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"Rainfall Infiltration"

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RAINFALL INFILTRATION

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General Principles

Infiltration is the process of water entry to the soil through its upper surface by downward flow. Water may reach the soil surface by flooding the surface, by sprinkling or as rain. The relation between the rate of water supply to the soil surface and the rate of infiltration through it determines the distribution of such water between runoff and storage in the root zone. The knowledge of the infiltration process as it is affected by the soil's dynamic properties and by the supply of water is very important for an efficient soil and water management and conservation, especially when the water supply is through rainfall.

Vertical infiltration into an initially dry (unsaturated) soil occurs under the influence of a combination of suction and gravity gradients. The resulting infiltration rate (units of velocity: length/time) is a consequence of both the hydraulic conductivity and the hydraulic gradients in the soil surface zone but it is also affected by the conditions in lower parts of the soil profile. The influence of the suction gradient decreases with time until it becomes negligible in the upper part of the soil profile leaving the constant gravitational gradient as the only force moving the water downward. Therefore, in a uniform soil, without sealing and after prolonged ponding, the flux of water tends to approach the hydraulic conductivity. As a consequence, the infiltration rate under atmospheric pressure (also called infiltrability) generally decreases from an initially high value in a dry soil, to a much lower constant value termed final infiltration rate or steady-state infiltrability. The cumulative infiltration, which is the term used for the time integral of infiltration rate, has a curvilinear time dependence with decreasing slope up to a constant value (Fig. 1 & 2).

The decrease of infiltration rate of a soil with time is not only due to the decrease of the hydraulic gradient (the suction component), but also to other factors like structural deterioration and sealing of the soil surface, swelling of clays, entrapment and compression of soil air, etc. These factors are generally more important when the supply of water is through natural rainfall.

Numerous empirical and theoretically based expressions have been developed to describe the time dependence of the infiltration rate and of the total (cumulative) quantity of water infiltrated in the soil. The Philips solution to the general flow equation:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}[D(\Theta)\frac{\partial \Theta}{\partial z} + K(\psi_M) \qquad \text{where: } D(\Theta) = K(\psi_M)\frac{\partial \psi_M}{\partial \Theta}$$

for downward vertical flow leads to (assuming flooding conditions):

I (cumulative infiltration)= $St^{1/2}+At$

i (infiltration rate)= $dI = 1/2\ St^{-1/2} + A$

where: S (sorptivity) embodies the influence of the soil-water relations (matric suction and conductivity) in the wetting process; and A, represents the effect of gravity. S and A depend on Θ (volumetric soil moisture) and on the soil surface conditions. Therefore, in these equations, the first term expresses the influence on the downward flux of the suction gradient, predominating on an initially dry soil, while the second term represents the contribution of gravity, more important when the soil is wetted. The second equation shows that the infiltration rate decreases with time, and that A is the final infiltration rate, close to the saturated hydraulic conductivity of the topsoil.

Rain Infiltration

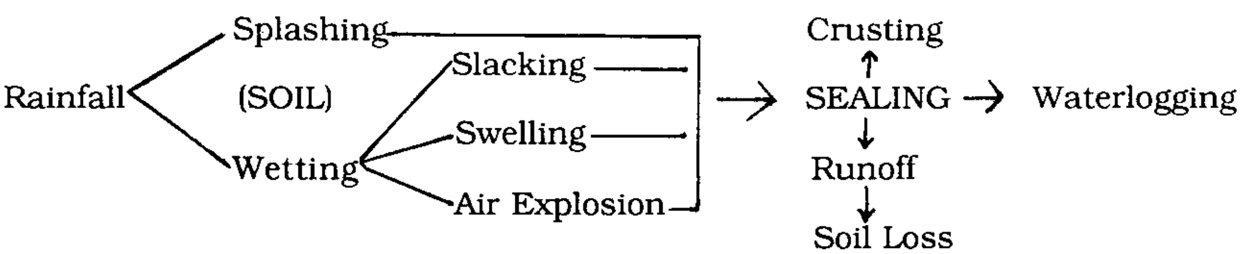
The decrease in the infiltration rate with time during a rainstorm may be attributed to:

1. A decrease in the vertical hydraulic gradient with wetting of the soil profile.
2. Surface sealing by raindrop action. A soil sealed once by rain and dried, will seal again rapidly when a new rainstorm begins.

