore does not participate in normal flow behaviour [12]. Capillary pores are the typical pores in a medium textured soil that range in width from several micrometres to a few millimetres.

(iv) Soil compaction

Soil compaction results from applying pressure on the soil surface, which reduces pore space, damages soil structure, reduces the air available to plant roots and other soil organisms and reduces infiltration rates. Rainfall on bare soil can cause soil compaction. Often where soils have been ploughed repeatedly with heavy equipment there is a hardened and compacted layer below the topsoil called a plough pan, which may impede redistribution. A naturally hardened layer called a fragipan may also obstruct the vertical movement of water[24].

(v) Antecedent or initial water content

This affects the moisture gradient of the soil at the wetting front, the available pore space to store water and the hydraulic conductivity of the soil. Initial water content is therefore a critical factor in determining the rate of infiltration and the rate at which the wetting front proceeds through the soil profile. The drier the soil is initially, the steeper the hydraulic gradient and the greater the available storage capacity; both factors that increase infiltration rates[3].

(vi) Vegetative and other ground cover

These are mulches and plant residues reduce soil temperature and evaporation from the soil surface, but vegetation also loses moisture through transpiration. Vegetation increases infiltration rates by loosening soil through root growth and along with natural mulches and plant residues, intercept raindrops, which compact and damage the structure of bare soil and cause surface sealing and crushing[19].

(vii) Slope

Slope also affects infiltration rate. A decrease in water infiltration rate was observed with increase in the slope steepness for grass-covered slopes[25]. According to these scientists, the slope may have the greatest effect on surface runoff production and infiltration rate when the soil is close to saturation. Rainfall intensity also affects water infiltration into soil, when the rainfall intensity exceeds the ability of the soil to absorb water, infiltration proceds at the infiltration rate. At the time of ponding, the infiltration rate can no longer keep pace with the rainfall intensity and depression storage fills up and then overflows as runoff. If the rainfall has a higher intensity, depression storage will fill faster and time of runoff will occur sooner, after the time of ponding[24].

(viii) Hydraulic conductivity

The hydraulic conductivity is a measure of the ability of the soil to route water[26]. From a theoretical view point K_θ can be expressed as:

$$K_\theta = k\frac{\rho_\omega\, g}{\mu_\omega}k_{rw}(\theta) \qquad 1$$

Where k is the intrinsic permeability; $k_{rw}(\theta)$is relative water permeability (namely ratio of the unsaturated to the saturated water permeability) that varies from zero for completely dry soils to one for fully saturated soils; and μ_ω is the water viscosity. This shows that the soil conductivity depends on the soil matrix k, the moving fluid ($\rho_w$and μ_ω) and the fluid contente in the soil ($k_{rw}(\theta)$). The dependence of k on θ is unaffected by hysteresis. The hydraulic conductivity at or above saturation ($h \geq 0$) is refered to as the hydraulic conductivity at natural saturation (k_s)[3].

Measurement of infiltration

Infiltration is the process by which water on the ground surface enters the soil[3]. Infiltration rate in soil science is a measure of the rate at which soil is able to absorb rainfall or irrigation[27]. Infiltration is measured in inches per hour or millimetres per hour. The rate decreases as the soil becomes saturated. If the precipitation rate exceeds the infiltration rate, runoff will usually occur unless there is some physical barrier. It is related to the saturated hydraulic conductivity of the near-surface soil[24].

Several methods for measuring infiltration has been developed by different scientists, which give insight into its significance in the hydrologic cycle[12]. Some of the methods widely used include rainfall simulators; runoff plots; basin method; furrow method; cylinder infiltrometer. There are two general approaches to the determination of infiltration rate[13]. One of these approaches analyses the observed rainfall hyetograph and the runoff hydrograph from a small plot or a natural watershed to estimate the infiltration rates. The other method uses infiltrometer (an instrument for measuring infiltration). All the methods discussed above are developed for different purposes and each method serves its purpose. In spite of some marginal differences, all these methods have a place in the evaluation of the factors that affect infiltration and in evaluation of different parts of watershed. The infiltrometer always gives the infiltration rate and the information from such infiltrometer tests at various locations in the basin way give a satisfactory estimate of the average infiltration rate for the entire basin as a whole. In the hydrograph analysis method and actual infiltration, rate curve is obtained. However, the derived estimate of infiltration is as accurate as the precision of the measurement of rainfall and runoff from the basin[13]. Infiltrometer are of two types; flooding type and rainfall simulators. In the flooding type of infiltrometer, water is applied in the form of a sheet usually with a constant depth of flooding. They may use a single ring or two rings to delineate the sample area. In the former case, it is known as a simple infiltrometer or a tube infiltrometer. In the latter case, it is called a double ring infiltrometer.

