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AIR-EARTH INTERFACE CONCEPT FOR WIDE-RANGE CONTROL OF INFILTRATION

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SUMMARY:
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AIR-EARTH INTERFACE CONCEPT FOR WIDE-RANGE CONTROL OF INFILTRATION[1/]

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ABSTRACT

A theory referred to as the *air-earth interface concept* is formulated and discussed relative to experimental verification, compatibility with Darcy-based infiltration theory, quantification for predictive purposes, and applicability to practical infiltration control problems.

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. Interfacial exchange of soil air and free surface water occurs freely across a *rough open* surface with consequent rapid water penetration via the relatively short, broad, straight paths of the macropore system. In contrast, surface exchange of air and water is greatly impeded by a *smooth closed* surface with consequent slow water penetration via the relatively long, narrow, tortuous paths of the micropore system. These relative differences in water penetration rates and routes are attributed to corresponding differences in phase continuity within the macropore system. Both air and water phases are maintained continuous by a rough open surface and discontinuous by a smooth closed surface. Discontinuity in the phases causes relatively high soil air back pressures and low soil water pressures, whereas phase continuity produces low air pressures and high water pressures.

The concept was tested by imposing standard rough open and smooth closed interfaces at four locations having diverse edaphic, climatic and vegetal conditions. Experimental results showed that infiltration into a rough open surface exceeds that into a smooth closed surface by a factor of 10 or more and that this factor tends to increase with the time during which these two extreme surface conditions are maintained. The infiltration rates are of such mangitude that a 1-year frequency storm would be partially shed by a smooth closed surface, whereas a 50-year storm would be completely absorbed by a rough open surface. Studies showed that soil water pressures are positive under a rough open surface and negative under a smooth closed surface during infiltration of free surface water. Soil air back pressures were found to greatly affect infiltration by impeding water entry and transmission in open macropores.

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The air-earth interface concept that *surface roughness and openness control infiltration* and the Darcy theory that *hydraulic conductivity and gradient control infiltration* are reconciled by introducing and defining a new hydraulic parameter referred to as the *effective surface head* and by showing that this parameter integrates the infiltration effects of soil roughness and openness. The effective surface head, defined as *ponded water pressure minus soil air pressure*, controls both the hydraulic conductivity and hydraulic gradient at the soil surface. Transmission characteristics of the soil profile are reflected in the magnitude of the effective surface head. The air-earth interface concept was quantified by relating roughness and openness or effective surface head to the two parameters in Kostiakov's equation. The first and second parameters in this equation exhibited power function and linear relationships, respectively. The air-earth interface concept should have considerable potential in the solution of land management problems wherein uncontrolled point infiltration, surface runoff, and erosion are contributing factors. Such problems would be alleviated by designing land management systems to achieve a given level of surface roughness and openness or effective surface head. The concept appears applicable to cultivated and uncultivated soils, and to soils severely disturbed by road construction and strip mining.

INTRODUCTION

Uncontrolled infiltration often causes the inefficient use and irreversible loss of our vital soil and water resources. For instance, excessive tillage and overgrazing diminishes the soil's ability to absorb water, thereby increasing soil and water losses from the soil surface through the processes of evaporation, runoff, and erosion. Erosion decreases the size of the soil water reservoir, with consequent increases in 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 and evaporation 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. Desertification of most semiarid and arid regions of the world is accelerated by excessive surface runoff and

evaporation resulting from uncontrolled infiltration. Uncontrolled infiltration often hampers the revegetation of lands denuded by short-term droughts, overgrazing, excessive cultivation, road construction, and strip mining.

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. Soil macropores often dominate hydraulic conductivity. Childs et al, (1957) 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 (Youngs, 1964). Childs (1969) calculated that 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.

Dixon and Peterson (1971) determined that a 0.1-percent macroporosity in the form of 1-mm diameter cylindrical pores (under a gradient of unity) can infiltrate ponded water at a rate of 11 cm/hr--a rate greater than that of one-hour maximum intensity rainstorms having a 100-year frequency that occur anywhere in the United States except in the Gulf of Mexico region (Hershfield, 1961). Considering that the porosity of a typical soil is about 50% or 500 times greater than that of the preceding example and that bare smooth soils often infiltrate rainwater at rates of less than 1 cm/hr, one must conclude that the geometry of such air-earth interfaces and the underlying pore space is not appropriate for conducting water rapidly into the soil. Accordingly a modest modification of this geometry would be expected to raise infiltration rates dramatically. In his theory for water absorption by aggregated media, Philip (1968) assumed that water transfer occurs only via the macroporosity. There is considerable evidence, however, that under field conditions the dynamic air-earth interface regulates water transfer within macropores, thereby controlling the infiltration (and also the hydraulic conductivity) contribution of such pores. Duley and Russell (1931) noted that surface sealing affects infiltration more than soil texture, slope, moisture content, and profile characteristics. Dixon (1966) 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 border irrigation by one-third or from 15 to 10 cm (Dixon and Linden, 1972). Soil air back pressure apparently hampers entry of free surface water into open macropores.

