OVERVIEW AND BIBLIOGRAPHY OF METHODS FOR EVALUATING THE SURFACE-WATER-INFILTRATION COMPONENT OF THE RAINFALL-RUNOFF PROCESS

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ABSTRACT

This report presents the results of a study by the U.S. Geological Survey, in cooperation with the Illinois Department of Transportation, Division of Water Resources, to compile a bibliography of the technical literature on the subject of rainfall infiltration. Three computerized data bases--Agricola, Applied Science and Technology Index, and Selected Water Resources Abstracts--were the primary sources of the bibliographic citations. In addition, the University of Illinois Library Computer System and Illinet Online (a search service provided at the University of Illinois) were used to assemble the bibliography. The initial search of the literature on the general subject of infiltration yielded more than 7,000 citations. Citations were selected for inclusion into the report bibliography if they addressed the topic of infiltration in the context of rainfall-runoff processes and rainfall-runoff-modeling studies. Approximately 1,000 citations met this criterion. A subset of approximately 300 bibliographic citations was cross-indexed according to infiltration-model type and the physical setting of the infiltration study.

An overview and critical analysis of selected infiltration equations is presented. Infiltration-estimation techniques can be broadly divided between the theoretical equations and the empirical equations. Practical applications of the theoretical equations generally have significant limitations because of the adequacy and accuracy of the input data required. By contrast, the simpler empirical equations commonly can yield satisfactory results provided that model assumptions and design parameters are adequately satisfied. A major shortcoming of most rainfall-infiltration modeling is a lack of soil-moisture field data. It is concluded that, although many soil physicists and theoretical researchers tend to favor physically based theoretical equations, practitioners of rainfall-runoff modeling most often use the simpler empirical equations to estimate infiltration.

INTRODUCTION

Water that reaches the ground as precipitation may evaporate, become surface-water runoff, and (or) infiltrate the ground. The entrance of water into the soil surface, or infiltration, is a very complex process and is only part understood. Because infiltration so dramatically affects the rainfall-runoff process, it remains an important topic of research and discussion to water-resource planners and managers. Partitioning the rainfall at the soil surface into either runoff (rainfall excess) or infiltration has been described by Smith and Chery (1973) as the second most complex process after evapotranspiration. However, the need for methods estimating infiltration has led to the simplification of theory and the development of numerous estimating equations and methods. This report will review the development of infiltration equations, discuss and critically examine infiltration-estimation equations common to most rainfall-runoff-modeling investigations, and present a bibliography and a selected index compiled from a review of the literature on infiltration. The bibliography also contains those citations that occur within the text of this report. The report was prepared in cooperation with the Illinois Department of Transportation, Division of Water Resources. Part of the bibliography was assembled from computerized catalogs and bibliographic-search systems at the University of Illinois Libraries in Urbana, Illinois.

The consideration of the infiltration component in rainfall-runoff models is a complex process that is affected by many factors. Although a large number of infiltration equations have been published, these equations provide relatively little information on real-world infiltration processes if the generally used assumptions of a stable porous medium and a constant boundary condition are not applicable. The infiltration process constitutes the connecting link between surface and subsurface water. With respect to methodology, the science of infiltration can be placed in the border area between hydrology and soil physics. The process of infiltration of water into soils is a function of soil properties, including temperature, moisture content, position of the ground-water table relative to the infiltration site, porosity and air movement within the soil profile, soil-plant relation, and microbial activities. Other important factors include the properties of the infiltrating water, dimensionality of flow, heat-transfer characteristics, surface conditions, and the time elapsed from the onset of the infiltration event. Although these factors are not all inclusive, they are representative of the major factors that govern the infiltration process.

Most of the recent research published in the infiltration literature stresses the development of rigorous mathematical theory and, to a lesser extent, the application of a relatively few well-established equations. However, some researchers and water-resource planners harbor the suspicion that the level of detail and mathematical sophistication presently implemented in numerical models of infiltration has exceeded the ability of field practitioners to quantify and parametize the associated properties of the infiltration flow system adequately. In other words, much of the state-of-the-art infiltration modeling and research require field data or assume field conditions that either do not exist, or exist with significant uncertainty. The sparsity of appropriate infiltration data has been a primary obstacle to reliable rainfall-runoff modeling. Explicit infiltration equations that can be used with readily available data are needed for practical applications. Engineers and water-resources planners have to solve common, everyday design and planning problems. Once the strengths, weaknesses, and assumptions of an infiltration equation have been defined, the practitioner can make the appropriate adjustments and allowances in the design criteria.

Fundamental Processes

Chow (1964) considered the infiltration process as a three-step sequence: surface entry, transmission through the soil, and depletion of storage capacity in the soil. The various conditions observed in the field will significantly affect each of these steps.

The soil surface can become encrusted with, or sealed by, the accumulation of fines or other arrangements of particles that prevent or retard the entry of water into the soil. A soil may have excellent underdrainage characteristics but still have a low infiltration rate because of the retardant effect of surface crusting or sealing.