In the rainfall simulator, water is applied by sprinkling at a uniform rate that is in excess of infiltration rate. The double-ring infiltrometer is often used for measuring infiltration rates[3]. The double-ring infiltrometer was introduced in an effort to eliminate the effect of divergence on measured infiltration[28, 29]. The Double ring infiltrometer requires two rings: an inner and outer ring. The purpose is to create a one-dimensional flow of water from the inner ring, as the analysis of data is simplified. If water is flowing in one-dimension at steady state condition, and a unit gradient is present in the underlying soil, the infiltration rate is approximately equal to the saturated hydraulic conductivity[30]. An inner ring is driven into the ground, and a second bigger ring around that will help to control the flow of water through the first ring. Water is supplied either with a constant or falling head condition, and the operator records how much water infiltrates from the inner ring into the soil over a given time period. There are three main problems related to the use of infiltrometer: 1. the pounding of the infiltrometer into the ground deforms the soil causing cracks and increasing the measured infiltration capacity. 2. Natural rainfall reaches terminal velocity. In addition, natural droplet sizes differ with different types of storms. Pouring water from a measuring cup however loses this momentum and variance. 3. With single ring infiltrometer, water spreads laterally as well as vertically and the analysis is more difficult. The double ring infiltrometer consists of two concentric rings; it works by directing water into a known surface area, the rate of infiltration is determined by the amount of water that infiltrates into the soils per surface area, per unit time. The purpose of the outer ring is to create a one-dimensional flow of water from the inner ring, as the analysis of data is simplified. The two rings are usually made of materials of same thickness; both rings are installed to a depth of more or less than 150mm using a hammer and a little to avoid seepage during infiltration test. A jute bag is wrapped around the surface before pouring water into the rings to avoid scouring of the soil within the rings. The depth of water in the inner ring is usually taken into account immediately, which marks the beginning of the infiltration measurement. Refilling is done when the water level in the rings has gone down considerably. The depth of water that infiltrated into the soil at a given time is considered as the change in depth of the graduated float or meter rule on the surface of water in the inner ring. [31]noted that in-situ infiltration testing such as pitot infiltration test, borehole test, and double ring infiltrometer provide an estimate of infiltration rates that are generally representative of the actual infiltration rate at a specific location on the site. [32] used a double ring infiltrometer and a single ring infiltrometer on the flood-plain in the Nylsvley Nature Reserve, in South Africa, during December 1997, and January 1998 and May 1998. The measured infiltration rates varied from 0.28mm/hour to 27.3mm/hour. The choice of any method depends on the purpose of study, operation cost and the availability of the equipment. The rainfall simulation method gives results closer to those under natural rainfall conditions. However, the construction cost and time for rainfall simulators when compared to the cylinder infiltrometer limit its use. Cylinder infiltrometer is cheaper to construct, easy to operate, transport and does not need any cumbersome site preparations, as does the rainfall simulator. Hence, double ring infiltrometer was used for this study. Figure 1 below are the front view and plan of double ring infiltrometer use for the experiment while figure 2 is the isometric of the double ring infiltrometer used for the infiltration runs.