The way in which air-earth interface conditions and soil macropores can affect infiltration processes can be deduced from the well-known hydraulic behavior of simple flow systems. According to Poiseuille's equation, volume fluid flow in a simple cylindrical pore system increases

with the fourth power of the 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 (Rode, 1969) indicates that capillarity decreases with increasing pore diameter (or diameter of curvature in air-water interface) and is < 3 cm 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 pores > 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 > 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 (Darcy, 1856), 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.

According to a new infiltration theory, referred to as the *air-earth interface AEI concept* (Dixon, 1972), interacting soil surface and water source conditions control rates of water infiltration and routes of water penetration. In this paper, the *AEI* concept is described, applications of the new concept to relative infiltration control are considered, and an approach to concept quantification for absolute infiltration control is presented.

AEI CONCEPT MODELING

The spatial domain of the *AEI* concept and its physical models is the *microinterface* and its physical properties, *microroughness* and *microporosity*. Microinterfaces, as used here, refer to square or circular surfaces less than one m^2 in size; microroughnesses refer to soil surface irregularities having horizontal periodicities ranging from one to 100 cm; and macropores refer to soil voids assumed to be cylindrical tubes and plane cracks having diameters and widths ranging from one to 10 mm at the *AEI*.

Infiltration as modeled by the *AEI* concept is considered to be a process, usually not exceeding a 2-hour duration, involving transmittal and storage of excess surface water into and within a soil profile usually less than 2 m deep. Thus throughflow and deep percolation processes are excluded from consideration. Also excluded is infiltration that is water-source rather than soil-profile limited, although under sprinkled-water infiltration both source and profile often interact to limit infiltration for long periods of time.

The *AEI* concept makes the general argument 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* with *roughness* referring to the microrelief that produces depression storage,

and *openness* referring 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 (Fig. 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 (Fig. 2)

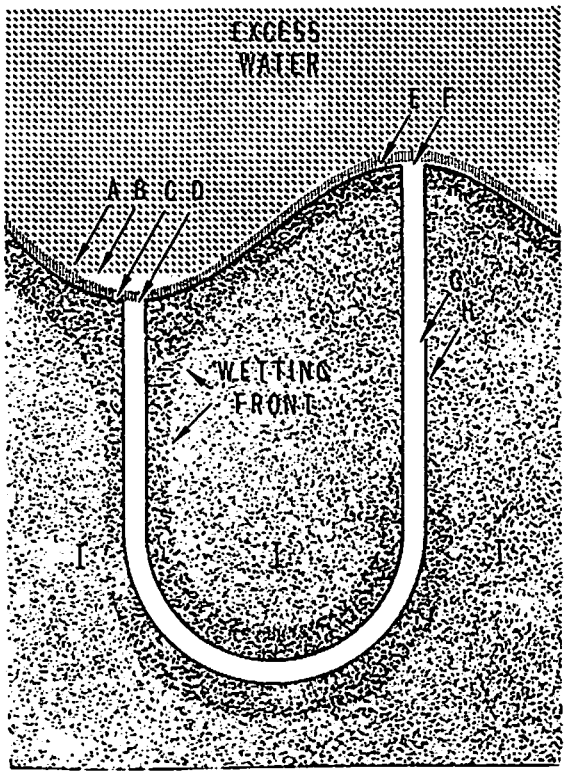

Fig. 1. Soil model containing a micropore system and a macropore system. Symbol definitions are: A = plant residue cover on air-earth interface; B = free water surface; C = microdepression in air-earth interface; D = water intake port of macropore; E = microelevation in air-earth interface; F = soil air exhaust port of macropore; G = macropore space; H = macropore wall; and I = micropore space. From Dixon and Peterson (1971).

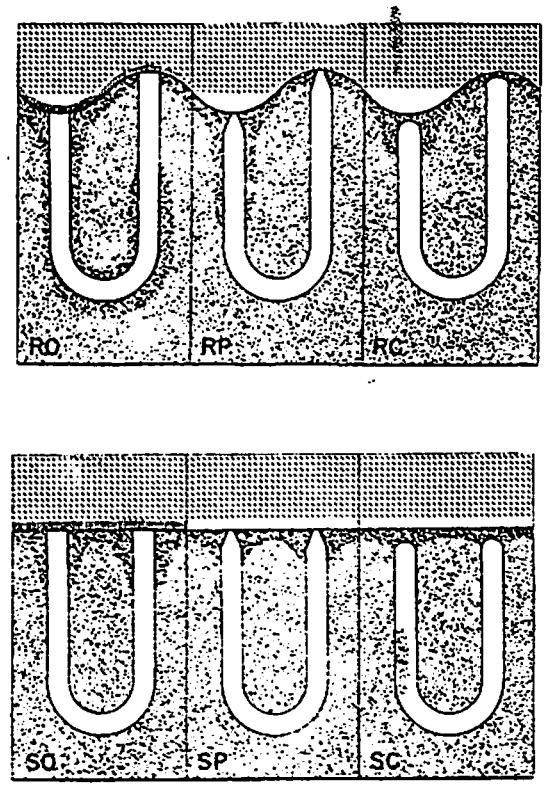

Fig. 2. *AEI* models and associated U-shaped macropore for water infiltration into soils. Models *RO*, *RP*, and *RC* represent rough interfaces containing open, partly open (unstable) and closed macroports, respectively; whereas models *SO*, *SP*, and *SC* represent smooth interfaces containing open, partly open (unstable) and closed macroports. From Dixon and Peterson (1971).

