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INFILTRATION CONTROL THROUGH SOIL SURFACE MANAGEMENT[a]

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ABSTRACT

The air-earth interface concept for controlling water infiltration into soils is reviewed. The basic principle established by this concept is discussed and applied to problems related to inadequate infiltration control. Methods are suggested for achieving both relative and absolute infiltration control through soil surface management.

The air-earth interface concept holds that *interfacial roughness and openness control the rates and routes of water infiltration by governing the flow of air and water in underlying macropore and micropore systems. Roughness* refers to the microrelief that produces depression storage, whereas *openness* refers to the macroporosity that is visible at the soil surface. If the soil surface is rough and open, interfacial exchange of soil air and free surface water occurs freely and water infiltrates rapidly via the relatively short broad straight paths of the macropore system. In contrast, if the surface is smooth and closed, surface exchange of air and water is greatly impeded and water infiltrates slowly via the relatively long narrow tortuous paths of the micropore system.

For most soils, infiltration into a rough open surface usually exceeds that into a smooth closed surface by a factor of 10 or more. This factor tends to increase with the duration of these two extreme surface conditions. Thus, infiltration may be controlled over a wide range by designing cultural practices for various levels of surface roughness and openness. These levels may be attained quickly by suitable tillage implements or slowly, but with much less energy, by guiding natural physical and biological processes.

Relative infiltration control may be achieved by simply applying the basic principle of the air-earth interface concept; i.e., to increase infiltration, increase the surface roughness and openness, and conversely. Quantification of the concept for predictive purposes may be accomplished by converting these two physical properties of the soil surface into their hydraulic equivalent. A newly defined parameter, termed *effective surface head*, is thought to adequately describe the infiltration role of surface roughness and openness.

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It is defined as the difference between the surface water hydrostatic pressure and the soil air back pressure and it is conveniently expressed as centimeters of water head. Infiltration is highly responsive to effective surface head in a narrow range of only a few centimeters surrounding zero; and this head, in turn, is highly responsive to the common cultural practices that affect surface roughness and openness.

Since effective surface heads occurring during natural rainfall and irrigation are often negative, and since conventional infiltrometers produce only positive heads, the newly developed *closed-top infiltrometers* are required to evaluate the infiltration responses to natural effective surface heads. The values of the two parameters in Kostiakov's equation are determined by fitting the equation to the resulting cumulative infiltration curves. The parameter values are then plotted as a function of effective surface head. Such a graph, in conjuction with Kostiakov's equation, may be used to predict the infiltration curve associated with a known value of effective surface head or with the corresponding values of surface roughness and openness.

Further research is needed to evaluate natural effective surface heads under diverse soil-surface and water-source conditions, to develop better methods for characterizing surface roughness and openness, to relate effective surface head to surface roughness and openness, and finally to develop new and improved cultural practices based on the air-earth interface concept.

INTRODUCTION

Uncontrolled infiltration often causes the inefficient use and irreversible loss of our vital soil and water resources. For instance, excessive tillage and over grazing diminishes the soil's ability to absorb water, and thereby increases soil and water losses from the soil surface through the processes of runoff and erosion. Erosion decreases the size of the soil water reservoir, with consequent increases in the probability of subsequent runoff, erosion and insufficient water for plants drawing from this reservoir. Where soil resources are critically limited, small soil losses can greatly reduce vegetal production. Similarly where water resources are very limited, small runoff losses can greatly restrict productivity. Where both are limited, either water loss or soil loss (or both) can curtail production. Virtually all agricultural lands of the world periodically fit one or more of these three categories and thus can benefit from improved infiltration control.

Many other problems are either directly or indirectly related to man's inability to control infiltration at appropriate levels. These include flash flooding of upland watersheds, excessive erosion of upland stream banks, sedimentation of waterways and reservoirs, pollution of surface and groundwaters, excessive evaporation from soil surfaces, inefficient leaching of soluble salts and excessive leaching of plant nutrients, inefficient on-site use of precipitation for vegetal production, inefficient water harvesting for off-site precipitation uses, slow recharge of ground water and declining water tables, and inefficient irrigation of various land areas.

Infiltration occurs when free surface water crosses the air-earth interface, thereby displacing soil air. Thus, infiltration usually involves the exchange of free water and soil air at the soil surface. Macroporosity (or the macropore network in a soil) often dominates hydraulic conductivity. Childs, Collis-George and Holmes (3) reported that macroporous clay soils have permeabilities comparable with gravelly soils. They found that structural fissuring in clay subsoil increases hydraulic conductivity by one to three orders of magnitude. Earthworm activity increased the permeability of clay soils to the order of that associated with coarse sands (34). Childs (2) calculated that a 1-percent macroporosity in the form of 1-mm wide plane cracks, could increase the hydraulic conductivity of an idealized clay of 50-percent microporosity by a factor of 30,000. In his theory for water absorption by aggregated media, Philip (25) assumed that water transfer occurs only via the macroporosity. There is considerable evidence, however, that under field conditions the air-earth interface regulates controls water transfer within macropores, thereby controlling the infiltration (and also the hydraulic conductivity) contribution of such pores. Duley and Russell (12) noted that surface sealing affects infiltration more than soil type, slope, moisture content, and profile characteristics. Dixon (5) showed that macropores dominated infiltration only when they were open to the soil surface, were exposed to free water, and were easily purged of air. Under these conditions, macropores carried enough water through the air-earth interface to obscure the relatively small infiltration effects of bulk density and antecedent soil water content. Soil air, at pressures greater than atmospheric, can prevent macropore dominance of the infiltration process. A displaced air pressure of only 18 cm of water reduced total infiltration under a border irrigation by one-third or from 15 to 10 cm (9). Soil air back pressure apparently hampers entry of free surface water into open macropores.

The physical basis for the large infiltration contribution of open macropores is that volume flow (according to Poiseuille's equation) increases with the fourth power of a cylindrical pore's diameter. Thus a pore of 1-mm diameter theoretically conducts downward 10,000 times as much water as a 0.1-mm pore. Volume flow into a plane crack increases with the cube of the crack's width. Furthermore, pore tortuosity (flow path length per unit vertical distance) decreases and pore continuity increases with increasing pore size. The tendency for macropores to fill with displaced soil air and thereby block infiltration paths would also be expected. Jurin's equation (27) indicates that capillarity decreases with increasing pore diameter (or diameter of curvature in air-water interface) and is < 3cm of H_2O for pores > 1 mm in diameter. Hence a displaced air pressure head of only 3 cm theoretically can eliminate the otherwise large infiltration contribution of macropores > 1 mm in diameter. By Boyle's equation, soil air pressure would rise 3 cm when only 0.3 cm of water infiltrates a soil 10 m deep that is initially 10 percent air. Consequently, air pressures $\geq$ 3 cm of water are probably common under natural field conditions during wetting. The need for macropores to be open and exposed to free surface water before they can contribute to infiltration is inferred by Darcy's equation (4), which indicates that water moves only in the direction of decreasing hydraulic head. Hydraulic head always increases in the direction of a macropore isolated from free water by a surface seal or a microporous region.