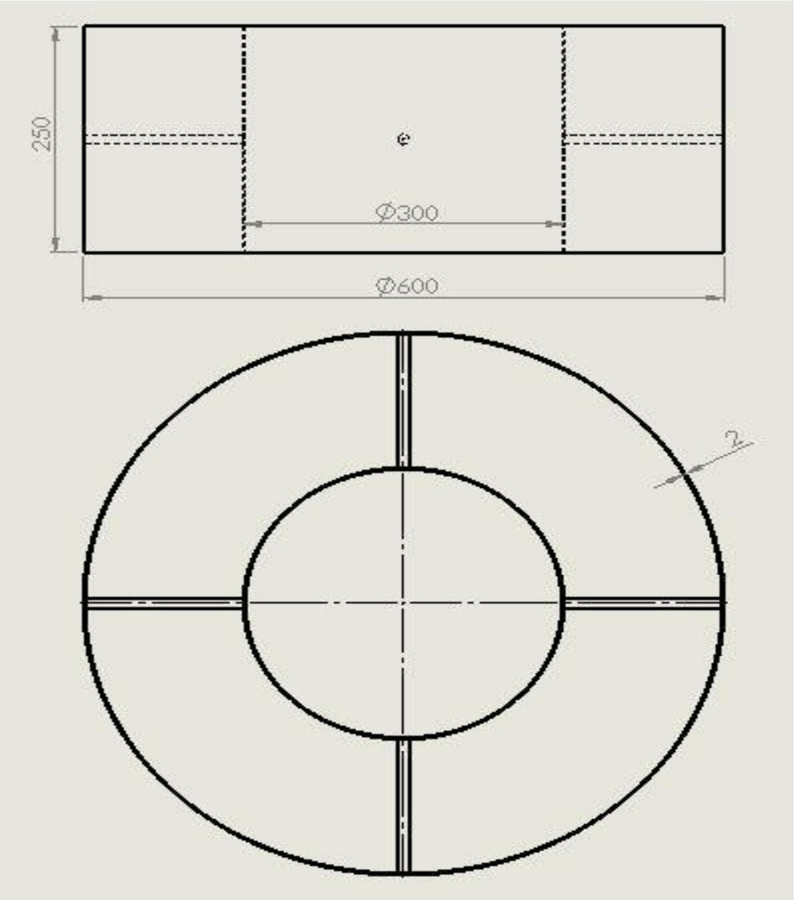

Fig. 1: Orthographic view of double ring infiltrometer

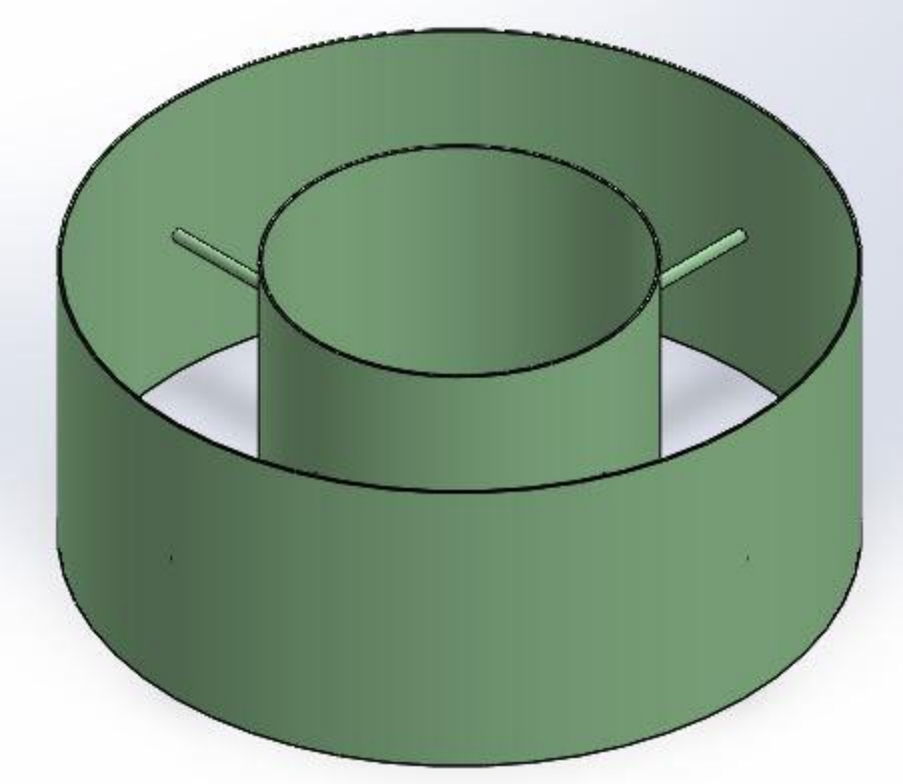

Fig.2: Isometric view of double ring infiltrometer

Infiltration equations

Many approaches have been presented over a century ago, to solve the problem of infiltration of water into a soil. Several analytical and semi-empirical equations for one-dimensional horizontal and vertical infiltration through homogeneous soil with specific simplified initial conditions have been developed. [33] reviews the historic development of infiltration theory over the last decades including the Green and Ampt infiltration model which was the first physically-based model develop in 1911 of which is almost a century old today.

(i) Green-Ampt equation[34]

Named after two scientists, Green and Ampt, the Green-Ampt (GA) method of infiltration estimation accounts for many variables that other methods, such as Darcy's law, do not. It is a function of the soil suction head, porosity, hydraulic conductivity and time [35]. Green-Ampt model was the first physically based model/equation describing the infiltration of water into the soil[36] The model yields cumulative infiltration and the infiltration rate as an implicit function of time. The volume of infiltration is a function of soil pores that is saturated behind wetting front; and wetting front moves in response to capillary forces. Green and Ampt (GA) model is a physically based or approximate model that directly applies Darcy’s law[37] The Green Ampt model has been found to apply best to infiltration into uniform, initially dry, coarse textured soils, which exhibit a sharply defined wetting front as depicted in Figure 3.

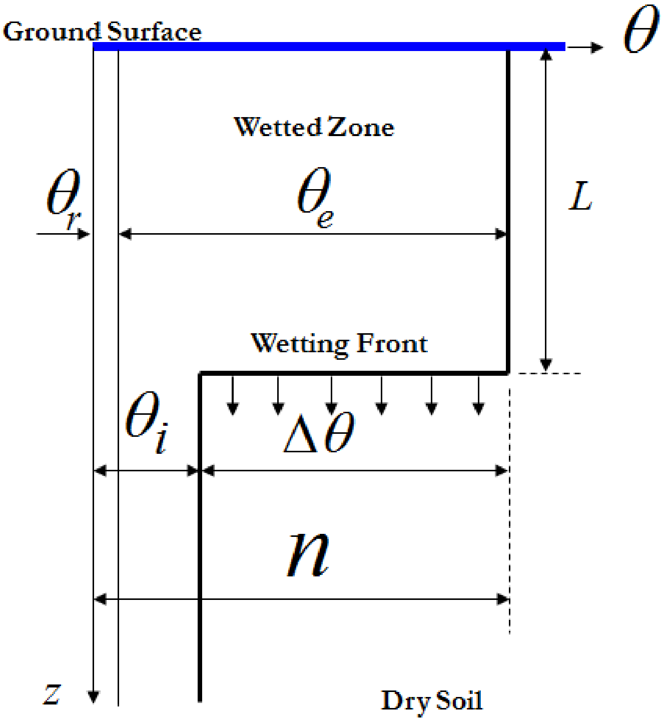

Figure 3: Illustration showing uniform water entry assumption, transmission zone, and sharply defined wetting front [32].

Where θ_r is residual water content of very dry soil in grams per grams, θ_e is effective porosity in grams per grams, n is the porosity in grams per grams, h_o is depth of water ponding on the surface in centimeter, and L is wetted depth in centimter.

This pattern is often called a downward piston displacement profile or plug flow with a well-defined wetting front[18].

It uses Darcy’s equation and is based on infiltration into deep homogeneous reservoirs with homogeneous initial water content distribution[37]. The Green-Ampt model assumed that transmission zone is a region of nearly constant water content above wetting front, which lengthens as infiltration proceeds; the wetting front is characterized by a constant matric suction, regardless of time or position and is a plane of separation between the uniformly wetted infiltrated zone, and the as-yet totally un-infiltrated zone [11]. These assumptions simplify the flow equation so that it can be solved. [34] recommended that soil physical properties should be measured in the field, so that undisturbed field conditions are reflected in the resulting values.