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 are 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 the *RO* model, interfacial exchange of soil air and ponded 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 the *SC* model, 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 the six models may be deduced from their ranking with respect to various properties or characteristics. By definition, interfacial roughness and depression storage rank in the order $RO=RP=RC>SO=SP=SC$. Also by definition, interfacial openness or physical continuity of the interface and macropores rank in the order $RO=SO>RP=SP>RC=SC$.

Characteristics which may be ranked $RO>RP\approx SO>RC\approx SP>SC$ are: air and water stream continuity between the *AEI* 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. Surface runoff; tortuosity of main flow routes for water penetration and air displacement; exhaust or bubbling pressure of displaced air; displaced air pressure rise per unit infiltration; entrapped air volume; and time required to attain steady state infiltration rank in the order: $RO<RP\approx SO<RC\approx SP<SC$.

By deduction, characteristics ranked in the order $RO>RP\approx SO>RC\approx SP>SC$ 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 $RO<RP\approx SO<RC\approx SP<SC$ 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.

The consequences of the physical properties and mechanisms hypothesized in the *AEI* concept may be readily deduced to produce the following detailed descriptions of the hydraulic and pneumatic behavior of individual physical models. Model *RO* represents a highly functional macropore system

that rapidly transfers and distributes free surface water to subsurface borders of the micropore system and that readily exhausts displaced soil air. Steep hydraulic gradients exist across a relatively large border area (both surface and subsurface) between the two systems, causing rapid movement of water into the storage space of the micropore system. A soil with this type of macropore system would have numerous stable macropores exposed to free surface water and some nearby exposed to the atmosphere. This means that the *AEI* would be rough, open, and covered with plant residue. The roughness provides microdepressions for water intake ports and microelevations for air exhaust ports, whereas the cover helps to stabilize these ports. Such interface conditions introduce a high degree of lateral pressure imbalance in the macropore system. The consequent steep hydraulic gradient and the relatively high hydraulic conductivity and low tortuosity of the macropore system produce rapid rates and direct routes of water infiltration. The *RO* interface allows both liquid and gas phases to flow between the *AEI* and soil macropores in continuous (uninterrupted) streams. Cultural practices such as stover and stubble mulch tillage, which stabilize the *AEI* in a rough open condition, approximate the model *RO* idealization. The *RO* interface occurs naturally under the thick layers of grass and tree litter in virgin lands.

Model *RP* is similar to *RO* except that the macroports are unstable and thus constrict when exposed to free water. These constrictions impede water entry and air exit; consequently macropore system *RP* contributes less to infiltration than system *RO*. Extent of macroport constriction depends partly on the water source. For instance an intense rainstorm may completely close such macroports, but basin and border irrigation may cause only minor constriction. Model *RP* is created approximately with tillage and planting implements that produce a rough but exposed surface, such as with moldboard plows, listers, and plow planters.

Model *RC* differs from *RP* in that macroports are completely closed initially; i.e., the macropore system is physically discontinuous at the air-earth interface. Consequently, macropores are hydraulically and pneumatically disconnected from the interface. Infiltrating water cannot enter such macropores until the bordering regions of the micropore system become saturated and not even then if macropore air pressure is above atmospheric. These closed macropores serve primarily as reservoirs for displaced air, and thus as barriers to water movement within the micropore system. However, some free water may finally enter the upper ends of macropores in the region beneath microdepressions where the micropore system first becomes saturated. Infiltration rates under system *RC* are lower than under *RP* since nearly all water entering the soil must now take the high resistance path of the small tortuous capillaries of the micropore system that are exposed to free water only along the rough soil surface. Build-up in displaced air pressure further limits infiltration under interface *RC* by blocking water flow in the larger structural pores of the micropore system. The air-filled macropores and large micropores not only reduce the cross sectional area available to water flow, but also greatly increase the tortuosity of remaining water flow routes that were already highly tortuous. The *RC* interface blocks flow of both liquid and gas phases between the *AEI* and soil macropores. Interface *RC* represents listed and plow-planted fields having unprotected surfaces sealed previously by intense rainfall or sprinkler irrigation.