The rate at which water enters soil cannot exceed the rate at which water is transmitted downward through the soil. Thus, soil-surface conditions alone cannot increase infiltration unless the transmission capacity of the soil profile is adequate. Under conditions where the surface-entry rate is slower than the transmission rate of the soil profile, the infiltration rate will be limited by the surface-entry rate. The transmission rates can vary at different horizons in the soil profile. After saturation, the infiltration rate is limited to the lowest transmission rate encountered by the infiltrating water as it travels downward through the soil profile.

As water infiltrates through successive soil horizons, the available storage capacity of the soil will decrease. The storage capacity available in any horizon is a function of the porosity, horizon thickness, and the amount of moisture already present. Total porosity and the size and arrangement of the pores have significant effect on the availability of storage. During the early stage of a storm, the infiltration process will be largely affected by the continuity, size, and volume of the noncapillary pores, because such pores provide relatively little resistance to the infiltrating water. If the infiltration rate is controlled by the transmission rate through a retardant layer of the soil profile, then the infiltration rate as the storm progresses will decrease as a function of the decreasing storage availability above the restrictive layer. The infiltration rate will then equal the transmission rate through this restrictive layer until another, more restrictive, layer is encountered by the water.

Factors Influencing Infiltration

The most significant factors affecting infiltration are the physical characteristics and properties of the soil layers. The porosity of the soil is commonly regarded as the single most important characteristic affecting infiltration (Linsley and others, 1982). The porosity determines the storage capacity of the soil and also strongly affects the resistance to flow encountered by the percolating water. The soil pores can store water to a certain upper limit; thus, the soil acts as a sponge. Initially, infiltrating water is stored in the soil column. When the storage capacity is reached, the column becomes saturated and no further storage is possible until the water passes through.

Numerous studies have shown that vegetation is one of the most significant factors affecting the ability of the soil to receive and transmit water. The presence of vegetation protects the soil surface from the impact of rainfall. Root systems of vegetation tend to enhance soil porosity and permeability. Organic matter greatly increases pore sizes and pore-size distribution. Maximum infiltration rates tend to prevail in forested areas where an undisturbed natural canopy and permeable organic-mat floor is present, and overland flow through a forest free of roads or logging activity is a relatively rare occurrence (Trimble and Weitzman, 1954). In view of this, many researchers have demonstrated that infiltration in forests is affected primarily by the characteristics of the forest floor. In instances where the forest floor has been removed, the infiltration rate tends to decrease significantly (Arend, 1942; Johnson, 1940; and others).

Soil temperature can greatly affect infiltration. If a soil is frozen while in a saturated state, it usually becomes nearly impermeable. However, some frozen soils can be highly permeable if the freezing action occurred when the soil was very dry.

Another major factor that affects infiltration is the extent of soil compaction. Steinbrenner (1955) demonstrated that one pass of a tractor can reduce the porosity by 50 percent and the infiltration rate by 80 percent. In a similar study, Doneen and Henderson (1953) showed that the infiltration rates in an irrigated soil can be reduced by more than 50 percent from two passes of a tractor. Soil compaction generally causes a major reduction in porosity. Thus, an agricultural field that has been compacted usually will have a significantly lower infiltration rate than a nearby woodland or open area. Soils compacted by grazing in rangelands and pastures also will exhibit lower infiltration rates.

Modifications to the physical characteristics of water itself, although often overlooked in the infiltration literature, also can affect the infiltration process. Most infiltrating rain water picks up colloids and fine clays on its passage through most common soils. The effect of this s pended material in infiltrating water is to seal the small pore spaces in the soil and decrease the rate at which the water can pass through the soil. If the infiltrating water contains salts, as might be expected during the passage of water through alkali soils or fertilizer residues, for example, complex soil colloids may be formed that could affect the infiltration rate. The water's temperature and kinematic viscosity also affects infiltration. Runoff rates tend to be higher in the cooler months of the year than in the warmer months for a given amount of rainfall.

OVERVIEW OF METHODS FOR EVALUATING THE SURFACE-WATER-INFILTRATION COMPONENT

Infiltration-estimation techniques can be broadly divided between use of empirical equations and use of the theoretical equations. The theoretical infiltration equations are physically based and were developed within the principles of soil physics. Theoretical infiltration equations can be further subdivided into algebraic equations and differential equations (Fok, 1987). Empirical infiltration equations rely on fitted parameters that commonly lack any physical significance. The fitted empirical parameters usually are valid only under the field conditions in which they were determined. The empirical infiltration-equation parameters can be difficult to determine without infiltration experiments, and the fitted parameters may not be suitable for application in other watersheds.

Empirical Equations

Lewis (1937) introduced an empirical infiltration equation that was based on his earlier unpublished report of 1927--

$$d = kt^n, \tag{1}$$

where d is the cumulative infiltration depth, t is the infiltration time, and k and n are empirical constants. This equation also was reported by Kostiakov (1932), and generally is referred to as the Lewis-Kostiakov equation.