In a new infiltration concept referred to variously as the *air-earth interface* concept, *channel system* concept, or *two-flow system* concept (6, and references therein), soil surface roughness and soil surface macroporosity play an important role in the infiltration process. The term, *air-earth interface,* is perhaps the most descriptive of the three since it focuses attention on the site of infiltration control; i.e., the immediate soil or ground surface. In this paper the air-earth interface concept is described, concept applications to relative infiltration control are considered, and an approach to concept quantification for absolute infiltration control is presented.

CONCEPT FORMULATION

The air-earth interface *AEI* concept established the general principle that *soil surface roughness and openness control infiltration of free surface water by governing the flow of air and water in underlying macropore and micropore systems,* wherein *roughness* refers to the microrelief that produces depression storage, and *openness* refers to the macroporosity that is visible at the soil surface. The macropore system includes the space immediately above the *AEI* and that space within macropores which fills and drains largely by gravity during and after soil surface exposure to free or ponded water (Figure 1). Macropores include those voids produced by clay shrinkage, tillage, earthworms, roots, internal erosion, ice lenses, pebble dissolution, and entrapped gas. In contrast, the micropore system includes the spaces within and between individual soil aggregates (textural and structural pores or simple and compound packing voids) that fill and drain largely by capillarity. Thus during rapid wetting of an initially dry soil, the macropore and micropore systems contain water at pressures of near atmospheric and below atmospheric, respectively. The two systems of pores share common porous borders at the *AEI* and along macropore walls which allow intersystem flow of water and displaced soil air.

The *AEI* concept embodies six physical interfacial models (Figure 2) representing two degrees of surface roughness and three degrees of surface openness. The subterranean part of the macropore system is depicted as a single U-shaped tube to graphically reflect its infiltration role as a water-intake air-exhaust circuit. Models *RO, RP,* and *RC* represent rough interfaces with open, partly open (unstable), and closed macropore interfacial openings or *macroports,* respectively. Models *SO, SP,* and *SC* represent plane (smooth) interfaces with open, partly open, and closed macroports, respectively. These models were intended to guide practical application of the concept by serving as a reference framework within which needed modifications in existing surface conditions may be considered.

Under the rough open surface of model *RO,* interfacial exchange of air and water occurs freely and water infiltrates rapidly via the relatively short broad straight paths of the macropore system; whereas under the smooth closed surface of model *SC,* surface exchange of air and water is greatly impeded and water infiltrates slowly via the relatively long narrow tortuous paths of the micropore system. Infiltration under these model extremes often differs by more than an order of magnitude. The general hydraulic behavior of these models

may be deduced by ranking them with respect to various properties or characteristics. By definition, interfacial roughness and depression storage rank in the order *RO*=*SO*>*RP*=*SP*>*RC*=*SC*. Also by definition, interfacial openness or physical continuity of the interface and macropores rank in the same order.

Characteristics which may be ranked *RO*>*RP*=*SO*>*RC*=*SP*>*SC* are: air and water continuity between the air-earth interface and macropores; border area between the two pore systems wetted with high pressure water; water infiltration, percolation and interflow rate; mean vertical and horizontal hydraulic conductivity and gradient; soil-water content and pressure; air permeability of soil surface and exhausting rate of displaced air; entrapped air pressure; and internal soil erosion.

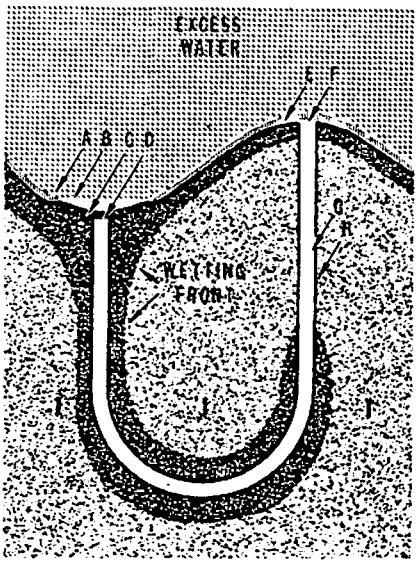

Figure 1. Soil model containing a micropore system and a macropore system. A = plant residue cover on air-earth interface; B = free water surface; C = microdepression in air-earth interface; D = water intake port of macropore; E = microelevation in air-earth interface; F = soil air exhaust port of macropore; G = macropore space; H = macropore wall; and I = micropore space. From Dixon and Peterson (10).

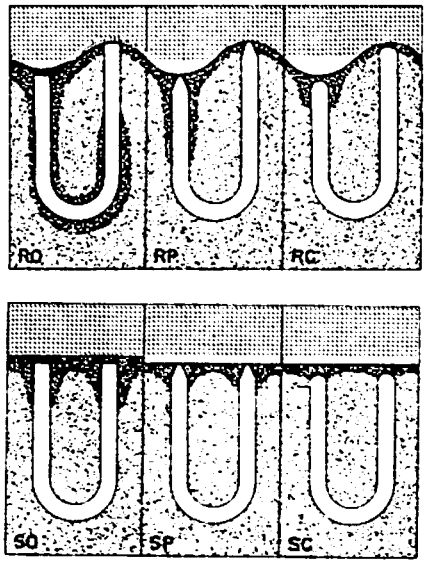

Figure 2. Air-earth interface models and associated u-shaped macropore for water infiltration into soils. Models *RO*, *RP* and *RC* represent rough interfaces containing open, partly open (unstable) and closed macroports, respectively; whereas models *SO*, *SP* and *SC* represent smooth interfaces containing open, partly open (unstable) and closed macroports. From Dixon and Peterson (10).

By inference, characteristics ranked in the order *RO>RP=SO>RC=SP>SC* are: downward movement of surface solutes per unit infiltration and pollution of groundwater with these solutes; groundwater recharge; water penetration depth from brief intense rainstorms; and soil-water evaporation during the falling rate period. Varying in the order *RO<RP=SO<RC=SP<SC* are flash flooding, surface erosion, pollution of surface waters and streambank erosion; downward movement of soil solutes per unit infiltration and pollution of groundwater with these solutes; interface evaporation of soil water from brief intense rainstorms; and soil-water evaporation during the constant rate period.