Model *SO* differs from *RO* only by soil surface roughness, but this profoundly affects system and intersystem flow, since the plane surface of interface *SO* favors lateral pressure balance. Under intense rainfall on sloping land, a thin relatively uniform layer of water accumulates on the *SO* interface. Hence, there are no optimal sites for either macropore intake or exhaust ports. Macroports receive too little water for rapid water intake and too much for low-pressure exhausting of displaced soil air. Macroports take in water and exhaust air intermittently since simultaneous flow in opposite directions would be unlikely except in the case of wide soil cracks or large animal burrows. Because of this inefficient port action, system *SO* contributes less to infiltration than system *RO*. Mean infiltration rates under systems *SO* and *RP* for perhaps the first hour would probably be comparable. Relative to system *RP*, system *SO* would have lower initial infiltration rates owing to greater lateral pressure balance, but the rates would fall off more slowly because of greater macroport stability. The intermittent air and water flow between the *AEI* and soil macropores leads to air-logging of the macropores as the soil becomes increasingly wetter. Interface *SO* is often found under turfgrass and under cultivated grass and legume crops. However, an accumulation of litter under such crops can lead to the development of the *RO* interface.

Model *SP* is like *SO* except that the soil surface lacks a cover of plants and is therefore unstable. As in interface *RP*, macroports constrict on exposure to free water. These constrictions reduce the infiltration contribution of macropore system *SP* to well below that of system *SO*. Mean first-hour intake rates under interfaces *SP* and *RC* would probably be similar. Relative to macropore system *RC*, system *SP* would have higher initial intake rates attributable to greater interface openness, but the rates would fall off more rapidly because of less surface stability. Model *SP* represents freshly prepared alfalfa and grass seedbeds and bare land areas opened by clay shrinkage or freezing and thawing.

Sealing an *SP* interface converts it to an *SC* interface. The smooth closed *SC* interface is hydraulically and pneumatically disconnected from macropores by the microporous seal; and movement of air and water between the *AEI* and soil macropores is blocked. Infiltration under interface *SC* is the lowest of the six interfaces since all infiltrating water must enter the flat surface border (a minimal surface area) of the micropore system and then must move along the small and highly tortuous pathways of this system against increasing displaced air pressure. Interface *SC* possesses the highest degree of lateral hydraulic balance of all surfaces and is approximated by smooth, water-sealed seedbeds and other bare and sealed land areas such as those which develop under the desertification process. Strip-mined land areas, devoid of organic matter, may also exhibit the *SC* interface after they are smoothed with bulldozers and sealed by rainfall.

AEI MODEL TESTING

Physical model validation involved the testing of several *AEI* concept

hypotheses and deductions including:

(1) infiltration rates are relatively high under a *RO* surface and relatively low under a *SC* surface.

(2) soil water pressure is relatively high under a *RO* surface and relatively low under a *SC* surface;

(3) water penetration routes are relatively short and direct under a *RO* surface and relatively long and tortuous under a *SC* surface;

(4) open macropores contribute markedly to infiltration where displaced air can readily escape laterally;

(5) soil air pressure rise under a *SO* surface restricts infiltration;

(6) imbalance between the pressures due to ponded surface water and soil air pressure, or the effective surface head, determines the route and rate of infiltration;

(7) infiltration is relatively high under positive effective surface heads and relatively low under negative effective surface heads;

(8) negative effective surface heads reduce infiltration by impeding water entry and transmission in open macropores;

(9) downward leaching of soluble salts is more efficient under a SC surface than under a rough open one;

(10) air and water phases are continuous in a *RO* macropore system, but discontinuous in a *SC* system;

(11) air and water flow intermittently in macropores terminating in *SO* surfaces; and

(12) infiltrating water causes a relatively small rise in soil air pressure under a *RO* surface and a relatively large rise under a *SC* surface.

Physical models of the six *AEI* conditions were constructed to test the preceding 12 hypotheses and deductions. Models consisted of a piece of blotting paper sandwiched between two glass plates with macropore systems cut out of the paper to match the configurations shown in Fig. 2. The glass-paper sandwich was clamped tightly and sealed along the sides and bottom with silicone rubber. The blotting paper, which simulated the micropore system, was spotted with food coloring at strategic locations to provide traces for demonstrating soluble salt movement. Water was introduced in the narrow slot between the two glass plates just above the simulated *AEI* with a special mariotte syphon device. All of the hypotheses and deductions listed above were successfully demonstrated. Differences in (1) flow rates and routes, (2) phase continuity, (3) air pressure rise

and (4) solute movement as affected by the *AEI* conditions could be readily observed. Although this demonstration did not constitute a very rigorous test of the *AEI* concept because of the unnatural pore systems, it did show that the *AEI* models as diagramed in Fig. 2 would function as expected.

The remaining tests were conducted on natural soil infiltration systems. Isolation of system components for determining their independent infiltration effects sometimes required the careful selection of natural systems for testing, appropriate modification of these systems, and the development of special procedures and instrumentation.