The high energy load of the raindrops is responsible for surface sealing on bare soil. The potential for seal development depends considerably on the particle size distribution. Clay and silt fractions should reach values high enough to be able to block pores and thus limit infiltration.

The formed seal acts as a bottleneck, and because of its high hydraulic resistance, this causes infiltration into the underlying soil to occur at a suction which generally results in unsaturated flow conditions. As the hydraulic conductivity of the seal decreases, the matric potential, and as a consequence the suction gradient across the seal increases, which partially offsets the decreased conductivity of the surface seal. The effect of the seal on the infiltration of water in the soil is a decrease on the initial and final infiltration rates and on the length of time necessary to reach the final or steady infiltration rate (Fig. 3 &4).

The rate of formation of a seal and its water transmission properties are determined by physical, mechanical and climate factors. Some important factors and processes leading to sealing, and the derived effects (Bergsma and Kamphorst) are:



Besides the raindrops' beating action, the percolation of rainfall water, decreasing the electrolyte concentration of the surface soil solution, contributes to the dispersion of clays which block the pores and decrease even further the saturated hydraulic conductivity of the upper soil layer. As a contrast, generally the use of irrigation waters with a moderate salinity help keep the hydraulic conductivity in the saturated surface soil more stable (Fig. 5).

The infiltration rate and suction profile are affected both by the seal and the underlying soil. A surface sealed tilled soil may be viewed as a self-adjusting system in which the physical properties of the seal and the underlying tilled and non-tilled soil interact in time to reach a steady infiltration rate and moisture profile. The suction in the tilled layer under the seal is such as to create a gradient through the seal, and a conductivity below the seal resulting in equal flux of water through both layers.

For a thin seal of low hydraulic saturated conductivity (Ks) and a shallow depth of surface water, at a steady infiltration rate, the flux is given by:

$$qs = -Ks \frac{-(h+Ls)+\psi^{M}(A)}{Ls} \approx -Ks \frac{\psi^{M}(A)}{Ls}$$

$$q_A = qs = K_A (\psi^{M}(A)) \qquad \psi^{M}(A) = f(\Theta(A)$$

$$-\frac{K_A (\psi^{M}(A))}{\psi^{M}(A)} = \frac{Ks}{Ls} = \frac{1}{Rs} \qquad (Rs = \frac{Ls}{Ks})$$ (Hillel and Gardner, 1969)

where: Rs; Hydraulic resistance of the seal (time units)
qs; Flux through the seal
qa; Flux through the underseal tilled layer A
Ks; Saturated hydraulic conductivity of the seal
h; Depth of surface water (insignificant)
Ls; Thickness of the seal (very thin)
$\psi^{M}(A)$; Matric potential in the layer A under the seal
$\Theta(A)$; Volumetric soil moisture
K_A; Hydraulic conductivity of soil A at a matric potential $\psi^{M}(A)$

Therefore, when we have a seal with a saturated hydraulic conductivity much less than the one in the layer below it, it happens like when we have a horizon of fine pores directly on top of a horizon of large pores. The advance of the wetting front is temporarily stopped and the water accumulates at the bottom of the upper horizon with finer pores until the potential reaches very low values allowing the entry of water in the coarse horizon. The final infiltration rate in a surface sealed soil:

$$i(f) \approx K_A (\psi^{M}(A) = - \frac{\psi^{M}_{A}(f)}{Rs}$$

will depend not only on the hydraulic properties of the seal, but also on the ones of the soil layer below it which remains unsaturated, and it will be lower when such layer (A) has coarser pores. Although $i(f)$ decreases with increasing aggregate size of the tilled layer under the seal because its macropores keep a matric potential with lower K, the total intake of water in plowed soils generally exceeds that on finely cultivated or unplowed natural soils because the time and rainfall energy required to form a continuous seal increases with increasing roughness of the surface. But this will depend on the structural stability and the size of the surface clods or aggregates, which will determine the evolution of Ks under natural rainfall. Different from what is generally thought, the tillage not always increases infiltration of rain water and in some cases the reverse may be true.

In the process of infiltration of rainfall water, we may distinguish (Fig. 6):

1. Non ponding infiltration (Rainfall intensity < Final infiltration rate. Supply controlled).
2. Preponding infiltration (Rainfall intensity lower than infiltration rate but higher than final infiltration rate. Supply and flux controlled).
3. Rainpond infiltration (Rainfall intensity > infiltration rate. Flux controlled).