[34] model/equation according to [37] is expressed as shown in equation 2

$$\int_0^{F(t)} \frac{F(t)}{F(t)+\varphi\Delta\theta}\,dF = \int_0^t Ksdt \qquad \mathbf{2}$$

Where, φ (phi) is soil suction head at the wetting front in centimetre; $\Delta\theta$ is change in water content in grams per grams, K_s is saturated hydraulic conductivity in centimetre per hour and F(t) is cumulative depth of infiltration in centimetre. Once integrated, one can easily choose to solve for either volume of infiltration or instantaneous infiltration rate, which gives,

$$F_t = K_s + \varphi\Delta\theta \ln\left[1+\frac{F_t}{\varphi\Delta\theta}\right] \qquad \mathbf{3}$$

Using the model one can find the volume easily by solving for cumulative depth of infiltration $F_{(t)}$ in meters. However, the variable being solved for is in this equation itself. When solving for this, one must set the variable in question to converge on zero, or another appropriate constant. Using the infiltration volume from this equation one may then substitute F(t) into the corresponding infiltration rate equation below to find the instantaneous infiltration rate at the time, t, and Fmeasured[33].

$$f_t = K_s\left[\frac{\varphi\Delta\theta}{F_{(t)}}+1\right] \qquad 4$$

The Green-Ampt model/equation assumed the following: Homogenous soil, uniform water content; Constant matric potential of the wetting front; Uniform constant water content and hydraulic conductivity above the wetting front, and Constant ponding depth at the soil surface.Table 2.1 show hydraulics properties for different soil texture.

Table 2.1: Green Ampt Parameters

Texture	Porosity N	Residual Porosity Θ_r	Effective Porosity Θ_e	Suction Head ψ (cm)	Conductivity K (cm/hr)
Sand	0.437	0.020	0.417	4.95	11.78
Loamy Sand	0.437	0.036	0.401	6.13	2.99
Sandy Loam	0.453	0.041	0.412	11.01	1.09
Loam	0.463	0.029	0.434	8.89	0.34
Silt Loam	0.501	0.015	0.486	16.68	0.65
Sandy Clay Loam	0.398	0.068	0.330	21.85	0.15
Clay Loam	0.464	0.155	0.309	20.88	0.10
Silty Clay Loam	0.471	0.039	0.432	27.30	0.10
Sandy Clay	0.430	0.109	0.321	23.90	0.06
Silty Clay	0.470	0.047	0.423	29.22	0.05
Clay	0.475	0.090	0.385	31.63	0.03

Source: [34].

(ii) Smith-Parlange infiltration model

Smith and Parlange‘s equation is a physically based equation[32]. They derived an infiltration equation for arbitrary rainfall rates. By adopting two extreme assumptions concerning the behaviour of unsaturated soil hydraulic conductivity K. One assumption was that k varies slowly near saturation and leads to an expression for ponding time and infiltration decay. For initially ponded conditions, ponding time is zero, and with rainfall rate greater than zero, the familiar [34], [38]). The other, rather opposite assumption was that K varies rapidly, e.g., exponentially. This model also holds for both rainfall and ponded surface conditions and, for ponded conditions, the expression is identical to that of Parlange’s model[39]. Each model uses only two parameters, saturated soil conductivity K_s and C_o, a parameter that is roughly related to Sorptivity and responds nearly linear to variations in initial saturation or determined from infiltrometer experiments [40]. Both parameters are physically related to measurable soil properties. The two models are compared with precise numerical solution of the unsaturated soil water diffusion equations for three soils that represent a range of soil behaviours near saturation. For soils in which hydraulic conductivity as a function of soil water content varies slowly near saturation,[39]expressed the cumulative infiltration as:

$$F_c(F_{cum}) = K_s \frac{exp^{(F_{cum}/B)}}{exp^{(F_{cum}/B)}} + 1 \qquad 5$$

Where, F_c is a potential infiltration in a time step (mmh^{-1}), F_{cum} is a cumulative infiltration since the start of rain (mm), B is a saturation deficit parameter (mm), K_s is the saturated hydraulic conductivity of the soil, B is a parameter combining the effective net capillary drive $G(mm)$and the saturated deficit of the soil.

$$B = G(\theta_s - \theta_i) \qquad 6$$

Where, G is effective net capillary drive (mm), θ_s is saturated soil water content (m^3/m^3), and θ_i is the initial soil water content (m^3/m^3).

(iii) Philips infiltration model

[41] presented an analytical infinite-series solution to the water content based form of Richards’equation for the case of vertical infiltration. Philip’s rapidly converging series solves the flow equation for a homogeneous deep soil with uniform initial water content under ponded conditions. With additional assumptions regarding the physical nature of soil water properties, [42]proposed joining solutions that are applicable for all times. [43]introduced a truncation of the small time series solution that is a simple two-parameter model equation (Philip model).

$$I_c = At + St^{0.5} \qquad 7$$

In which A is a parameter related to the analysis leading to the equation 2.7 and S is the soil sorptivity.

Differentiating the above equation yields the infiltration rate, or

$$i_c = 0.5St^{-0.5} + A \qquad 8$$

In which S is called sorptivity and is a function of the boundary and initial water contents, θ_0 andθ_i. The parameter $A\,(cm/hr)$ is the transmissivity or permeability coefficient or gravity term, which is equivalent to the saturated hydraulic conductivity of the soil.

(iv) Kostiakov’s model

The Kostiakov’s model [44], named after its founder Kostiakov, proposed a simple empirical infiltration equation based on curve fitting from field data. It relates infiltration to time as a power function. This empirical model expresses cumulative infiltration I as a function of time t thus,

$$I = kt^{a} \qquad 9$$

In which $\boldsymbol{I}$ is the cumulative infiltration($\boldsymbol{cm}$), $\boldsymbol{t}$ time from the start of infiltration ($\boldsymbol{hr}$), and $\boldsymbol{a}$ and $\boldsymbol{k}$ are empirical parameters that needed to be estimated.

The characteristics of equation 9 are that the initial value of the infiltration rate which is infinite and that as time increases, the infiltration rate approaches zero instead of a constant (non-zero) value has been observed practically[38].The model is ideal for expressing horizontal flows (where the effect of gravity is essentially zero) but is grossly deficient for vertical flows. One limitation of this model is that it does not predict a final and constant infiltration rate. [45]found the Kostiakov model better than the philip model for conditions where field infiltration data varied substantially. A characteristics of the ‘a’ term in Kostiakov model which is that the value lies betweeen zero and one was challenge by [46]who proved mathematically that the value of “a” can be greater than unity and that in fact the philip and Kostiakov models are identical. [47]however, found experimentally that the value of “a” was cosistently less than one.