It should be stressed that the *AEI* concept is consistent with Darcy-based flow theory and the view of surface infiltration held by Childs (2). Darcy's Law implies that infiltration rates of a given soil are the product of the hydraulic conductivity and hydraulic gradient for given times; however, the *AEI* concept of infiltration states that soil surface roughness and openness control infiltration rates and routes by governing the flow of air and water in underlying macropore and micropore systems. These two contrasting views are not contradictory, since both the hydraulic conductivity and hydraulic gradient depend on the surface conditions of roughness and openness. Thus, these two conditions control infiltration through their domination of the effective hydraulic conductivity and gradient; i.e., these two surface properties govern the internal transmission characteristics of the soil profile. This may be explained by the fact that free surface water crossing an *RO* interface drops a minimal hydraulic head, whereas water crossing an *SC* interface drops a maximal head relative to other possible combinations of surface roughness and openness. Consequently, both the hydraulic conductivity and gradient will be much greater beneath an *RO* surface than beneath an *SC* surface during the course of free surface water infiltration. Under an *RC* surface, the soil's macropores can rapidly fill with free surface water and simultaneously surface vent, at minimal pressures, the soil air being displaced. Both such fluid transfer functions are essentially precluded by an *SC* surface. The hydraulic head loss across the *SC* surface, combined with a soil air pressure rise, produce a positive hydraulic gradient in the direction of macropores; and thereby prevent water from entering the macroporosity or that pore space which would otherwise dominate hydraulic conductivity and infiltration. Thus a wide-ranging family of infiltration curves can be generated for a given soil profile merely by altering soil surface roughness and openness. Such curves do not parallel each other since initial as well as final infiltration rates vary widely. This contradicts the popular belief that a soil has a final infiltration rate closely approximating the saturated hydraulic conductivity of the profile which is valid only under the *RO* surface or under soil surface conditions conducive to nearly complete water saturation of the soil profile. Both initial and final infiltration rates decrease with decreasing surface roughness and openness, and the consequently reduced degree of attainable soil saturation.

CONCEPT TESTING

A series of field experiments were conducted to test the performance of selected interfaces and to thereby evaluate the potential of the *AEI* concept as a practical scheme for controlling infiltration (10).

Standard interfaces *RO* and *SC* were hand imposed for comparison with the natural interface. The *RO* interface was prepared by (i) contour furrowing the soil surface, (ii) vacuum cleaning the furrow trough and (iii) completely covering the new surface with plant material. By cutting and filling, furrows were shaped to fit a sine wave having a 5-cm amplitude (vertical distance from original soil surface to furrow trough or to furrow crest) and a 50-cm wave length (horizontal distance between adjacent crests and troughs). The purpose of the *RO* treatment was to increase and stabilize soil surface roughness and openness in order to maintain continuity of both air and water phases between the surface (air-earth interface) and subsurface components of the macropore system in the presence of free surface water. The *SC* interface was prepared by (i) removing all plants and plant residues from the soil surface, (ii) passing the surface 2.5 cm of soil through a 6-mm mesh screen, and (iii) planing the soil surface smooth. The purpose of this treatment was to eliminate soil surface roughness and openness in order to maintain discontinuity of both air and water phases between the surface (air-earth interface) and subsurface components of the macropore system in the presence of free surface water.

These studies encompassed a wide diversity of vegetal, edaphic, and climatic conditions. Infiltration tests were conducted on an East Fork loam near Reno, Nevada; a Miami silt loam near Madison, Wisconsin; a Sprole loam near Sidney, Montana; a Gardnerville clay loam near Minden, Nevada; and a Laveen loam near Tombstone, Arizona. The East Fork, Miami, Sprole, Gardnerville and Laveen are alluvial, gray-brown podzolic, chestnut, sierozem, and red desert soils; having silt loam, silty clay loam, clay loam, clay, and loam subsoils; and receiving annually about 89, 76, 33, 20, and 27 cm of water, respectively. The East Fork and Miami soils were both in alfalfa for hay production at the time of the infiltrometer tests; whereas the Sprole, Gardnerville and Laveen soils supported vegetation consisting mainly of western wheatgrass, sagebrush and sideoats grama, respectively.

Results from the infiltration tests indicated that standard air-earth interfaces can be imposed to control infiltration of a given soil within a range often exceeding an order of magnitude (Figure 3). This range widened with time after interfaces were imposed (6), since the infiltration capacity of macropore system *RO* increased while the capacity of system *SC* decreased (Table 1). Observed increases under interface *RO* were largely attributed accelerated earthworm activity. Such activity not only improved the surface continuity (openness) of the macropore system, but also increased its subsurface continuity and extent. Time-dependent decreases under interface *SC* reflected the absence (or low level) of interfacial biotic activity with consequent decreases in macropore system continuity at the soil surface. Thus, apparently cultural practices that maximize biotic activity at the soil surface create open interfaces *RO* and *SO*, whereas practices that eliminate such biotic activity lead to closed interfaces *RC* and *SC*. Tillage plus wetting of the soil create the partly open interfaces *RP* and *SP* (unstable, transitory interfaces). Interfaces *RP* and *SP* subsequently trend toward interfaces *RO* and *SO* if they are biologically active or toward *RC* and *SC* if they are inactive.

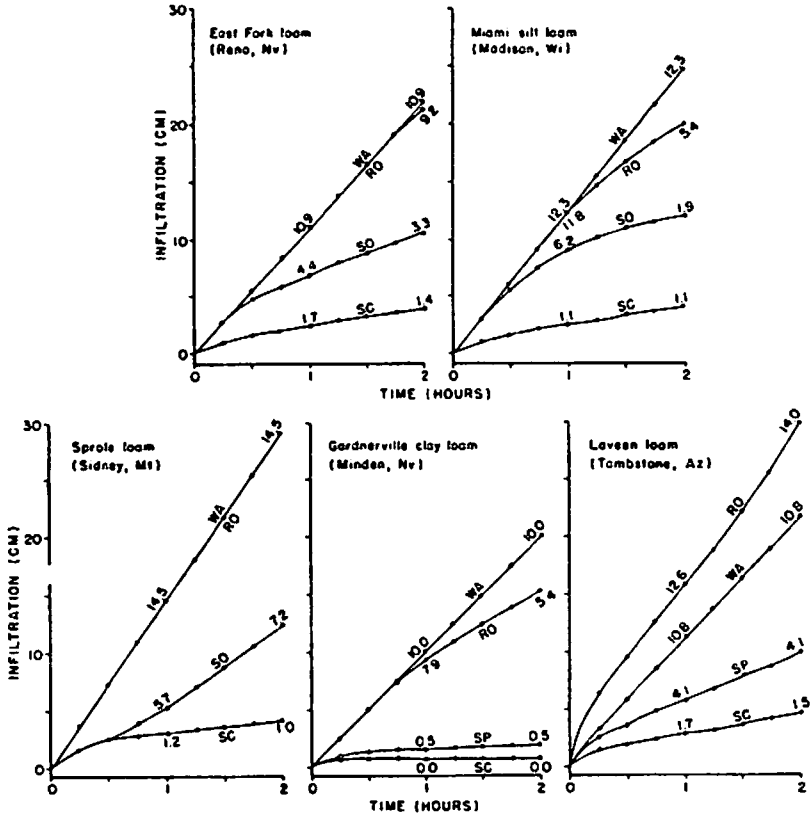

Figure 3. Infiltration volume (depth) under imposed air-earth interfaces *RO* and *SC* and naturally occurring interface either *SO* or *SP*. The curve labeled WA gives the total water applied by the infiltrometer spray nozzle. Numbers near curves at 1- and 2-hour times denote infiltration rates in cm hr^{-1} for these times. Modified from Dixon and Peterson (10).