Horton (1940) expressed infiltration by the relation

$$I = I_c + (I_o - I_c)e^{-bt}, \tag{2}$$

where I is the instantaneous infiltration rate, I_c is the constant infiltration rate, I_o is the initial infiltration rate, e is the base of natural logarithms, b is an empirical constant, and t is the infiltration time. This expression, commonly referred to as the Horton equation, is commonly cited in the scientific literature and enjoys significant acceptance in applied hydrology.

An empirical infiltration equation introduced by Holtan (1961) described infiltration by the relation

$$I - I_c = a\ (F_p)^c, \tag{3}$$

where F_p is the volume of potential infiltration, a and c are empirical constants, and I and I_c have been previously defined.

The Lewis (1937), Horton (1940), and Holtan (1961) equations are formulated to describe infiltration in a one-dimensional sense. Toksoz and others (1965) and Fok (1970) suggested a two-dimensional empirical infiltration equation of the form

$$d = \pi/2\ (ka\ t^{n+c}), \tag{4}$$

where $\pi = 3.1416...$ and the other terms have been defined above. This equation is of the form originally proposed by Lewis (1937) but accounts for soil-moisture movement in the vertical and horizontal directions for a semi-elliptical wetting pattern.

The U.S. Soil Conservation Service (SCS) developed a method to estimate infiltration quantity and rainfall excess based on a hydrologic soil-cover complex. First published in 1956, the method was reported in Section 4 of the SCS National Engineering Handbook (NEH-4) and was officially revised in subsequent versions of NEH-4 (1964, 1972, and 1985) and in another SCS publication (U.S. Soil Conservation Service, 1975). Although the SCS method is not literally an infiltration-estimation equation, the method accounts for rainfall-infiltration losses as well as losses due to interception and surface storage. The SCS method is reported as

$$p = \frac{(P-0.2S)^2}{(P+0.8S)} \quad (P \geq 0.2S) \tag{5}$$

$$p = 0 \quad (P<0.2S), \tag{6}$$

where p is the rainfall excess (runoff), P is the cumulative storm rainfall, and S is a factor related to watershed storage transformed to the runoff curve number (CN) as

$$CN = \frac{1,000}{10+S}, \tag{7}$$

with units of p, P, and S in inches. The runoff-curve number reflects the land condition and is derived from soil type, land use, cover, and watershed antecedent moisture. Numerous SCS and other agencies' documents report CN's for a wide range of conditions.

Theoretical Equations

Theoretical infiltration equations are physically based and derived from principles of soil physics. These equations may be reported either in algebraic- or differential-equation form (Fok, 1987). Infiltration equations in differential-equation form generally require an explicit algebraic lution to be of use to rainfall-runoff practitioners. Algebraic equations are reported both explicitly and implicitly, although the algebraic equations, like the differential equations, generally require an explicit solution to be of value in the practical sense. Each of these two general categories of theoretical infiltration equations, algebraic and differential, are discussed in the following sections.

Algebraic Equations

Green and Ampt (1911) introduced an algebraic equation to relate soil-water content, soil permeability, and soil capillary force to wetting lengths in the soil for upward, downward, and horizontal directions. A common method of expressing the Green and Ampt (1911) infiltration equation is

$$I = K_s + \frac{K_s P_w}{L}, \tag{8}$$

where I is the infiltration rate, K_s is the hydraulic conductivity, P_w is the capillary suction at the wetting front, and L is the distance from the soil surface to the wetting front. The Green and Ampt (1911) equation assumes a piston-type water profile with a well-defined wetting front, characterized by a pressure value constant in time and space. Although the equation is based on some physical considerations, assigning the parameter values on the basis of strict physical significance or relating the parameters statistically to soil properties can generate large inaccuracies with respect to infiltration estimates. Because of these uncertainties, the Green and Ampt (1911) equation was not widely applied until the 1950's when Hansen (1955) redefined Green and Ampt's dependent variables. To illustrate the near constant value of hydraulic conductivity in the transmission zone and the net capillary potential head at the wetting front, Hansen (1955) incorporated a zone of soil-water flow during infiltration into the Green and Ampt (1911) model. The infiltration zones of soil-water flow had been earlier defined by Bodman and Colman (1944) as the transmission zone, saturation zone, wetting zone, and the wetting front. In considering these zones in the development of an algebraic infiltration equation, Hansen (1955) was able to use the Darcy (1856) equation of motion and the principle of continuity to obtain the Green and Ampt semilog implicit algebraic equations for horizontal, upward, and downward directions. Further investigation of the Green and Ampt (1911) equation continued when Fok and Hansen (1966) modified the Green and Ampt (1911) equation into a dimensionless form that could be solved graphically for infiltration rate and infiltration depth. A Green and Ampt (1911) approach to water infiltration into nonuniform soil was investigated by Bouwer (1969) to account for the nonuniformity of the hydraulic conductivity and the soil-water content in the soil profile. Van Keulen and Van Beek (1971) developed a model of infiltration into layered soils. Mein and Larson (1973) formulated an equation to calculate infiltration under a steady rainfall. Later, Morel-Seytoux (1978) published an equation to calculate infiltration under an unsteady rainfall condition. Chu (1978) estimated the starting time of rainfall runoff under unsteady rainfall conditions by using the Green and Ampt (1911) equation to determine rainfall-ponding time. Hachum and Alfaro (1980) revisited the problem of estimating rainfall infiltration into layered soils, and Fok and others (1982) developed a set of two-dimensional algebraic infiltration-estimation equations.