To test the hypothesis that open macropores contribute greatly to infiltration where these pores are fed by an abundant supply of free surface water and where displaced soil air is free to escape laterally, macropores greater than 1.6 mm in diameter were plugged with silicone rubber after they were exposed on the plow sole of a Miami silt loam by excavating the plow layer and vacuum removal of loose particles (Dixon, 1966). Plugging of macropores reduced one-hour infiltration of ponded-water by 42 and 34% where such macropores represented only 1.0% and 0.6% of the total plow sole area, respectively. Considering that this treatment achieved only partial blockage of water movement in the macropore system, the infiltration response was surprisingly large. Comparison of absolute infiltration amounts further supported the hypothesis being tested. One-hour infiltrations for the plow soles having 0.6 and 1.0% macroporosity (macropores > 1.6 mm) were 13 and 39 cm, respectively; i.e., a doubling of these macropores was associated with a tripling of cumulative infiltration.

To test the hypothesis that infiltration rates of a given soil are relatively high under a *RO* surface and relatively low under a *SC* surface required minor manipulations of the natural surface existing at the time of the test (Dixon and Peterson, 1971). Standard conditions for the *RO* and *SC* interface were first established and then these conditions were hand imposed for comparison with each other and the natural interface. The *RO* interface was prepared by (1) contour furrowing the soil surface, (2) vacuum cleaning the furrow trough and (3) 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 (1) removing all plants and plant residues from the soil surface, (2) passing the surface 2.5 cm of soil through a 6-mm mesh screen, and (3) 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 and subsurface components of the macropore system.

This study encompassed a wide diversity of vegetal, edaphic, and climatic conditions. Infiltration runs were made 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 runs supported the hypothesis being tested and 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 (Fig. 3). This range widened with time after interfaces were imposed (Dixon, 1975b), since the infiltration capacity of the *RO* macropore system increased while the capacity of the *SC* system decreased (Table 1). Observed increases under the *RO* interface were largely attributed to 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 the *SC* interface reflected the absence (or low level) of interfacial biotic activity with consequent decreases in macropore system continuity at the soil surface. Thus, land management practices that maximize biotic activity at the soil surface lead to *RO* interfaces whereas practices that eliminate such biotic activity lead to *SC* interfaces.

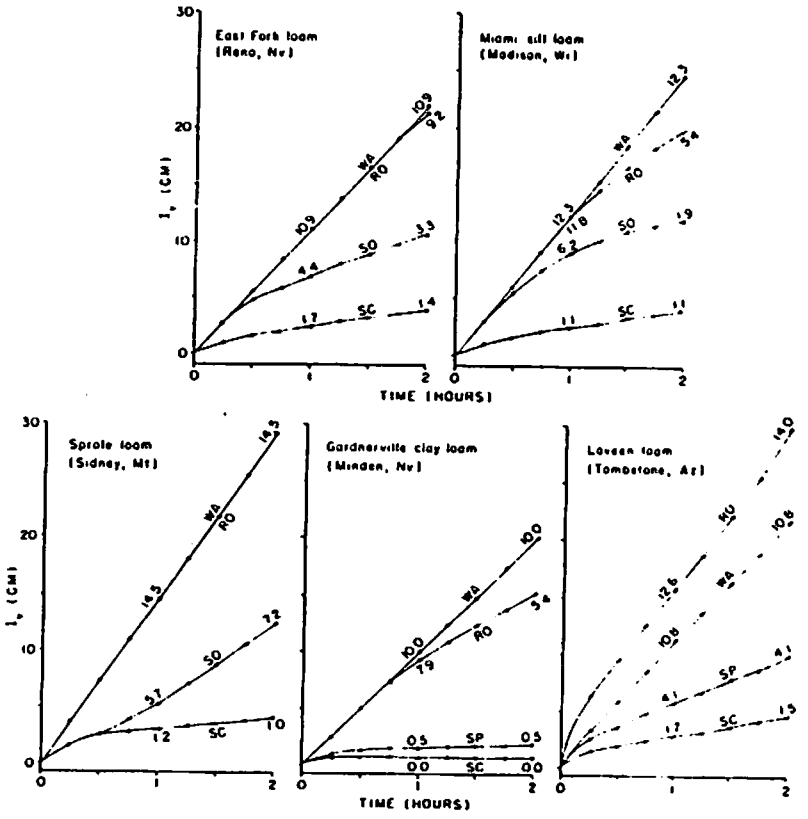

Fig. 3. Sprinkled-water infiltration I_V under imposed air-earth interfaces *RO* and *SC* and naturally occurring interface either *SO* or *SP*. The curve labeled *WA* gives the total water applied by the infiltrometer spray nozzle. Numbers near the curves at 1- and 2-hour times denote infiltration rates in cm/hr for these times. From Dixon (1975b).

Table 1. Two-hour infiltration volumes and rates 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 Volume** Absolute (cm)	Infiltration Volume** Relative (1)	Infiltration Rate** Absolute (cm/hr)	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.