Under rainpond infiltration the wetted profile consists of an upper saturated part underlined by an unsaturated layer. The higher the rain intensity, the shallower the saturated layer will be at the beginning of ponding and the steeper the moisture gradient will be in the wetting zone.

Measurements and Calculation of Rainfall Infiltration

Failure to account for the seal formation can result in gross over-estimation, sometimes by a factor of 10^3, of infiltration of rainfall water. It has been measured and concluded that the decrease in infiltration rates are mainly due to the evolution of the seal during the rainfall. Therefore, the values obtained under flooding using double-ring infiltrometers, are clearly higher than the ones under rainfall. This is solved by the use of rainfall simulators of different models with variable plot size, drop size distribution, uniformity over the plot, drop velocity, intensity of water application, etc.

Theoretical studies of rain infiltration have problems to be applied to conditions where sealing occurs by raindrop impact, and in general to the process of natural rainfall intake by the soil. The main difficulties arise because of the inability to take into account the:

1. Discreteness of raindrops
2. Variability of rainfall intensities and energies
3. Dynamics of the soil physical properties

More complications arise when idealized theories are tried to apply to soils with profile heterogeneity, with cracks, and with swelling properties. In swelling soils the rainfall infiltration may be regarded in most of the cases more as an absorption process than one influenced by gravity. In cracking soils, the infiltration of the first rains is very different from the one-dimensional vertical process described by most of the theories, because water runs directly into the cracks where it is absorbed three-dimensionally.

Soil and Water Conservation Problems

The ***surface runoff*** is the portion of the water supply to the surface by rainfall which neither is absorbed by the soil (infiltration) or accumulates on the surface, but which runs downslope (overland flow) and eventually concentrates (stream flow) in channels (rills or gullies). The water available for runoff is determined by the process of infiltration which is in turn influenced both by the ***rainfall characteristics*** and by the ***physical properties*** of the soil.

In agricultural areas, specially in arid and semi-arid zones, the occurrence of runoff is generally undesirable since it results in loss of water for the growing crops, and often causes erosion.

Soil properties which influence runoff, and erodibility by water are:

1. Properties affecting infiltration rate and permeability
2. Properties affecting dispersion, splashing, abrasion and transporting forces of rainfall and runoff

As the seal is formed, the runoff rate increases with a corresponding increase in erosion or soil loss rates. The major damages by sealing and the resulting runoff and erosion losses is caused at the start of the crop season and generally is more a matter of a short number of rainfall events.

Most of the physical models used by the hydrologists to preview runoff assume that the soil is mainly a reservoir and that runoff losses only start when the soil is saturated by water after a given accumulated rainfall, independently of it's intensity and sealing effects. The use of rainfall simulators as infiltrometers allows to precise the factors influencing the runoff, and although their measurements in a reduced area of one to several m^2 cannot be directly applied to a watershed level, their results are very useful for analyzing the phenomena.

In order to reduce runoff is is necessary to:

1. Protect the soil surface against raindrop splash
2. Increase soil infiltrability
3. Increase soil surface storage of water
4. Obstruct or slow-down overload flow

Modifications by mechanical or by chemical means of the properties of the surface soil are generally for the purpose of promoting infiltration of rainfall water and achieve a more effective control, conservation and efficient use of the moisture in the field. The formation and stabilization of aggregates in the surface soil can provide a volume where the excess of water, due to rainfall intensities higher than infiltration rates, can be stored momentarily so that during intense rainstorms a longer time is available for rainwater absorption by the soil reducing the runoff and erosion. Often the rainfall amounts are insufficient to support a crop with an economical production.
In such cases, and depending on the soil properties and other factors, it may be possible to farm part of the land which would receive the ***runoff induced*** rainfall water from the rest of the land surface, if this has been appropriately shaped and treated for such purpose.