Differential Equations

Buckingham (1907) introduced a conceptual physical model of soil moisture in saturated soils. This pioneering contribution related diffusivity, D, to the product of hydraulic conductivity, K, and the change in capillary potential, $d\psi$, with the change in the soil-water content, $d\theta$, as

$$D = K \frac{d\psi}{d\theta}. \tag{9}$$

After Gardner (1920) did experimental studies on the tensiometer and saturated media diffusion, Israelson (1926) published the theory of the tensiometer. These contributions laid much of the groundwork for the use of differential equations in infiltration research. The differential equation soon became the most commonly used mathematical technique to describe flow through unsaturated porous media. The Richards (1931) model described infiltration with a partial differential equation. The general solution of the Richards (1931) equation is a semilogarithmic algebraic equation that appears quite similar to the Green and Ampt (1911) equation developed 20 years earlier. The Green and Ampt (1911) equation and the Richards (1931) equation both can be solved as implicit algebraic equations. However, the soil-science community was searching for an explicit algebraic solution to the differential equation techniques, and much of the literature after 1931 focuses on this effort. Kirkham and Feng (1940) published the results of tests they performed on diffusion theory. Klute (1952) rewrote the Richards (1931) equation into a one-dimensional equation that describes the downward infiltration of water through soil as

$$\frac{\partial \theta}{\partial t} = \nabla \, (D \nabla \theta) \, \frac{dK}{d\theta} \, \frac{\partial \theta}{\partial z}, \qquad (10)$$

where t is time, z is the downward ordinate in a positive sense, and ∇ is the vector differential operator. The work of Klute exerted a significant influence on Philip (1957a, b, c, d, e; 1958a, b) who published landmark work on infiltration theory. Philip (1957a) introduced a physically based converging-series solution to describe the Klute (1952) partial-differential infiltration equation. Philip (1957d) later proposed a new physical property of porous media known as sorptivity. Sorptivity, in some ways similar to permeability, is a measure of the capacity of the porous medium to absorb or desorb liquid by capillarity. Philip (1957d) kept the first two terms of the converging-series solution to the Klute (1952) equation and described cumulative infiltration under ponded conditions as

$$F = St^{\frac{1}{2}} + At, \qquad (11)$$

where F is the cumulative infiltration at time t, S is sorptivity, and the parameter A is physically based on the initial hydraulic conductivity and a function of the soil moisture, θ. Thus, the Philip's two-term infiltration equation is an explicit algebraic equation that is obtained from the general solution to the Richards (1931) partial-differential equation.

The Klute (1952) equation was solved numerically by Hanks and Bowers (1962) for the case of infiltration into layered soils. The work of Hanks and Bowers (1962) was among the earliest to model infiltration using digital computer technology. Rubin (1966) reported on rainfall-infiltration theory and suggested that empirical infiltration equations generally are superior to physically based (theoretical) infiltration equations when modeling rainfall runoff. After Philip published the theory of infiltration (1957a, b, c, d, e), much of the research activity on differential infiltration equations tended to focus on two- and three-dimensional modeling and the development of theory on heterogeneous media.

Application of Selected Equations to Rainfall-Runoff Modeling

A major consideration of the rainfall-runoff-modeling process is the capability of the selected rainfall-runoff model to estimate that portion of the rainfall that infiltrates into the soil. Infiltration can be estimated with a high degree of precision for small-scale simulations by using, for example, a finite element solution to the variably saturated flow equation (Cooley, 1983). However, estimating infiltration with such methods is too computationally intensive and cumbersome to be of practical value in most rainfall-runoff studies. There are many equations and techniques available that estimate the infiltration component of the rainfall-runoff relation. Most rainfall-runoff models use some type of empirical relation to estimate the amount of rainfall or precipitation that infiltrates into the soil. Generally, the parameters associated with the infiltration model, along with the other river-basin parameters used in the model, are calibrated according to measured precipitation and available streamflow data. Good estimates of the infiltration-model parameters usually are difficult to obtain because of the variabilities in antecedent soil-moisture conditions, soil hydraulic properties, precipitation patterns, and errors in the measured rainfall and streamflow. For many years, rainfall-runoff researchers and soil physicists have been especially concerned with the spatial variability of soil properties in the river basin and the effect of this variability on estimating infiltration.