The infiltrometer plots at the East Fork loam site were used to test the deduction that soil water pressure is relatively high under a *RO* surface and relatively low under a *SC* surface (Dixon and Peterson, 1971). One year after the standard interfaces were imposed, tensiometers were installed 50 cm beneath the *AEI* and soil water pressure heads h_p were observed during a period of ponded-water infiltration under high antecedent moisture conditions. The results, shown in Fig. 4, support the preceding deduction and also the deduction that water penetration routes are relatively short and direct under a *RO* surface and relatively long and tortuous under a *SC* surface. The almost instantaneous response of the tensiometer under the *RO* surface and the subsequent rapid rise to an equilibrium h_p of a positive 37 cm indicates that water flow routes were short and direct. In contrast, the delayed response under the *SC* surface and the subsequent slow rise to equilibrium h_p of a negative 12 cm indicates that water penetration pathways were long and tortuous. By the equilibrium time of 1.5 hours, 24 cm of water had infiltrated through the *RO* surface; whereas by the equilibrium time of 5 hours only 8 cm of water had infiltrated through the *SC* surface.

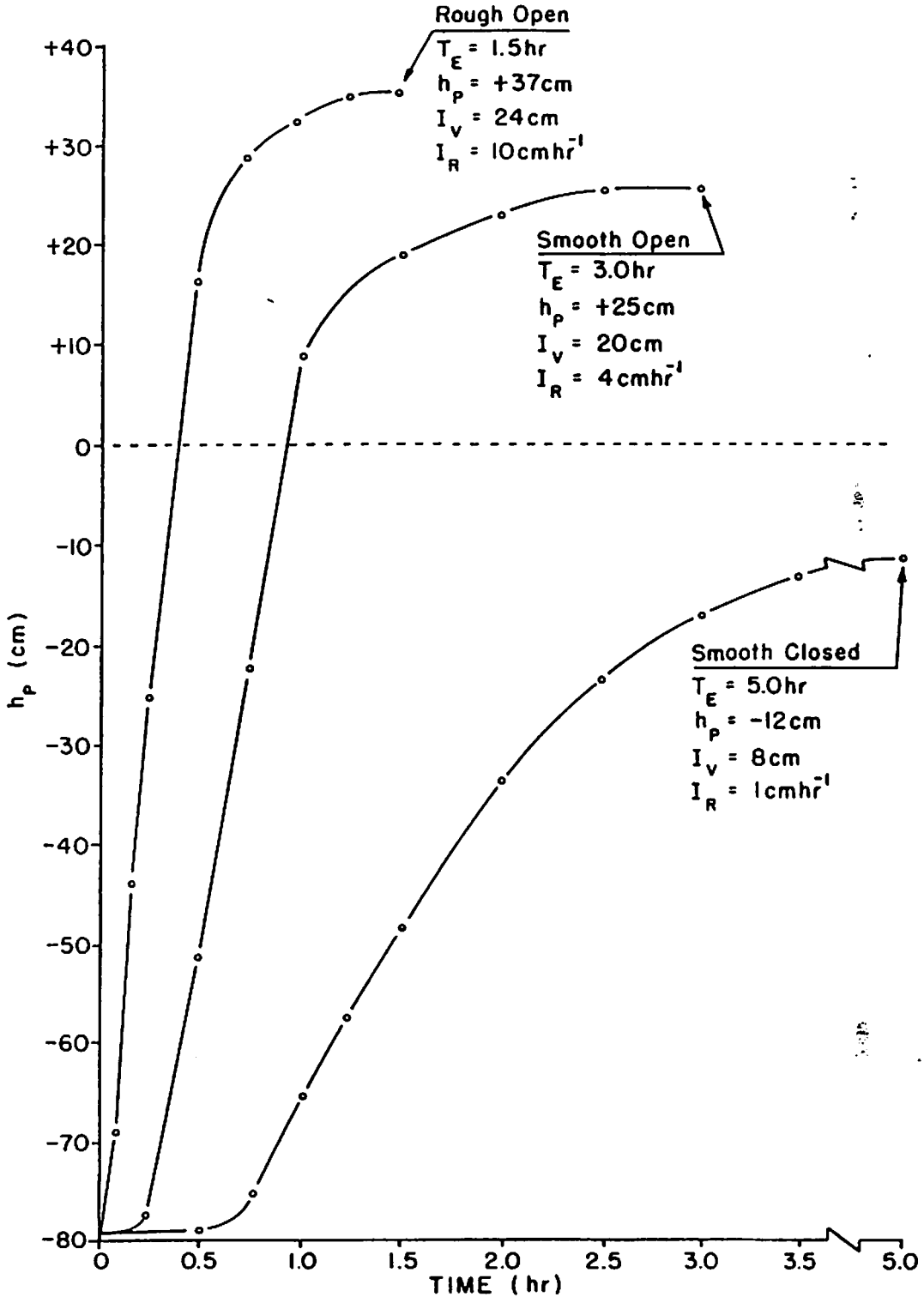

Fig. 4. Soil water pressure head h_p at a 50-cm soil depth as a function of time and the three indicated *AEI* conditions. Time T_E required for h_p to approach an equilibrium and the corresponding h_p infiltration volume I_V and infiltration rate I_R are listed for each interface condition. From Dixon and Peterson (1971).