When equation Eq.9 is differentiated, the infiltration rate $i(cm/hr)$ is obtained as:

$$i = akt^{a-1} \qquad 10$$

The parameters, a and k must be evaluated from measured infiltration data, since they have no physical interpretation. The equation describes the measured infiltration curve and give the same soil and same initial water condition, allows prediction of an infiltration curve using the same constants developed for those conditions. The Kostiakov’s equation is widely used because of its simplicity, ease of determining the two constants from measured infiltration data and reasonable fit to infiltration data for many soils over short time periods[46]. The major flaws of this equation are that it predicts that the infiltration rate is infinite at t equals zero but approaches zero for long times, while actual infiltration rate approaches a steady value.

(v)Modified Kostiakov’s model

Kostiakov [44]was modified by adding the term of ultimate infiltration capacity, b, as follow:

$$I = at^{b} + c \qquad 11$$

Where a, b, and c are three characteristics constants and c is the rectifying factor which depends on the soil and initial conditions a and c which are the same with the Kostiakov model.

According to [48]‘c’ is regarded as the rectifying factor. The first step was to plot I against t. Two points were chosen (t_1, I_1 and t_2, I_2) on and near the extremities of the smoth curves representing the data. Then a point, t_3, equals the square root of the product of t_1 and t_2 is chosen. The I_3 is then read against t_3 on the curve of' $'I'$ versus $'t'$. The value of ‘c’ was determined using the formula:

$$c = \frac{(I_1 \; x \; I_2) - {I_3}^2}{(I_1 \; + I_2 \;) - 2I_3} \qquad 12$$

where $t_3 = \sqrt{t_1 x \; t_2}$

Differentiating equation 2.12, gives the infiltration rate $i(cm/hr)$

$$i = abt^{a-1} \qquad 13$$

It expresses infiltration volume explicitly as a function of time, and coefficients can be found by straight-line fit of infiltration depth, I, *versus* time on a log-log plot. Original developers and some other investigators used it for infiltration and runoff prediction[4]. Due to its simplicity and ease of use, this equation is very commonly used in agricultural engineering for designing surface irrigation and estimating infiltration in level borders and furrows [48]. Obviously, the equation is considered adequate for most common irrigation durations. In order to eliminate the limitations of the Kostiakov[44]model which is that the steady state infiltration rate approaches zero as time increases, [12] and [50] added a term they referred to as steady state infiltration rate to the Kostiakov [44]equation to give an accurate infiltration result at longer time (t). Thus, cummulative infiltration was expressed as:

$$I = akt^{a} + f_c t \qquad 14$$

Where, f_c is the steady state infiltration rate. Taking the differential of equation 14 with respect to time, we have the infiltration rate i,

$$i = akt^{a-1} + f_c \qquad 15$$

(vi) Horton's model[51]

Infiltration process was thoroughly studied by Horton in the early 1930s[52]. The model was finally developed by Horton in 1940[51]. It is one of the best-known models in hydrology. [51]recognized that infiltration capacity $f_0$decreased with time until it approached a minimum constant rate f_c. He attributed this decrease in infiltration primarily to factors operating at the soil surface rather than to flow processes withn the soil. Critical to Horton's views on infiltration was the idea of infiltration capacity[52]. Horton realized that, as the soil wets and dries, the rate at which water can infiltrate into the soil will change, but that at any point in time there will be a limit, the infiltration capacity, that will be the maximum rate at which rain falling on the soil surface can infiltrate [51]. He also realized that rainfall falling at rates less than the infiltration capacity of the soil would all infiltrate and, therefore, that it was impotant to distinguish between the terms infiltration rate and infiltration capacity [52]. It is worth noting that Horton did not introduce infiltration equation in his classic 1933 paper[53].

$$i = f_c + (f_o - f_c)e^{-k_f t} \qquad 16$$

where f is infiltration-capacity, inches per hour, at time t, in hours, f_0 infiltration- capacity at time $t = 0$; f_c is minimum constant infiltration capacity; K_f is constant for a given curve. The cummulative infiltration becomes the integral of equation 16.

$$I = f_c t + \frac{f_o - f_c}{k}[1 - e^{-kt}] \qquad 17$$

Horton's invokes exhaustion processses in the derivation of this equation by assuming that all of the processes in the dervation of this equation by assuming that all of the processes affecting the rate of change of infiltration capacity are linearly proportional to the work remaining to be performed $(f - f_c)$. [51] also recognized that the experiments on infiltration capacity were affected by the nature of the experiments on infiltration capacity were affected by the nature of the experiments themselves, and gives an extended discussion of the effects of drop size on infiltration rates but suggests that there is little evidence of any increase in infiltration capacity with either rainfall intensity or drop sizes [53]. He also suggest that rough surfaces might have lower infiltration capacities than smooth surfaces because if very large drops fall a steep sloping surface, such as the slope of a tillage mark, a part of the drop runs downward into the intermediate gully or depression and begins to build up surface detention and runoff, even at times when the soil surface is not all absorbing water at its maximum rate [26].

(vii) Natural Resources Conservation Service (NRCS)

Experts of United States Deapartment of Agricultural, Natural Resources and Conservation Service[54] found that when the Kostiakovs's [44]model was used after a long time the value of infiltration rates becomes zero and this differs greatly from actual field result. The NRCS model was modifield from Kostiakov's [44] model as reported by Cuenca [30]. It was given as

$$I = at^{b} + 0.6985 \tag{18}$$

$$i = abt^{b-1} \tag{19}$$

The NRCS expert carried out many experiments and concluded that c is equal to the coefficient 0.6985 which added to this model, would, work well at all times for all soils.