In rainfall-runoff studies, the extent of hydrologic data available and project economics usually determine the detail required for an infiltration-modeling effort. In general, infiltration-estimating techniques can be divided into two families: those for small watershed areas and those for large watershed areas (Chow, 1964; Linsley and others, 1982). The distinction between a small watershed and a large watershed is not sharply defined, but a small-watershed area usually refers to areas or projects involving airports, road construction, agricultural fields, residential and commercial plot development, or other such areas that are relatively limited in areal extent. In contrast, large watersheds can be defined simply as anything larger than a small watershed or a combination of small watersheds. Field data are easier to collect in small-watershed areas because variations in field conditions, such as land cover, soil type, and antecedent soil moisture, tend to decrease in importance with increasing watershed area. Moreover, field measurements of infiltration capacity, infiltration rate, and rainfall intensity and volume can be determined with greater accuracy for smaller watersheds than larger watersheds. However, use of point-specific data, such as infiltrometer-measurement results and small-plot soil characterization, to predict infiltration in large watersheds is exceedingly difficult. The inherent variability of large watershed field conditions makes it very difficult to estimate infiltration parameters. Such variability of field conditions in large watersheds has motivated the use of approximate methods and averages, such as infiltration indices, infiltration curves, and soil-vegetative arrays.

The infiltration literature indicates the availability of a substantially large family of infiltration-estimating equations. Studies of the equations applicable to rainfall-runoff modeling tend to be limited to the separation of rain water into either precipitation excess or subsurface water, paying little or no attention to the further distribution of the latter. Such approaches are necessarily typical in the analysis of short-term rainfall-runoff relations as encountered in most hydrologic studies. Thus, surface-water hydrologists frequently use empirical infiltration equations to partition rain water into rainfall excess and infiltrated water. Although a large number of equations have been developed, relatively few equations account for the large majority of infiltration-estimation methods used in rainfall-runoff studies.

Four infiltration equations or infiltration-estimating methods--the Green and Ampt (1911) equation, the Philip (1957b) equation, the SCS (1956) method, and the Horton (1940) equation--are most frequently used in rainfall-runoff-modeling studies. A review of the infiltration literature indicates that, in general, the Green and Ampt (1911) and the Philip (1957b) equations have been applied most often to studies of small watersheds. Conversely, the Horton (1940) equation and the SCS (1956) method have been applied most often to studies of large watersheds. Each of these methods is discussed in the next sections.

Green and Ampt Equation

The equation developed by Green and Ampt (1911) is one of the earliest equations on record and is theoretically based on principles of soil physics. The original derivation is linked closely with the capillary-tube hypothesis, in which the soil or porous medium is portrayed as a bundle of parallel, noninterconnected capillary tubes, all of the same diameter. Although theoretically sound, the Green and Ampt (1911) equation was often criticized for lacking physical meaning. However, the extension of the Green and Ampt (1911) equation by Mein and Larson (1971) was found to be widely applicable to modeling the infiltration process. The Green and Ampt (1911) equation can be modified for sealing (Moore, 1981a) and consolidation (Wolfe and others, 1985). This equation also has been shown to apply under conditions of intermittent wetting (James and Larson, 1976) and to layered soils (Moore, 1981b; Moore and Eigel, 1981).

Application of the Green and Ampt (1911) equation first requires estimates of the parameters. Pioneering work on parameter evaluation was first reported by Bouwer (1969). The parameters for this equation were further investigated by Clapp and Hornberger (1978), Aggelides and Youngs (1978), Brakensiek (1977), Brakensiek and others (1981), and Rawls and others (1983). Work on scaling the soil-water parameter variability was reported by Nielsen and others (1973) and Warrick and others (1977). A number of studies have used the Brooks and Corey (1964) equation to describe soil-water-retention properties. The Green and Ampt parameters can be estimated from soil-water data and the Brooks and Corey parameters (McCuen and others, 1981).

Philip Equation

The Philip (1957b) two-term infiltration equation is a truncated form of a physically based converging series solution (Philip, 1957a) that describes cumulative infiltration under ponded conditions. The first term of the Philip infiltration equation is the sorptivity parameter. This parameter is physically interpreted as the ability of the soil to absorb water by capillary forces during the early stages of infiltration, when effects due to gravity may be ignored. Philip (1969) transposed the solution for one-dimensional horizontal absorption and showed that sorptivity could be interpreted in the vertical sense. Philip (1958a, b), Youngs (1968), and Parlange (1975) further investigated the physical meaning and interpretability of the sorptivity parameter. Chong and Green (1984) showed that sorptivity depends on the initial soil-water content.

The second term of the Philip infiltration equation represents the ability of the soil to transmit water under the influence of gravity in the transmission zone. This parameter depends on the properties of the porous medium and has been shown to be closely related to the saturated hydraulic conductivity. When considering infiltration over a relatively long period of time, some researchers have concluded that the saturated hydraulic conductivity can be readily substituted for the second term of the Philip infiltration equation (Philip, 1969; Ghosh, 1980; Maller and Sharma, 1984). Moreover, Swartzendruber and Youngs (1974) showed that such substitution does not introduce any serious errors, although Collis-George (1977) suggested this practice may lead to over prediction of cumulative infiltration with increasing time. Finally, Shirmohammadi and

Skaggs (1984) indicated that Philip's second term can never truly equal the saturated hydraulic conductivity because of air trapped within the transmission zone.