The hypotheses indicating that (1) soil air pressure h_a rise under a *SC* surface restricts infiltration and that (2) imbalance between the pressures due to ponded surface water and soil air pressure (or the effective surface pressure h_s) determine the route and rate of infiltration were tested in a border irrigated alfalfa field in Western Nevada (Dixon and Linden, 1972). Special instrumentation and methodology were developed to measure soil air pressures and water infiltration as produced by actual and simulated border irrigations. The results shown in Fig. 5 indicate that soil air pressure h_a building to a maximum of about 19 cm of water (or about 5 cm greater than the surface water head h_w) reduced total infiltration volume by about one-third or from 15 to 10 cm at a site located in the central upslope part of the border irrigation strip. In the central region of the irrigated strip where h_a exceeded h_w, macropores vented displaced air upward; whereas along the border dikes where h_w exceeded h_a, macropores conducted free surface water downward. These differences in air and water flow were deduced from observed differences in air bubbling rates at the soil surface and differences in depth of soil air entrapment.

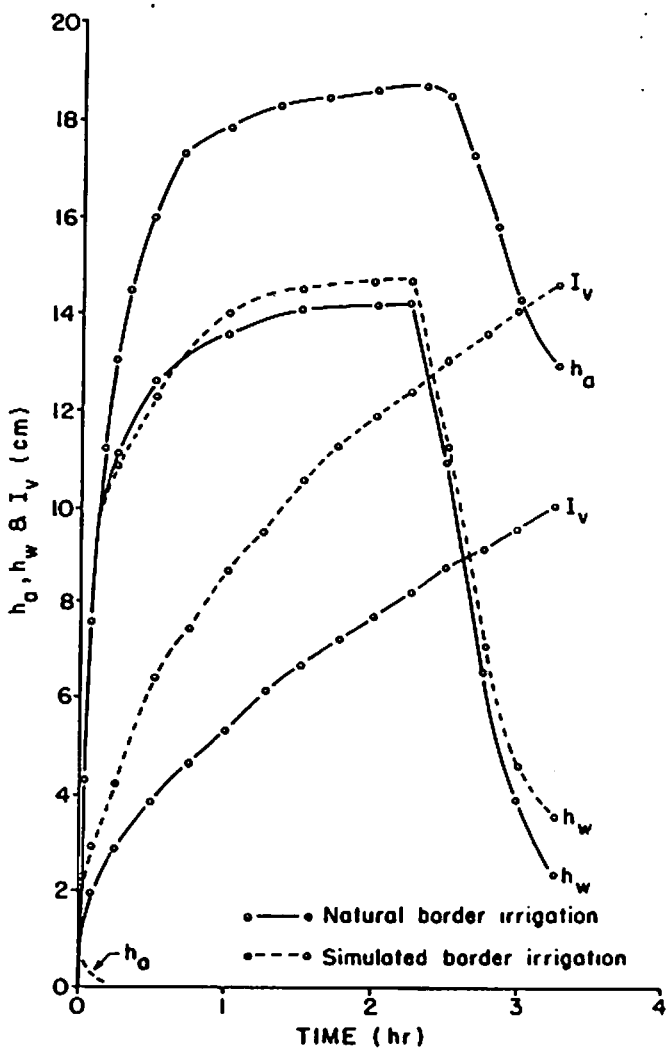

Fig. 5. Soil air pressure h_a, surface water head h_w, and infiltration volume I_V under natural and simulated border irrigation versus time. From Dixon and Linden (1972).

The preceding tests of h_a effects led to the deductions that (1) infiltration is relatively high under positive h_s and relatively low under negative h_s, (2) h_s affects infiltration by determining the degree of macropore system saturation, and (3) the hydraulic effects of surface microroughness and macroporosity are reflected in the magnitude of natural h_s. The need for testing the first deduction and realization that the h_s of natural infiltration systems are often negative and that existing sprinkled-water and ponded-water infiltrometers produce only positive h_s, led to the development of several unique devices referred to as *closed-top infiltrometers* (Dixon, 1975a). By closing the top of the infiltrometer frame and exposing the ponded water surface surface to negative air pressures, realistic negative h_s can be produced. Closed-top infiltrometer results, given in Fig. 6, indicate that infiltration is highly responsive to h_s in a narrow range surrounding zero or atmospheric pressure, thereby confirming the first deduction. The second deduction was essentially confirmed by a test, to be discussed subsequently, involving infiltration rates and routes as affected by soil air back pressure, h_a. The third deduction is yet to be confirmed; however, the evidence at hand indicates that natural h_s is affected not only by *AEI* conditions but by soil and lower boundary conditions as well.