Table 1. Two-hour infiltration for an East Fork loam soil under the air-earth interfaces *RO* and *SC* and the natural interface *SO* where interfaces *RO* and *SC* were imposed in 1969 and then maintained until 1972.

Air-Earth Interface*	Observation Year	Infiltration Total Absolute (cm)	Infiltration Total Relative** (1)	Infiltration Rate Absolute (cm)	Infiltration Rate Relative** (1)
RO	1969	13.0	1.6	3.6	1.5
RO	1970	39.2	5.0	10.0	4.2
RO	1971	74.6	8.6	20.4	8.9
RO	1972	115.6	11.6	36.6	13.1
SO	1969	8.0	1	2.4	1
SO	1970	7.9	1	2.4	1
SO	1971	8.7	1	2.3	1
SO	1972	10.0	1	2.8	1
SC	1969	6.1	0.8	1.6	0.6
SC	1970	5.3	0.7	1.5	0.6
SC	1971	3.7	0.4	0.6	0.3
SC	1972	5.3	0.5	1.4	0.5

* *RO* = rough open, *SO* = smooth open and *SC* = smooth closed.

** Relative values are expressed as a fraction of the infiltration occurring under the natural interface *SO* for the specific year.

CONCEPT UTILITY

The *AEI* concept established the principle that prevailing soil surface roughness and openness control infiltration rates of a given soil. This generalization unifies and explains a wide range of infiltration-related phenomena, including: the dominating influence of the soil surface on infiltration; large infiltration effect of surface water head in macroporous soils; relatively small infiltration effect of soil texture, bulk density, and moisture content; runoff and erosion acceleration resulting from clean cultivation; erosion control effectiveness of mulching and minimum tillage practices; interflow in sloping forest lands while the soil is relatively dry; flash flooding of upland watersheds before the topsoil is nearing saturation; and faster infiltration into some clayey soils than into sandy soils.

The major significance of the *AEI* concept lies in its potential for practical field application (22). Since the soil surface controls the rate and route of water movement into, within, and through the soil, soil and water management practices which appropriately alter this surface can be used to control various infiltration-related problems. Surface management practices can be directed to changing the existing interface into the desired one by means of the *transformation* processes shown in Figure 4. For example, interface *RO* is changed to *SC* by the *exposing-smoothing-sealing* sequence of processes. Although the transformation processes often occur naturally, their rates may be controlled by appropriate cultural practices. For instance, *exposing* of the soil surface may occur slowly through biological decomposition of plant residue, or very rapidly via cultural practices such as burning and moldboard plowing. Similarly *covering* of a barren soil in a semiarid region may be achieved rapidly with combinations of cultural practices such as

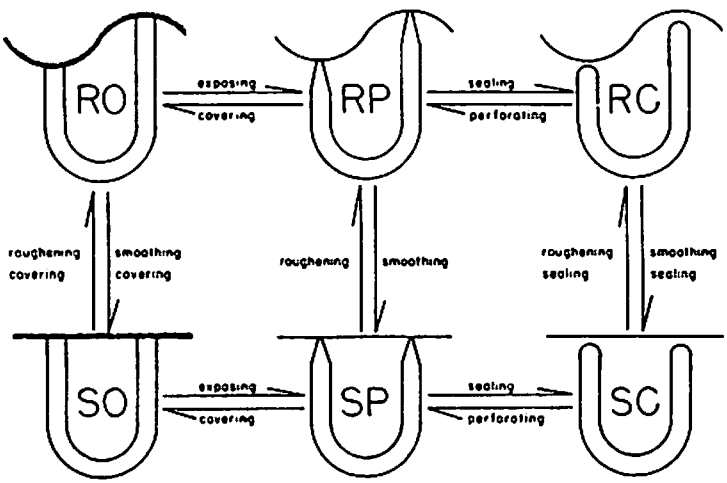

Figure 4. Air-earth interface cycles and transformation processes.

irrigation, fertilization and mulching. The transformation processes are general processes which include many specific processes such as physical, chemical, and biological processes, and man-imposed processes (cultural practices). A field guide for applying the *AEI* concept can be developed from Figure 4 by identifying the interfacial conditions resulting from existing cultural practices, and by extensive detailing of the general transformation processes. This detailing should consider the effectiveness and economic feasibility of alternative cultural practices and combination of practices.

The *AEI* concept appears applicable to a wide range of problems caused by uncontrolled rate and route of water infiltration. To control runoff, erosion and pollution of surface waters, the existing interface could be transformed to interface *RO*. This could raise intake rates well above the intensity of 50-year storms to essentially eliminate runoff. Upland flooding of much of interior United States often occurs when the storage space of the topsoil is just partially filled. Accessibility (even beneath water-repellent surfaces) of this storage space to free surface water is greatly increased by the short circuits of the *RO* macropore system.

This concept also appears useful in controlling soil leaching and groundwater pollution. Interface *SC* would give the most efficient leaching of soluble salts (where evaporation is small relative to infiltration) because infiltrating water would move slowly via long, small, tortuous routes through the micropore system. Thus diffusion distance would be minimized and diffusion time would be maximized. However, if pollution of ground or drainage water is to be controlled, interface *RO* would be appropriate, since much of the infiltrating water (in this case) would move horizontally rather than vertically into the salt-containing micropore system. Thus, net downward movement of salt per unit of water applied would be greatly reduced. However, when the pollutants are on the soil surface or in the water source rather than in the soil, interface *SC* would minimize the pollution of groundwater since more of the pollutants would be deposited in the soil and/or removed in surface runoff.

The *AEI* concept could be useful in controlling lateral distribution of soil water replenished by surface or sprinkler irrigation and rainfall. To achieve more uniform distribution, inherent infiltration variability (due to soil texture, slope, etc.) could be minimized by imposing the appropriate interface, *RO* through *SC*. More uniform lateral distribution of soil water would lead to more efficiency in irrigation and in crop use of the resource.

Interface *RO* could be imposed to augment aeration, drainage, and groundwater recharge. Interface *RO* may also be useful in reducing surface evaporation in regions where much of the annual rainfall is intense but of short duration. It would permit deeper water penetration per unit of rainfall since some of the storage space near the soil surface would be bypassed. Water held deeper in the soil profile is less subject to evaporation. For regions where annual precipitation is insufficient to support a complete vegetal cover, efficient runoff-irrigation practices could be developed by imposing and maintaining alternate contour strips of interfaces *RO* and *SC*.

This concept may permit greater latitude in designing surface irrigation systems since it facilitates infiltration control by cultural means. Existing irrigation systems could be made more efficient by

converting the prevailing interface into one giving an appropriate infiltration capacity.

In many cropland situations, the *AEI* concept can be applied by merely altering tillage practices to effect the appropriate change in soil surface roughness and openness. Both roughness and openness would be functions of tillage implement type and setting, crop residue placement, and soil conditions. Crop residue placed at the soil surface would help to maintain the roughness and openness created by the tillage implement. Although cropland applications have been stressed, the *AEI* concept is general enough to apply to other land areas as well. For instance, the runoff-irrigation practices suggested above have considerable potential in increasing the forage productivity of semiarid rangelands.