An often-cited criticism of the Philip (1957b) infiltration equation is the restrictive boundary condition applied by the assumptions of (1) uniform and constant concentration of soil moisture and (2) instantaneous surface ponding of noninfiltrated surface water. The assumption that rainfall will cause immediate surface ponding generally is unsubstantiated in the field. Even under conditions of relatively high rainfall intensity, the time to surface ponding can be appreciable. Further, the assumption of uniform soil-moisture concentration and soil hydraulic properties rarely is observed under actual field conditions. Thus, it is likely that the Philip infiltration equation is most theoretically sound under one-dimensional, isotropic systems where Horton-type overland flow regularly occurs.

Soil Conservation Service Method

The U.S. Soil Conservation Service (SCS) (1956) method estimates infiltration quantity and rainfall excess based on a hydrologic soil-cover complex. The SCS method was designed primarily for watersheds where no measurements of rainfall or runoff are available but where detailed information on soil and land cover is available. The SCS method estimates a runoff-curve number based on soil characteristics and land use. This runoff-curve number, which ranges from near 100 for an impermeable surface to near zero for highly permeable soils, describes the amount of precipitation that contributes to runoff. The method is applicable to any size watershed. If, however, the watershed varies in soil type or in cover, the watershed should be broken into regions of similar character and the regions analyzed separately. It also should be noted that the intensity of rainfall over very large watersheds is usually highly variable.

Soil Conservation Service Technical Release no. 55 (1975) presents a general comprehensive guide for estimating the effects of land-use changes and structural measures on hydraulic and hydrologic parameters, runoff volume, and peak discharge. Appendices in SCS Technical Release no. 55 provide a classification of the hydrologic soil groups and 24-hour rainfall-frequency curves for various rainfall accumulations in the United States.

Kao and others (1973) used the SCS method to consider the effects of urbanization on peak runoff and runoff volume in small watersheds. Urbanization effects also were evaluated by Rawls and others (1981) and McCuen and Miller (1984). The sensitivity of runoff estimates from the SCS method to changes in the runoff-curve number were investigated by Hawkins (1975) and Bondelid and others (1982). Bondelid and others (1982) concluded that the effect of variability in the runoff-curve number decreases as the design-rainfall depth increases. Aron and Lakatos (1976) integrated the SCS runoff-curve number into an urban rainfall-runoff model. Hawkins (1978a, b) investigated the effect of spatial variation in watershed soil-moisture and rainfall intensity on the predictive accuracy of runoff-curve numbers. Chong and Teng (1986) studied the relation between the runoff-curve number and the hydrologic soil properties and concluded that introducing the parameter sorptivity into the runoff-curve-number estimation can enhance the accuracy of the predicted runoff-curve number of a number of soils. Miller and Cronshey (1989) examined the reliability of runoff-curve numbers and suggested that use of infiltration-curve-based procedures, which are defined as the average curves of recession in the infiltration-capacity rate over time for a homogeneous single-practice watershed, might be more appropriate. They concluded that infiltration-curve-based procedures can be particularly advantageous where continuous simulation models are used.

Research has shown that satellite imagery can be used to determine the land-cover component for runoff-curve-number determination. Blanchard (1975), Slack and Welch (1980), and Jackson and Bondelid (1984) used multispectral digital imagery from the Landsat satellites to estimate runoff-curve numbers for various areas in the United States. Johnson and others (1983) used a multilayered approach that combined remote-sensor data, ground observations, soils maps, and drainage-basin maps to estimate an average runoff-curve number for each drainage basin. Zevenbergen and others (1988) related Landsat digital-reflectance values directly to the measured runoff-curve number for a variety of rangeland watersheds.

Horton Equation

One of the best known and most widely used methods for estimating infiltration is the equation proposed by Horton (1940). The Horton infiltration equation is based on an empirical relation and is not theoretically derived from principles of soil physics as are, for example, the Philip (1957b) equation or the Green and Ampt (1911) equation. Yet, despite this lack of physical correlation, a number of commonly used hydrologic-simulation programs make use of the Horton infiltration equation. Huber and others (1982) suggested that the Horton equation enjoys widespread acceptance because many hydrologists are able to develop a "feel" for the best values of its three parameters. Hydrologic-simulation programs that use the Horton equation to assess infiltration rates include the Illinois Urban Drainage Area Simulator, ILLUDAS (Terstriep and Stall, 1974); the Stormwater Management Model, SWMM (Huber and others, 1982); and the Queen's University Urban Runoff Model, QUURM (Watt and Kidd, 1975). The Horton equation is used both in its original form and in various modified forms in a number of other hydrologic modeling programs as well.