(viii) Talsma and Parlange equation

[55]infiltration equation is similar to the Philip's equation. They found that the coefficient, A in Philip equation could be represented with K_s, where K_s is the saturated hydraulic conductivity of the soil.

$$\tau = \lambda - 1 + \exp(-\lambda) \tag{20}$$

Where τ and λ are related to time, t, and cumulative infiltration, I, by the following equations:

$$\tau = \frac{2K_s^2 t}{S^2} \tag{21}$$

$$\lambda = \frac{2K_s^2 I}{S^2} \tag{22}$$

The series expansion of equation 21 and the substitution of equation 22 gives

$$I = St^{1/2} + \frac{K_s}{3} + \frac{K_s^2 t^{3/2}}{9s} \tag{23}$$

Differentiating eq. 2.2.12 we have, the infiltration rate (i)

$$i = \frac{S}{2\sqrt{t}} + \frac{K_s}{3} + \frac{3K_s^2 t^{1/2}}{18s} \tag{24}$$

Where: S and K_s are Sorptivity, and Saturated hydraulic conductivity. The apparent steady state infiltration rate sustained for about 1 hour is used as an estimate of the saturated hydraulic conductivityK_s. For the measurement of sorptivity, the second term of the right-hand side of Philip equation 23 can be neglected. Therefore, if one plots the early portion of the experimental cumulative infiltration versus the square root of the elapsed time on a normal scale paper, the Sorptivity for the existing antecedent soil condition can be obtained from the slope of the curve [56]. The advantage of this equation is that it is simple and rapid. Hence, many measurement can be made with limited resources like fund and labour.

(ix) Swartzendruber's equation

This infiltration equation was derived exactly from a quasi-solution of the governing differential flow equation. Based on least squares fitting, the new equation in three parameter dimensionless form is

$$I = f_c t + \frac{c}{a}\left[1 - \exp(-dt^{0.5})\right] \tag{25}$$

Where: c and d are empirical constants.

In order to get the infiltration rate (i), Eq. 25 is differentiated with respect to time.

$$i = f_c + \frac{c}{2} * \frac{e^{-d\sqrt{t}}}{\sqrt{t}}$$

The parameters of Swartzendruber's equation are f_c, c and d. The value f_c, is the final infiltration while c and d are numerical constant depending on the time interval. Two equations were obtained, solving them simultaneously gave the values of c and d which were substituted into equations 25 to obtain cumulative infiltration and infiltration rate respectively.

(x) Kostiakov-Lewis equation

The Kostiakov-Lewis variant equation corrects for Kostiakov infiltration equation by adding a steady intake term to the original equation:

S/N	Model Name	Cumulative Infiltration equation	Infiltration rate equation	Fitting parameters
1	Kostiakov (1932)	$I = kt^a$	$i = akt^{a-1}$	$k \ and \ a$
2	Green-Ampt (1911)	$I = kt + \varphi\Delta\theta \ln[1 + \frac{I}{\varphi\Delta\theta}]$	$i = k[\frac{\varphi\Delta\theta}{I} + 1]$	$\varphi, I \ and \ i$
3	Modified Kostiakov (1978)	$I = at^b + c$	$i = abt^{a-1}$	$k, a \ and \ b$
4	Philip (1957)	$I = s\sqrt{t} + At$	$i = \frac{S}{2\sqrt{t}} + A$	$S \ and \ A$

$$I = kt^a + f_c t \qquad 3.$$

Where a, and k are empirical parameters and f_c approximates, but does not necessarily equate to the final infiltration rate of the soil.

5	Horton (1940)	$I = f_c t + \frac{f_o - f_c}{k}[1 - e^{-kt}]$	$i = f_c + (f_o - f_c)e^{-kt}$	$k, f_o \text{ and } f_c$
6	Kostiakov-Lewis (1982)	$I = kt^a + f_c t$	$i = akt^{a-1} + f_c$	$a, k \text{ and } f_c$
7	NRCS (1989)	$I = at^b + 0.6985$	$i = abt^{b-1}$	$a \text{ and } b$
8	Talsma and Parlange	$I = St^{1/2} + \frac{k_s t}{3} + \frac{K_s^2 t^{3/2}}{9s}$	$i = \frac{s}{2\sqrt{t}} + \frac{K_s}{3} + \frac{3K_s^2 t^{1/2}}{18s}$	$S \text{ and } K_s$
9	Swartzendruber (1972)	$I = f_c t + \frac{c}{d}[1 - \exp(-dt^{0.5})]$	$i = f_c + \frac{c}{2} * \frac{e^{-d\sqrt{t}}}{\sqrt{t}}$	$c \text{ and } d$
10	Smith &Parlange (1978)	$I = K_s t[\frac{C_o}{K_s I} + 1]$	$i = K_s[\frac{C_o}{K_s I} + 1]$	$C_o \text{ and } K_s$

Table 3.1: Soil infiltration Models and their fitting parameters
The parameters in the table are as defined above.

Conclusion

Infiltration is the process by which water on the ground surface enters the soil. It is one of the important components of the hydrological cycle. Water content, field capacity, suction head, temperature, humidity, rainfall intensity, and type of impurity play an important role in influencing the infiltration rate. It provides soil moisture in the vadose zone to support plant growth. Ten empirical models, namely, Kostiakov, modified Kostiakov, Philip, Kostiakov-Lewis, and National Resource Conservation model, Three (3) physically based (Green-Ampt (GA), Smith-Parlange(SP), Talsma-Parlange (TP)) and two semi-empirical (Swartzendruber (SW) and Horton (HT)), were reviewed extensively.,In irrigation engineering, infiltration is one of the most critical processes to control the surface irrigation uniformity and efficiency [57]. Infiltration is a key dynamic process during irrigation events to be considered for irrigation system design, irrigation scheduling, and irrigation system optimization and management. The use of infiltration models becomes necessary because field measurements of soil infiltration are cumbersome, expensive, time-consuming and give only local scale results.