MACROPORE FORMATION

In the *AEI* concept, soil pores were separated on the basis of origin into micropore and macropore classes. While the origin and geometry of micropores depend largely on the nature of the basic soil material (mineral particles and colloids), origin and geometry of macropores are largely controlled by dynamic external factors of structure formation, including surface management practices. Consequently, the origin, age and geometry of macroporosity in a cropland soil reflect the effect of current and past cultural practices. Soil-surface macroporosity usually responds the most rapidly and intensely to any change in cultural practice, since the structure-forming processes are greatly accelerated at the *AEI* relative to soil depths.

The *AEI* concept infers that soil surface openness and roughness not only reflect the condition of existing macroporosity but also influence its subsequent development. For instance, interface *RO* provides physical and biotic conditions favoring the time-dependent increase of both surface and subsurface macroporosity. The high water pressure of the macropore system leads to internal erosion and ruptures in pore system borders with consequent enlargement and extension of existing macropores, linking of isolated macropore segments, and even the development of new surface-connected macropores. Micropore system saturation and subsequent dehydration in regions bordering the macropore system create a highly complex pattern of wetting and drying stresses with corresponding shrinkage cracks.

Microdepressions of the *RO* interface provide attractive feeding sites for earthworms and other soil fauna. Earthworms, sensing the organic acids of the decomposing plant residue, migrate rapidly (often via subterranean routes) to these depressions and perforate them with their burrows. Some species such as *Lumbricus terrestris* form essentially vertical burrows 1- to 3-m deep and 6 to 8 mm in diameter, whereas other species tend to burrow horizontally. Thus, a crisscrossing and sometimes intersecting network of burrows continuous to the *AEI* is developed. Such earthworm burrowing under the *RO* interface increased 2-hour cumulative infiltration from an initial 13 cm at the treatment time to 39, 75 and 116 cm at one, two and three years later, respectively (Table 1).

Interacting physical and biological processes may also assist in macropore system formation. Vegetal residue and its decomposition

products often fall or wash into shrinkage cracks. Earthworm and other biotic activity is then stimulated in the region of deposition and the macropores are thereby extended. Soil bacteria and fungi undoubtedly play an important role in stabilizing macropores through the cementing and waterproofing effects of their metabolic products. In reverse, biotic activity may lead to macropore formation or extension by physical means. For example, insect and earthworm burrows following an infiltration event become highly efficient conduits for venting soil water vapor. Consequently, cracking is often profuse along burrow walls.

In contrast with interface *RO*, interface *SC* provides physical and biotic conditions favoring the time-dependent decrease in both surface and subsurface macroporosity; however, some macroporosity beneath the tillage depth persists for many years. Such porosity can be reconnected to the soil surface merely by deep tillage combined with surface mulching (5). As might be expected, the six interfaces of the *AEI* concept appear to affect the rate of macropore development in the same order as they affect fluid flux in the macropores; i.e., in the order *RO>RP=SO>RC=SP>SC*. Thus the six interfaces may be viewed as natural stages in a cycle of macropore formation (Figure 4). Interface *RO* commonly occurs on virgin prairie, virgin forest and mulch-tilled soils, whereas interface *SC* is common on clean-tilled and some desert soils.

CONCEPT QUANTIFICATION

Effective Surface Head

Although the *AEI* concept, as formulated in an earlier section, helps to explain the wide range in infiltration observed in the field for a single soil (with varying surface conditions) and provides physical principles upon which to base the design of surface management practices for relative infiltration control, it does not facilitate infiltration prediction or quantitative control. Progress toward concept quantification involved the simplifying assumption that the infiltration role of soil surface roughness and openness is adequately represented by a single hydraulic parameter that combines the effects of surface water head and soil air pressure on the performance of the U-shaped water-intake air-exhaust circuits or the macropore systems (8). This new parameter, referred to as the *effective surface head* h_s, is defined as the difference between surface water head h_w and soil air pressure head h_a, or $h_s = h_w - h_a$. It usually has a narrow range of only a few centimeters of water surrounding the reference zero taken as ambient atmospheric pressure. The effective surface head is commonly less than zero where a large surface area becomes saturated such as during intense rainfall, and basin and border irrigation.

Studies of air pressure build-up under border-irrigated alfalfa (9) led to the definition of h_s by showing that soil air pressure affects infiltration by opposing the downward force of surface water within the macropore system. Whenever soil air pressure exceeded the sum of the hydrostatic pressure due to surface head and the soil bubbling pressure, macropores would exhaust soil air rather than infiltrate surface water, as evidenced by streams of bubbles emanating from surface openings of macropores. Thus

it became apparent that the surface head effective in driving water into open macropores was the actual surface head minus the soil air pressure head.

Because of the limited area wetted, conventional infiltrometers and rainfall simulators cannot ordinarily produce measureable soil air back pressures, and the resulting negative effective surface heads that are common during natural infiltration. Consequently, the actual surface head and effective surface head associated with these devices are essentially identical and always greater than zero. Several new infiltrometers, referred to as *closed-top infiltrometers* (7), were developed to simulate negative as well as positive h_s in a narrow range surrounding zero. The design of these infiltrometers is based on the principle that a positive soil air pressure can be simulated by imposing an equivalent negative air pressure above the ponded-water surface.

Data from the closed-top infiltrometers indicated that infiltration is highly dependent on h_s in a narrow range surrounding zero (7). Thirty-minute cumulative infiltration increased 19% per cm *of* h_s for one soil and 33% for another within an h_s range of -3 to +1 cm. Such large effects are not consistent with some theoretical studies and some field studies that have been reported. For instance, Philip (24) suggested about a 2% theoretical infiltration increase per cm of surface head at small times. In field studies, Horton (17) and Lewis and Powers (20) found no clear effect of ponded water depth on infiltration. The large infiltration response to h_s that was observed is attributed to the control that h_s exerts over fluid flux in soil macropores; i.e., the rate and ultimate degree of macropore water saturation depends on h_s.

The simplifying assumption that the interacting infiltration roles of surface roughness and openness could be represented by the single hydraulic parameter, effective surface head, was a major step forward in quantifying the air-earth interface concept. From this assumption and the *AEI* concept, it may be concluded that h_s controls infiltration--a conclusion consistent with Child's view (2) that infiltration is determined by the surface hydraulic gradient once the surface becomes saturated. This conclusion is also consistent with the findings of Duley and Kelly (11), Horton (17) and Holtan (16) that surface conditions largely control infiltration. Surface control views are not necessarily contrary to the profile control views of Darcy based-flow theory as pointed out by Swartzendruber and Hillel (30), because physical conditions of the soil profile are often reflected in surface conditions, and vice versa. For instance, the antecedent soil air volume (a function of depth to impermeable layer and soil moisture content) affects the rate of soil air pressure rise and thereby the effective surface head. In reverse, the effective surface head controls the extent to which the underlying macropore system can become saturated, thereby controlling the hydraulic conductivity (and infiltration) contribution of this system. The effective surface head is the only component of the surface gradient that is highly responsive to cultural practices and thus is easily controlled by them.