The Horton equation expresses the infiltration capacity of the soil at any particular time as a function of the initial infiltration rate, the final infiltration rate, and a time-dependent constant of decay. The equation assumes an unlimited supply of water is available at the soil surface during the time period of observation. As such, a common criticism of the Horton equation is that it fails to account for infiltration rates under variable rainfall conditions except in the case of a relatively heavy storm where rainfall intensity always exceeds the potential infiltration rate (Verma, 1982). Rainfall-runoff and soil-science researchers have proposed various modifications to the Horton equation to extend its applicability to field conditions where, for at least part of a storm, the rainfall intensity is exceeded by the potential infiltration rate (Bauer, 1974; Chu, 1978; Mls, 1980; Verma, 1982; Green, 1986; and others). Gifford (1978) concluded that the Horton equation achieved the best correlation with infiltrometer data relative to other commonly used infiltration equations for both United States and Australian soils. A number of other researchers have conducted studies comparing the accuracy and reliability of the Horton equation to other widely used infiltration-estimation techniques. Swartzendruber and others (1968) compared the Horton equation to the Green and Ampt (1911), Philip (1957b), and Holtan (1961) equations for small field plots and concluded the empirical equations of Horton (1940) and Holtan (1961) were superior to the theoretically based ones. Rawls and others (1976), Singh and Buapeng (1977), and Davidoff and Selim (1986) also reported that the empirically based Horton equation was consistently more accurate than the theoretically derived family of infiltration-estimation equations. Berndtsson (1987) concluded that the Horton equation is superior to the Philip (1957b) equation when there is a large degree of spatial variability in the infiltration characteristics of the watershed. However, Haverkamp and others (1988) reemphasized that the calibrated coefficient values of Horton's equation (as well as other empirical infiltration equations) are fitted parameters that generally lack physical significance and are valid only under the field condition from which they were determined.

BIBLIOGRAPHY OF LITERATURE ON METHODS FOR EVALUATING THE SURFACE-WATER COMPONENT

An extensive search of the scientific literature was performed through several large, computerized data-base systems. Three bibliographic data bases--Agricola[1], Applied Science and Technology Index, and Selected Water Resources Abstracts--provided a large majority of the citations. Additional citations also were obtained from the University of Illinois Library Computer System and Illinet Online, an Illinois statewide computerized search service provided through the University of Illinois. More than 7,000 citations in the scientific literature on the subject of infiltration initially were compiled. Most of the citations were eliminated from this bibliography as having limited usefulness based on examination of the citation's abstract and title or title only (whichever was available). The eliminated citations generally reported on the subject of infiltration either in the context of chemical processes related to water-quality effects, fate of pollutants, and water-supply augmentation and conservation, or treated infiltration as a purely soil-physics phenomenon in the context of ground-water management, aquifer recharge, and the mechanics of ground-water flow. Thus, citations selected for inclusion in this bibliography share the common theme of considering infiltration only in the context of the rainfall-runoff process. About 1,000 citations satisfied this criterion and are alphabetized by the last name of the author, or last name of the first author in the case of multiple authors (Appendix A).

Each citation is assigned a unique five-digit identification number. Approximately 300 of the citations are cross-referenced by their respective identification numbers to a categorical index (Appendix B). Selected citations are first indexed by one of eight infiltration equations or estimating methods: Green and Ampt, Holtan, Horton, Lewis and Kostiakov, Mein and Larson, Philip, Richard, and SCS. These eight equations or methods account for many of the

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[1]Use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

infiltration-estimation techniques used by water-resource planners and engineers to evaluate the infiltration component of the rainfall-runoff process. Citations that refer to one of these eight equations or methods are further divided, or subindexed, according to the physical setting or location where the study occurred. Thus, the indexes provide, when available, both the equation or method used and the physical setting it was used in. For example, an individual indexed citation might refer to a study that used the Horton infiltration equation in an urban environment, or perhaps the Philip equation in a forested area.

SUMMARY

This report reviewed the development of infiltration estimation equations and methods and examined those common to rainfall-runoff-modeling studies. The infiltration process was described by Chow (1964) as a three-step sequence: surface entry, transmission through the soil, and depletion of storage capacity in the soil. The noncapillary porosity of the soil is commonly regarded as the single most important factor influencing infiltration. Other factors influencing infiltration include moisture content, temperature, position of the ground-water table relative to the infiltration site, air movement within the soil profile, soil-plant relations, microbial activities, dimensionality of flow, properties of the infiltrating water, heat-transfer characteristics, surface conditions, and the time since the onset of the infiltration event.

Infiltration-estimation techniques can be broadly vided between the empirical equations and theoretical equations. The theoretical equations can be further subdivided into algebraic equations and differential equations (Fok, 1987).

Empirical infiltration equations are site-specific and are derived from experimental and (or) observational data. The calibrated coefficients of the empirical equations are fitted parameters that generally lack physical significance and are valid only under the field condition from which they were determined. Empirical infiltration equations were reported by Kostiakov (1932), Lewis (1937), Horton (1940), and Holtan (1961), among others. The SCS method (1956) estimates infiltration quantity based on soil characteristics and land use.

Theoretical infiltration equations generally are physically based and derived from principles of soil physics. The theoretical equations can be further subdivided into the algebraic equations and the differential equations (Fok, 1987). Green and Ampt (1911) published what is now the most frequently cited theoretical algebraic infiltration equation. The Green and Ampt (1911) infiltration equation has been modified by Fok and Hansen (1966), Bouwer (1969), and Chu (1978), among others. Algebraic infiltration equations also were reported by Van Keulen and Van Beek (1971), Mein and Larson (1973), Morel-Seytoux (1978), and others. Differential infiltration equations were reported by Richards (1931) and Klute (1952), among others, and are based, in part, on the physical model of soil moisture published by Buckingham (1907). Philip (1957d) published an explicit algebraic solution to the Richards (1931) differential infiltration equation.