REFERENCES

[1] Adeniji, F. A., Umara, B. G., Dibal, J. M., and Amali, A. A. (2013). Variation of infiltration rates with soil texture. A laboratory study. *International Journal of Engineering and Innovative Technology*, 3 (2), 454-459.

[2] Runbin, D., Clifford, B. F., & John, B. (2011). Field Evaluation of Infiltration Models in Lawn Soils. *Irrigation Science, 29*, 379-389.

[3] Bhattacharya, A. K., & Michael, A. M. (2010). *Land Drainage Principles, Methods and Application*. New Delhi: Vikas Publishing House PVT Ltd.

[4] Ellen, R. T. (2006). *Comparison of Infiltration Equations and their Field Validation by Rainfal Simulation*. University of Maryland, Department of Biological Resources Engineering. Maryland: Faculty of the Graduate School.

[5] Mishra, S. K., Tyagiand, J. V., & Singh, V. P. (2003). Comparison of Infiltration Models. *Journal of Hydrological Processes, 17*, 2629-2652.

[6] Oku, E., & Aiyelari, A. (2011). Predictability of Philip and Kostiakov Infiltration Models Under Inceptisols in the Humid Forest Zone, Nigeria. *Kasetsart Journal (Natural Science), 45*, 594-602.

[7] Shukla M. K., Lal R., Owen L. W, Unkefer P. (2003b). Land use and management impacts on structure and infiltration characteristics of soils in the North Appalachian region of Ohio. Soil Sci. 168:167-177.

[8] Lili, M., Bralts, V. F., Yinghua, P., Han, L., & Tingwu, L. (2008). Methods for Measuring Soil Infiltration. State of the Art. *International Journal of Agricultural and Biological Engineering, 1*, 22-30, 66.

[9] Turner, E. R. (2006). Comparison of infiltration equations and their field validation with rainfall simulation. MSc. Thesis (unpublished), Department of Biological Resources Engineering, University of Maryland, USA.

[10] Suresh, R. (2008). *Land and Water Management Principles*. Nai Sarak, Delhi, India: A. K. Jain, Standard Publishers Distributors.

[11] Jonah, J. (2012). *Determination of Infiltration Rate Using Pressure Head Differential Approach in Dry Season*. ABU. Zaria: Department of Agricultural Engineering.

[12] Atanda, O. A. (1988). *Evaluation of Infiltration Rates on a Border Irrigation system*. ABU, Agricultural Engineering. Zaria: ABU.

[13] Reddy, P. R. (2008). *A textbook of hydrology*. Bangalore: University Science Press Publishers.

[14] Chow, V. T., Maidmen, D. R., & Mays, L. W. (1988). *Applied Hydrology*. Presville, Singapore: McGraw- Hill.

[15] Gupta , B. L., & Gupta, A. (2008). *Water Resources Systems and Management*. Delhi: Standard Publishers Distributors.

[16] Essien, O. E. (2011). Effects of Varying Rates of Organic Amendments on Porosity and Infiltration Rate of Sandy Loam Soil. *The Journal of Agriculture and Environment, Vol. 12*, 123-130.

[17] Okai, I. A., Ramalan, A. A., & Adeoye, K. B. (2000). Infiltration Characteristics of Soils as Relate to Other Soil Physical Properties of Soil Subgroup in Kadawa Research Station of Nigeria. *Nigeria Journal of Soil Science Research, 1*, 8-11.

[18] Mbagwu , J. C. (1995). Testing the Goodness of Fit of Infiltration Models for Highly Permeable Soils Under Different Tropical Soil Management Systems. . *Soil and Tillage Research, 34*, 199-205.

[19] Skaggs, R. W., & Khaleel, R. (1982). Chapter 4: Infiltration. Hydrologic Modelling of Small Watershed. *St Joseph, Mich.*, 200-201.

[20] Serrano, S. E. (1997). *Hydrology for Engineers, Geologists and Environmental professionals*. Delhi: Hydro science, Incorporated.

[21] Ayeni, L. S., & Adetunji, M. T. (2010). Integrated Application of Poultry Manure and Mineral Fertilizer on Soil Chemical Properties, Nutrient Uptake, Yield and Growth Components of Maize. *Nature and Science Journal , 8*(10), 60-67.

[22] Atta, P., Agyarko, K., Dapaah, H. K., & Dawuda, M. M. (2014). Influence of Mucunapruriens Green Manure, NPK and Chicken Manure Amendments on Soil Physio-chemical Properties and Growth and Yield of Carrot (Daucuscarota L.). *Journal of Agriculture and Sustainability Volume 5, Number 1*, 26-44.

[23] Haghighi, F., Gorji, M., Shorafa, M., Sarmadian , F., & Mohammadi, M. H. (2010). Evaluation of Some Infiltration Models and Hydraulic Parameters. *Spanish Journal of Agricultural Research*, 210-217.

[24] Arora, K. R. (2008). *Soil Mechanics and Foundation Engineering*. Delhi: A. K. Jain For Standard Publishers Distributors.

[25] Haggard, B. E., Moore, P. A., & Jrand, K. R. (2005). Effect of Slope on Runoff from a Small Variable-Slope Box. *Journal of Environmental Hydrology, 13*(25). Retrieved from http:/hydroweb.com

[26] Bouwer, H. (1969). Infiltration of water into non-uniform soil. *Journal of Irrigation and Drainage Division, ASCE, 95*(IR4), 451-462.