Equation Selection and Interpretation

The next steps in quantifying the *AEI* concept were to (i) select

a suitable infiltration formula from those reported in the literature and (ii) physically interpret its parameters in terms of effective surface head and other factors affecting infiltration (8). The purpose of all such formulas is to express infiltration as a function of time after incipient ponding in a way which accounts for the falling infiltration rates initially, and (for uniform soils of infinite depth) the final constant rate occurring after sufficient time (2).

Childs (2) suggested that the infiltration rate may be determined either as the product of the hydraulic conductivity k and hydraulic gradient i at the soil surface, or as the rate of increase of the total amount of water stored in the soil profile. The first approach (the Darcy equation approach) is difficult to apply since, during the falling rate period, k and i are not constants but rather are interdependent variables. The second approach, which seems to be well described by Kostiakov's equation (18), is easy to apply since the two parameters of this equation are reasonably constant during the falling-rate period and may be easily determined.

Kostiakov's equation was selected from the many reported theoretical and empirical equations for adaptation to the air-earth interface concept because of its simplicity, generality, proven physical soundness and easily estimated and meaningful parameters. Kostiakov's equation $I_v = aT^b$ can be considered a general infiltration equation, whereas Ostiachev's equation $I_v = AT^{1/2}$ (21) and Darcy's equation $I_v = kiT$ (4) are applicable to the special cases of capillary-induced flow into dry infiltration systems and gravity-induced flow into near-saturated systems, respectively. In these equations, I_v is the cumulative infiltration volume, T is the time elapsed after incipient ponding and a, b, A, k, *and* i are constants. Kostiakov's equation is inherent in the other two; in Ostiachev's equation, $a=A$ and $b=1/2$, whereas in Darcy's equation $a=ki$ and $b=1$. The infiltration conditions under which Kostiakov's equation can be applied include: (i) small, intermediate or large elapsed times; (ii) one-, two- and three-dimensional flow (iii) uniform and non-uniform porous media; (iv) open, partly open, and closed lower boundaries; (v) time-invariant or variant moisture content; (vi) zero to many infiltration-related decay processes; and (vii) capillary and/or gravitational infiltration driving forces. The equation has been successfully fitted to data from flooded basins, single and double ring infiltrometers, sprinkling infiltrometers, closed-top infiltrometers, long laboratory columns and numerical analyses of Philip's flow equation. It has been precisely fit to field infiltration data collected under a wide range of vegetal, edaphic and climatic conditions (13, 19, 33). This success suggests that the general form of Kostiakov's equation is appropriate for the initial and boundary conditions of field infiltration systems. Kostiakov's equation is more convenient to use as a model for infiltration control than equations which do not express infiltration explicitly as a function of time, such as the Green-Ampt equation (15) and the Holtan equation (16).

Kostiakov's equation seems to be physically more sound as a model for natural infiltration than the soil physics-based equations (14, 31) and those empirical equations containing constant rate terms. Kostiakov's equation has been accurately fitted to field data from unstable soils to which Philip's two-term equation could not be fitted (32), yet, it compared favorably with this same two-term equation in the fitting of data from a numerical analysis of Philip's

flow equation (23). Skaggs, et al. (29) found that the equations of Horton and Holtan fitted data better than those of Philip, and Green and Ampt. The apparent reason for the better fit of empirical equations to field data, relative to physics-based equations, is that the parameters of empirical equations can be more appropriately adjusted to fit the complexities of natural infiltration systems. Many such complexities are neglected necessarily in the derivation of the physics-based equations.

Infiltration has long been recognized as a process reflecting the net effect of numerous concurrent decay or abatement processes (17), since the rate of the infiltration process is inversely related to the time elapsing after the onset of the process. Physics-based equations usually only account for the abatement in capillary pressure gradient resulting from the ever-deepening wetting front in a simple column model assumed to be homogeneous, initially uniformly dry, hydrophilic, stable and open to atmospheric pressure at the lower end. In natural soils, under complex initial and boundary conditions, the abatement of capillary pressure gradient may be relatively unimportant compared with other infiltration abatement factors some of which are infiltration-related abatement processes. These include (i) capillary pressure head reduction at the wetting front (resulting from increasing moisture content with depth), (ii) surface crusting or sealing, (iii) soil subsidence or settling, (iv) soil air pressure buildup and air entrapment, (v) clay mineral hydration, (vi) eluviation and illuviation, (vii) surface water head dissipation, (viii) macroporosity extent and continuity reduction with depth in the profile, and (ix) anaerobic slime formation. Some other soil conditions, which will be referred to here as infiltration augmentation factors, tend to offset the normal abatement in infiltration rates. Such conditions include (i) increasing flow dimensionality with time, (ii) increasing wettability with depth, (iii) decreasing moisture content (or increasing air porosity) with depth, (iv) decreasing water repellency with depth, and (v) eluviation (micropiping) that increases surface macroporosity and subsurface macropore continuity. The parameters of Kostiakov's equation can be adjusted by simple curve fitting techniques to account for the interacting effect of most (if not all) of these abatement and augmentation factors.

As implied previously in connection with Kostiakov's and Darcy's equations, $b=1/2$ is appropriate when only the abatement in capillary pressure head is affecting infiltration, whereas $b=1$ is appropriate when only the gradient due to gravity is affecting infiltration. However, $b=1$ may also occur when the infiltration abatement factors are completely compensated for by augmentation factors. The resulting constant infiltration rate may be mistaken for the constant rate produced by a gravitational gradient of unity. However, the rate will be constant only as long as the effects of abatement and augmentation factors are exactly balanced. Thus the course of the infiltration process depends upon the net effect of infiltration abatement-augmentation factors. Some of the infiltration augmentation factors are more probable and more pronounced under the boundary conditions imposed by infiltrometers than under the natural infiltration conditions produced when large surface areas are wetted by rain, flood, and irrigation waters.

Kostiakov's equation is often thought to be of the wrong form because it lacks a constant rate term (1, 30); however, there seems to be no clear physical basis (28) for such a term in the modeling of natural infiltration systems. In fact, the constant rate term may be largely an experimental artifact associated with the inability to detect small rate changes and the increasing dimensionality of flow (with time) beneath the typical infiltrometer. Such constant rate terms are also supported by the mistaken notion that soils are modeled adequately by columns (open at the bottom but bounded laterally) of stable soil material for which a constant rate does exist in both theory and fact. Kostiakov's equation does allow for a diminishing rate of infiltration decrease (for $0<b<1$) such that after sufficient time, the rate does become practically constant or undetectably variable.