Modelling the Soil Moisture Regime for Crops

To develop and apply rational and efficient systems for the management and conservation of water in rainfed agriculture, and to preview requirements of supplementary irrigation it will be required to consider the main factors influencing the evolution of the soil water reserves available for the crop during the growing cycle. among those factors, the ones affecting the infiltration and storage (and drainage) of water in the soil's effective rooting depth, have to be specially considered. Beside climatic and soil's characteristics, problems like the effects of sealing and layering, (natural or induced by tillage operations), on the water intake, internal drainage, and rooting development, have to be considered. This is specially important in semi-arid to subhumid tropical and subtropical areas where intense and irregularly distributed rainfall, surface sealing and layering of soils, and soil physical and chemical limitations for the development of roots, are very common. In most of the cases, the success or failure of cropping in those areas depends primarily on the water regime maintained in the root zone during the crop cycle (Fig. 7,8 & 9).

Most of the models used to predict soil water balances do not take into consideration many or some of the previously named critical conditions. The following model integrates all those factors, and with the help of a computer-based programme helps to rapidly identify in a quantitative way, which of those factors may be the most limiting for the soil and water conservation and for the crop development. This will help to select and to apply the most appropriate treatments and management practices to avoid or to diminish such limitations.

Required information:

- HP: Daily Rainfall in mm
- IP : Rainfall intensity in mm/hour
- VI : Rainfall intake rate in mm/hour
- DS: Soil rooting depth in mm
- ΘC: Soil moisture in DS at "field capacity" in mm
- ΘT: Soil moisture in DS at -0,15 MPa in mm
- ΘP: Saturated hydraulic conductivity of the soil layer below root depth in mm/hour
- HET: Daily evapo-transpiration in mm
- Yes or No: Possibilities of water losses through surface drainage or runoff.

The model calculates for each day during the growing season and for the soil rooting depth:

- HS: Soil moisture stored at root depth at the end of each day in mm
- HDE: Water lost by runoff or surface drainage in mm
- TW: Duration of waterlogging in hours
- HDI: Water lost by deep drainage below the rooting zone in mm
- TDI: Duration of soil moisture levels above field capacity at the root zone in hours

Calculations

A. Surface drainage or runoff - YES

Day (1):

$HS(1) = (\Theta T.DS)+HP(1)-HET(1)$ if $HS(1)>(\Theta P.DS)$

$HS(1) = (\Theta T.DS)$ if $HS(1)<(\Theta P.DS)$

$HDE(1) = 0$

$HDI(1) = 0$

$TDI(1) = 0$

Day (i>1):

$HDE(i) = (HP(i).((1-(VI/IP)))-10$ if $(VI/IP)<1$

$HDE(i) = 0$ if $(VI/IP)>=1$

$HS(i) = HS(i-1)-HDI(i-1)-HET(i)-HDE(i)$ if $HS(i)>(\Theta P.DS)$

$HS(i) = (\Theta P.DS)$ if $HS(i)<=(\Theta P.DS)$

$HDI(i) = HS(i)-(\Theta C.DS)$ if $HS(i)>(\Theta C.DS)$

$HDI(i) = 0$ if $HS(i)<= (\Theta C.DS)$

$TDI(i) = HDI(i)/KDI$ if $HS(i)<=(\Theta C.DS)$

B. Surface drainage or runoff - NO

Day (1)

    HS(i) = (ΘT.DS) + HP(1) - HET(1)
    HDI(1) = 0
    TDI(1) = 0
    HW(1) = 0
    TW(1) = 0

Day(i>1):

    HS(i) = HS(i-1)-HDI(i-1)+HP(i)-HET(i)   if HS(i)>(ΘP.DS)
    HS(i) = (ΘP.DS)   if HS(i)<(ΘP.DS)
    HW(i) = (HP(i).((1-(VI/IP)))   if (VI/IP)<1
    HW(i) = 0   if (VI/IP)>=1
    TW(i) = HW(i)/VI
    HDI(i) = HS(i) - (ΘC.DS)   if HS(i)>(ΘC.DS)
    HDI(i) = 0   if HS(i)<=(ΘC.DS)
    TDI(i) = HDI(i)/KDI

It is considered:

    DW: Day with waterlogging   if TW(i)>=12
    DE: Day with excessive soil moisture   if TDI(i)>=12
    DA: Day with adequate soil moisture   if (ΘC.DS)>= HS(i)>(ΘT.DS)
    DT: Day with moderate (or temporary soil moisture deficit
                                                 if (ΘS.DS)>= HS(i)>(ΘP.DS)
    DP: Day with extreme (or permanent soil moisture deficit
                                                 if HS(i)<= (ΘP.DS)

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