[27] Marshal, T. J., & Holmes, J. W. (1988). *Soil physics* (Vol. 2nd Edition). New York, NY, USA: John Wiley.

[28] ASTM. (2009). Test Method for Infiltration Rate of Soils in Field using Double-Ring Infiltrometers. *D3385-03 ASTM*, 123-126.

[29] Bouwer, H. (2009). "Intake Rate: Cylinder Infiltrometer." Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, Agronomy Monograph No. 9 2nd Ed. *American Society Agronomy, Soil Science Society America*, 825-855.

[30] Cuenca, R. H. (1989). *Irrigation System Design - An Engineering Approach*. New Jersy, Eaglewood Cliff, USA: Prentice-Hall.

[31] Philips, C. E., & Kitch, W. A. (2011). A review of methods for characterization of site infiltration with design recommendation. *Proceedings 43rd Symposium on Engineering Geology and Geotechnical Engineering* (pp. pg 130-140). Las Vegas: University of Las Vega Nevada.

[32] Blight, G. E., Fourieand, A. B., & James, C. S. (2001). Measurement of infiltration and evaporation characteristics of soils in the Nylsvlei Flood-Plain. *4th Environmental management, Technology and Development Conference.*

[33] Youngs , K. (1995). The physics of infiltration. *Soil Science Society of America Journal, 59*, pp 307-313.

[34] Green, H. W., & Ampt, G. A. (1911). Studies on Soil Physics. Part 1. The flow of air and waterthrough soils. *The Journal of Agricultual Sciences, 4*, 1-25.

[35] Mays, L. W. (2005). *Water Resources Engineering* . John Wiley and Sons Inc.

[36] Oram, B. (2015, 12 11). *B.* Retrieved October 13th, 2016, from www.google.com: http:/www.soilsinfiltration

[37] Sonaje, N. P. (2013). Modelling of Infiltration Process. *Indian Journals of Applied Research, Vol. 3*(9), 226-230.

[38] Barry, D. A., Parlange, J. Y., Haverkamp, R., & Rose, P. J. (1995). Infiltration under pondede conditions: 4. An explicit predictive infiltration formular. *Soil Science*, 160:8-17.

[39] Parlange, J. Y. (1975). On solving the flow equation in unsaturated soils by optimization: horizontal infiltration. *Soil Science Society of Americal*, 415-418.

[40] Smith, R. E. (1978, June). A Parameter-Efficient Hydrologic Infiltration Model. *Water*

Resources Research, *14*(3), 531-533.

[41] Philip, J. R. (1957a). The theory of infiltration: 1. The infiltration equation and its solution. *Soil Science*, 83:345-375.

[42] Philip , J. R. (1987). The infiltration joining problem. *Water Resources Research*, 2239-2245.

[43] Philip, J. R. (1957c). The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Science, 84*, 257-264.

[44] Kostiakov, A. N. (1932). On the Dynamics of the Coefficient of Water-percolation in Soils and On the Necessity for Studying it from a Dynamic Point of View for Purpose of Amelioration. *Transactions Congress International Society for Soil Science*, 17-21.

[45] Gosh, R. K. (1983). "A note on the infiltration equation". *Soil Science*, *139*, 333-338.

[46] Gosh, R. K. (1985). "A note on Lewis-Kostiakov's infiltration equation". *Soil Science, 139*, 193-196.

[47] Mbagwu, J. C. (1990). "Mulch and tillage effects on water transmission characteristics of an Ultisol and maize grain yield in South East Nigeria". *Pedology*, *40*, 155-165.

[48] Michael , A. M. (1978). Irrigation theory and practice. *Vikas Publishing House PVT Ltd*, 678-679.

[49] ASTM. (2003). D293785-03 Standard test method for infiltration rate of soils in field using double-ring infiltrometer. In A. S. Materials, *Annual Book ASTM Standards 04.08* (pp. 363-375). West Conshohocken, PA: American Society Testing Materials.

[50] Elliot, R. L., & Walker, W. R. (1982). Field evaluation of furrow irrigation and advance functions. *Transaction of ASAE*, *25*(2), 396-400.

[51] Horton, E. R. (1940). Anpproach Towards a Physical Interpretation of Infiltration Rate. *Soil Science Society of America*, *Vol. 5*, 399-417.

[52] Horton, R. E. (1939). Analysis of runoff plots with varying infiltration rate. *Transactions of the Amrican Geophysicists, Part IV*, 693-694.

[53] Beven, K. (2004). Robert E. Horton's Perceptual Model of Hydrological Processes. *Hydrological Processes, Vol. 8*, 3455-3456.

[54] National Resource Conservation Services (NRCS), United States Department of Agriculture (USDA).*Technical Resources*, 2014.

[55] Talsma, T., & Parlange, J. Y. (1972). One Dimentional Vertical Infiltration. *Australia Journal of Soil Research*, *10*, 143-150.

[56] Mudaire, J. O., & Adewumi, K. J. (Mudair2000). Mudair Estimation of Infiltration from Field Measured SorptivityValues. *Mudaire, O .J. and Adewumi, J. K. (2000): Estimation of Infiltration from Nigeria Journal of Soil Science Research*, *1*, Mudaire, O .J. and Adewumi, J. K. (2000): Estimation of Infiltration from Field Measured SorptivityValues. 1 -3. Retrieved Mudaire, O .J. and Adewumi, J. K. (2000): Estimation of Infiltration from Field Measured SorptivityValues. Nigeri2016

[57] Walker, W. R., Prestwich, C., & Spofford, T. (2006). Development of Revised USDA-NRCS Intake Families for Surface Irrigation. *Agricultural Water Management*, *85*(1-2), 500-503.