If infiltration rate is identified with rate of water storage within the soil profile, as suggested by Childs (2), then certainly the need for a constant rate term would be greatly diminished and the appropriateness of the form of Kostiakov's equation would be enhanced. Kostiakov's equation correctly provides for high storage rates when available storage is large or time is small and for an asymptotic approach to zero storage rate upon complete exhaustion of the finite storage space at large times. In a nonleaky infiltration system, total infiltration and infiltrated water storage would be identical, whereas in a leaky system they would be the same until leakage begins, after which time total infiltration would be the sum of storage and leakage. For infiltrometers, leakage is in the form of lateral flow and profile drainage, whereas for watersheds under natural rainfall leakage would be in the form of return flow (seepage) and profile drainage. The steady state leakage term (relating to a condition seldom found in nature), although identifiable with final infiltration rate, is perhaps a preferable term since it does not imply a measure of vertical hydraulic conductivity of the soil profile. According to Philip (26), the final infiltration rate, as measured with an infiltrometer, is not directly related to (and not necessarily well correlated with) the final infiltration rate for one-dimensional infiltration over a large area. This is because the boundary conditions, imposed by an infiltrometer and the underlying soil profile, usually allow increasing dimensionality of flow with time; and the greater the dimensionality of flow the greater the final infiltration rate. Thus, to a certain degree, final infiltration rates are affected by infiltrometer type and should not be identified with hydraulic conductivity at residual air saturation. Instead, they merely reflect the manner in which water can most readily leak from the system. Steady state leakage from a natural-watered soil system would also be multi-dimensional, although natural infiltration seldom continues long enough to closely approximate a steady-state condition. Thus, the presence of a final infiltration rate term in an equation modeling natural infiltration systems is at best misleading, if not essentially superfluous. Accordingly, a leakage term would seem appropriate to reflect the rate of water outflow from the system under study. Such a term could also be modeled by Kostiakov's equation, in which case T would be time elapsing after the inception of leakage and the condition $b \geq 1$ would be typical.

Similarly, the Kostiakov's equation can be fit to an S-shaped infiltration curve like the two shown in Figure 3 by separate evaluations of the two parameters for the periods of infiltration abatement and infiltration augmentation occurring before and after the inflection point on the curve.

In the integral form $I_v=aT^b$, and derivative form $I_r=abT^{b-1}$ of Kostiakov's equation, parameter a is the infiltration volume I_v during the first unit of elapsed time T after the onset of ponding, ab is the infiltration rate I_r at the end of this unit and parameter b is the ratio of the two (31). Thus, if time is in hours, parameter a is estimated by the first-hour infiltration volume, ab is estimated by the intake rate at the end of the first hour, and b is a ratio reflecting relative intake abatement during the first hour.

If Kostiakov's equation is regarded as modeling infiltration storage rather than total infiltration, then I_v becomes the storage volume of infiltrated water, I_r is the storage rate, T is the elapsed time after incipient ponding (during which storage has been occurring), parameter a is the storage during the first hour, ab is the storage rate at the end of the first hour, and b is a ratio of the two which reflects the degree of storage abatement during the first hour with $b=1$ indicating no abatement and $b=0$ complete abatement. The range $0<b<1$ is represented in the shapes of most of the infiltration curves shown in Figure 3. The magnitude of parameter b is inversely and directly related to the number and intensity of infiltration abatement factors and augmentation factors, respectively.

Most of the curves shown in Figure 3 are convex, reflecting the typical infiltration abatement with time ($b<1$), however two of the curves are convex in the initial period, but then become concave ($b>1$) in the final period. The convex part of the curve indicates the dominating influence of abatement factors, whereas the concave part indicates the dominance of augmentation factors. At the inflection point neither set of factors is predominant. Parameter a is simply the product of first-hour time-weighted means for hydraulic conductivity and hydraulic gradient (or $a=ki$ for $T=1$) at the soil surface in accordance with Darcy's law and the view of surface infiltration presented by Childs (2). Parameters a and b are interdependent since the mean conductivity and gradient are affected by all of the abatement and augmentation factors. Some of these factors affect (and are affected by) boundary conditions. Thus, the magnitude of parameters a and b are controlled by an extraordinarily complex interaction of numerous abatement and augmentation factors, some of which in turn depend on system boundary conditions. Since boundary conditions are partially dependent on the infiltrometer type, the values of a and b will be similarly dependent.

Since both i and k (at the soil surface) are functions of effective surface head, it follows that parameter a in Kostiakov's equation is also a function of effective surface head. In turn, effective surface head depends upon the soil surface management practice and the inherent level of surface roughness and openness associated with the practice.

The remaining steps in the procedure for quantifying the *AEI* concept (8) are illustrated in Figures 5 and 6. A family of cumulative infiltration curves (Figure 5) are generated

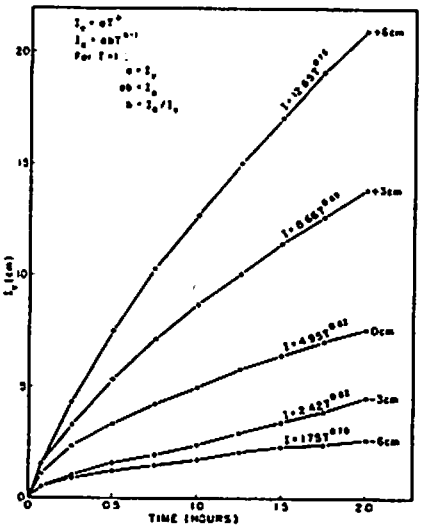

Figure 5. Infiltration volume (depth) I_v as a function of time and effective surface head in the range-6 to +6 cm water and the equations resulting from the least square fit of Kostiakov's equation to the experimental data.

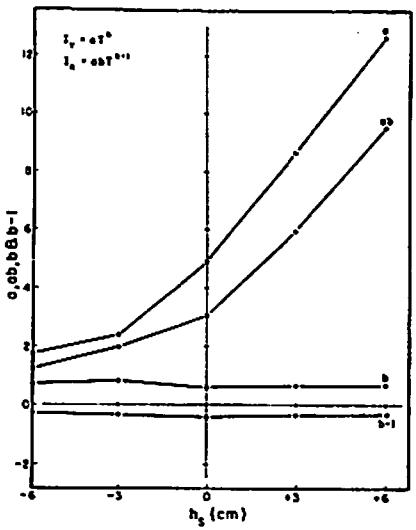

Figure 6. Parameters, a, ab, b and b-1, of the integral and derivative forms of Kostiakov's equation as functions of the effective surface head h_s.

by operating a closed-top infiltrometer in an h_s range of a few centimeters on either side of zero. Kostiakov's equation is then fitted to these curves by the method of least squares in order to estimate parameters a and b. As noted previously, these parameters may also be estimated from the one-hour infiltration volume I_v and infiltration rate I_r since $a=I_v$ and $ab=I_r$ for $T=1$. The parameter values are then plotted graphically as a function of effective surface head (or the corresponding surface roughness and openness) as shown in Figure 6. Such a graph, in conjunction with Kostiakov's equation, can then be used to predict the infiltration curve associated with a given value of effective surface head or the corresponding values of surface roughness and openness.