Most rainfall-runoff models use empirical infiltration equations or estimation techniques to estimate the proportion of rainfall that infiltrates the soil. Infiltration-estimation techniques used in rainfall-runoff modeling can be subdivided into two general classifications according to watershed size and availability of data. The density of available data tends to decrease as the watershed size increases. Methods commonly used in rainfall-runoff modeling of small watersheds include the theoretical, physically based equations of Green and Ampt (1911) and Philip (1957d), among others. Methods commonly used in rainfall-runoff modeling of large watersheds include the empirical equations of Horton (1940) and the SCS (1956), among others.

An extensive search of the scientific literature initially yielded more than 7,000 citations on the general subject of infiltration. About 1,000 citations were selected for inclusion in the report bibliography. Selected citations share the common theme of considering infiltration in the context of the rainfall-runoff process. Subsets of the citations are indexed by eight infiltration equations or estimating methods: Green and Ampt, Holtan, Horton, Lewis and Kostiakov, Mein and Larson, Philip, Richards, and SCS. Citations that refer to one of these eight equations or techniques are subindexed according to the physical setting or location of the study.

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APPENDIX A -- Selected Bibliography

Bibliographic citations are numbered consecutively, beginning at 00010, and ending at 10190.

A: - denotes author(s) and date

T: - denotes title

S: - denotes source

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S: Journal of Range Management, v. 26, no. 3, p. 212-214.

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S: Water Resources Research, v. 19, no. 1, p. 194-200.

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S: Journal of Climate, v. 1, no. 9, p. 921-941.

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S: Soil Science of America Journal, v. 49, no. 1, p. 186-190.

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T: Overland flow on pervious, converging surface
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S: International Journal of Remote Sensing, v. 9, no. 3, p. 495-502.

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S: Journal of Soil and Water Conservation, v. 42, no. 6, p. 447-449.

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APPENDIX B -- Index of Selected Citations

Agriculture

01140 01940 01970 01980 03230 03240 03290 03640 03740 03780 04470 04550 05860 05870 06460 07600 08730

Forest

03200

Grassland

00120 05850

Laboratory

00065 00860 01200 01360 01700 03640 04520 04550 04610 05870 06460 06750 07585 08170 08470 08955 09550

Range

02620 03200 05400

Strip Mines

05700 05870 09550

Semi-Arid

01630 09950

Sub-Tropical

00090 01830 03600 06280

Urban or built-up

00160 00460 01700 06280 10020

Unspecified physical setting

00080 00130 00140 01060 01190 01210 01220 01230 01240 01330 01920 01950 02100 02160 02400 03190 03650 03730 04130 05620 05730 05740 05800 05970 06020 06030 06110 06120 06540 06870 08640 08940 09290 09420 09870 09950

HOLTAN

Agriculture

04290 04470 07870

Coastal Plain

07560

Laboratory

01700 08470 08955 09550

Strip Mines

09550

Urban or built-up

01700 01870 07870

Unspecified physical setting

01710 02100 04230 04460

Agriculture

02395 07340 08405 09330

Coastal Plain

07560

Forest

09800

Laboratory

01700 08470 08955

Range

03430 03440 03450 04600

Semi Arid

00815 05580 05590 06200

Strip Mine

04680

Sub-Tropical

09800

Urban or built-up

00460 01700 04360 05690 09070 09700

Unspecified physical setting

00600 00910 01490 01940 02160 02260 02590 03300 03590 03890 04350 04900 06030 06630 08440 09480 09720

LEWIS-KOSTIAKOV

<u>Agriculture</u>

02700 03420 05230 06870 09330

<u>Laboratory</u>

01700

<u>Range</u>

02700 03420

<u>Urban or built-up</u>

01700

<u>Unspecified physical setting</u>

03220 03225 03410 03890 04630 04991

<u>Agriculture</u>

<u>Forest</u>

<u>Laboratory</u>

<u>Sub-tropical</u>

<u>Urban or built-up</u>

<u>Unspecified physical setting</u>

PHILIP

<u>Forest</u>

00100

<u>Sub-tropical</u>

00100

<u>Urban or built-up</u>

03770

<u>Unspecified physical setting</u>

04260 04930 06050 07760 07950

SCS METHOD

Agriculture

01840 05040 07630 07640 08400 09370 09371 09372 09374

Coastal

06260

Forest

01740 04020

Laboratory

09550

Range

01010 10000 10160

Semi-Arid

01740 03940 04770

Strip Mine

05700 09550

Urban or built-up

00440 00450 00460 04770 05610 05630 07660 09373

Unspecified physical setting

00430 01080 01220 03895 03900 03920 04230 04500 04660 05800 08500 08550 09940

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