CONCEPT REFINEMENT

Further refinement of the *AEI* concept will necessarily involve improvement of methods for characterizing surface roughness and openness. These two surface properties must be characterized in a way that accurately reflects their infiltration roles. This presents a formidable task because of the great rapidity and intensity of physical and biotic structure-forming processess at the *AEI*.

Characterization of openness and roughness would first require selection of a delineating dimension to define the lower and upper limits of roughness and openness, respectively; i.e., the dimension at which roughness ends and openness, begins. The upper dimension of roughness and the lower dimension of openness would then be selected to include those statistical populations of importance in the infiltration system being studied. Size of the interfacial sample would be determined by the upper dimensions of openness and roughness that were selected. Because of the large dimensions and infrequent horizontal repetition of many types of surface roughness and openness, an adequate-sized sample would usually be in the 1- to 100-m^2 range. The sample required to take into account large long shrinkage cracks common in some clay soils would be prohibitive in size regardless of whether these cracks were defined by the delineating dimension as macropores or as downward surface extensions.

Soil surface roughness and openness could be measured by either direct or indirect field methods; however, laboratory determinations would usually be impractical because of the large sample required. Direct roughness evaluations, using microrelief techniques, should include the microtopographical elevations and depressions (within the selected dimensional range), their orientation relative to the general land slope, and their origin. Roughness could also be evaluated indirectly by measuring depression storage. Roughness, thus determined, could be expressed as an effective roughness index by relating it to a standard roughness such as a sine wave curve of specified wave length and amplitude.

Direct openness (or surface macroporosity) evaluations based on various visual approaches, should include macroport size, shape, origin, and distribution pattern. The distribution pattern should include the spatial repetition of ports according to their

origins and port locations relative to microrelief features. Openness could be evaluated indirectly by measuring (i) soil surface bubbling pressures, (ii) air flow rates through a saturated surface, or (iii) simultaneous air and water exchange rates across the soil surface. Percent basal area of vegetation (16) and percent plant residue cover could be measured for indirect estimates, since they seem to be functionally related to openness.

In addition to developing better methods for characterizing surface roughness and openness, further refinement of the *AEI* concept will entail evaluating natural effective surface heads under diverse soil surface and water source conditions; correlating measured effective surface heads and surface roughness and openness; and finally, developing and testing new and improved cultural practices based on the *AEI* concept.

SUMMATION

The block diagrams given in Figure 7 illustrate the mechanisms by which soil surface management and the resulting effective surface head control infiltration. The management practice determines soil surface roughness and openness and their hydraulic counterpart, effective surface head. Rough open surfaces are associated with positive mean effective surface heads having maximal areal variability, whereas smooth closed surfaces are associated with negative mean effective surface heads having minimal areal variability. The effective surface head, by determining the hydraulic gradient at the surface openings of the macropores controls fluid flux into (or out of) and within the macropores. This includes the transmission of both free surface water downward and soil air upward. In general, water will flow downward displacing the soil air ahead of it when the effective surface head is positive. In contrast, when the effective surface head is negative, macropores serve to vent the soil air upward that is being displaced by water infiltrating the bordering microporosity. When the effective surface head is near zero, a condition approaching static equilibrium may be appraoched between the counteracting hydraulic and pneumatic forces at the macropore openings. Thus, the effective surface head and the resultant nature of fluid flux in macropores will determine the degree to which these pores can become saturated as infiltration progresses. Since the macropores and micropores share a common porous border, the water saturation of macropores regulates water flow into micropores and this flux in turn determines the degree of water saturation of this pore space. The four lower blocks in Figure 7A reflect the fact that the infiltration process involves both transmission and storage--first the transmission and storage of water in the macropore system and then the transmission and storage of water in the micropore system. The two lateral blocks indicate that the prevailing soil surface roughness and openness influence subsequent developmental changes in the macropore system. These changes are usually generative under a rough open surface or high effective surface head and degenerative under a smooth closed surface or low effective surface head.

The block diagrams can serve as a basis for relative infiltration control, whereas Kostiakov's equation can be used in absolute infiltration control. Parameter a may be interpreted as a function of effective surface head with large a values being associated with rough open surfaces and positive effective surface heads, and small a values with smooth closed surfaces and negative effective surface heads. Parameter b may be viewed as a function of infiltration abatement-augmentation factors with values near zero, near one, and above one, indicating the dominance of abatement factors, little dominance of either the abatement or augmentation factors, and dominance of augmentation factors, respectively.

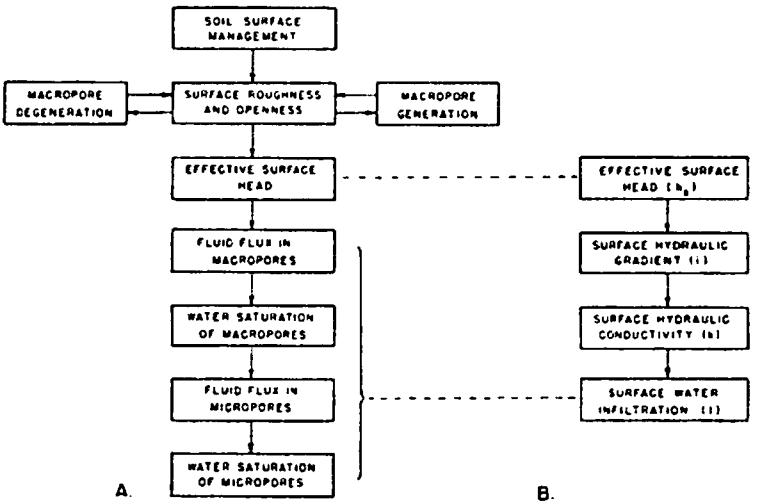

Figure 7. A: Mechanisms by which soil surface management controls surface water transmission into a soil, and subsequent storage of this water within soil pores. B: Mechanism by which effective surface head controls infiltration.

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APPENDIX II-NOTATION

The air-earth interface concept symbols used in this paper are:

AEI = air-earth interface;

RC = rough closed;

RO = rough open;

RP = rough partly open;

SC = smooth closed;

SO = smooth open; and

SP = smooth partly open.

The algebraic formula symbols are:

a = parameter in Kostiakov's equation, L/T^b;

A = parameter in Ostiachev's equation, $L/T^{1/2}$;

b = dimensionless parameter in Kostiakov's equation;

h_a = soil air pressure (head) L;

$h_s=h_w-h_a$ = effective surface head L;

h_w = surface water head, L;

i = dimensionless parameter (hydraulic gradient) in Darcy's equation;

$I_r=abT^{b-1}$ = infiltration rate according to Kostiakov's equation, L/T;

$I_v=aT^b$ = infiltration volume (depth) according to Kostiakov's equation, L;

$I_v=AT^{1/2}$ = infiltration volume (depth) according to Ostiachev's equation, L;

$I_v=kiT$ = infiltration volume (depth) according to Darcy's equation;

k = parameter (hydraulic conductivity) in Darcy's equation, L/T; and

T = time elapsed after incipient ponding, T.