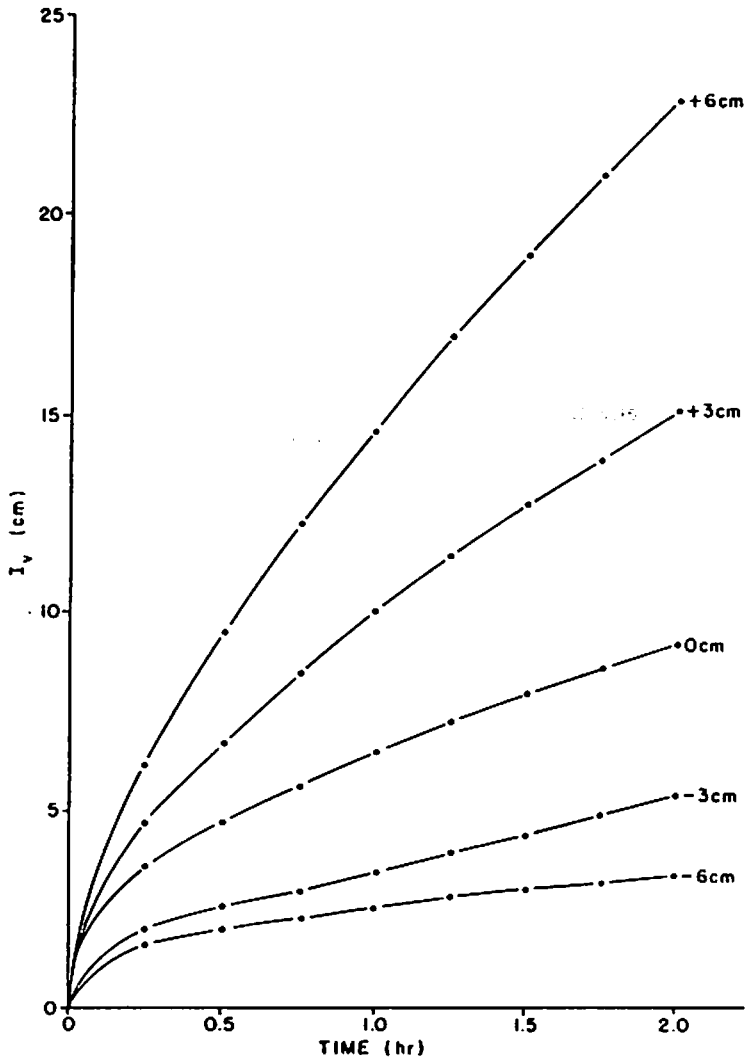

Fig. 6. Ponded-water infiltration I_V as a function of time and effective surface heads h_s ranging from a minus 6 to a plus 6 cm of water as produced by a closed-top infiltrometer.

To test the deduction that negative h_s (h_a exceeds h_w) reduces infiltration by impeding water entry and transmission in open macropores, Linden and Dixon (1977) developed an apparatus capable of infiltrating a 1-cm slug of water against h_a ranging from zero to 5 cm and capable of tracing water penetration pathways by methylene blue staining. Results indicate that with no h_a water infiltrated at a mean rate of 46 cm/hr, penetrating along macroporous routes to depths up to 30 cm; whereas with 5 cm of h_a water infiltrated at a mean rate of only 3 cm/hr taking microporous routes to a maximum depth of only a few centimeters. These results also support the deduction that depth of water penetration per unit of infiltrating water is much greater where most of the water penetrates the soil via macropores than where it penetrates along tortuous microporous pathways. Macropores can route rainwater past microporous storage space near the soil surface, thereby making the infiltrated water less susceptible to subsequent loss by surface evaporation.

AEI CONCEPT QUANTIFICATION

Although the *AEI* physical models help to explain the wide range in infiltration rates resulting from varying surface conditions and provide physical principles upon which to base the design of surface management practices for relative infiltration control, they do not facilitate quantitative prediction for absolute control. Unfortunately, the physical infiltration system assumed in the development of the *AEI* concept is far too complex for detailed mathematical modeling. It is much more complex, both internally and externally, than the system commonly assumed in Darcy-based infiltration theory that has been difficult to model adequately. Even if the *simultaneous flow rates and routes of two fluids in two interacting pore systems as affected by two dynamic AEI conditions* could be successfully modeled, the large number of parameters required to do so would make the resulting mathematical model too cumbersome for practical infiltration control. Perhaps the most notable progress toward mathematical modeling of simple infiltration systems with some added complexities was recently reported by Morel-Seytoux (1976, and references therein). Natural complexities of delayed ponding and viscous flow of air were both considered in the derivation of equations for rainfall infiltration. However, the time of ponding is spatially highly variable under the upper boundary conditions assumed in the *AEI* concept. Micropores located in the microdepressions saturate quickly under high intensity rainfall, but macropores located on microknolls may never saturate.

Progress toward quantification of the *AEI* concept has involved three major steps: (1) identification, definition, and interpretation of important *AEI* concept parameters; (2) selection and interpretation of an appropriate two-parameter equation for modeling the *AEI* concept; and (3) determination of functional relationships between concept and equation parameters.

Theory Parameter Identification. Surface microroughness and surface macroporosity are the two principal physical parameters of the *AEI* concept. These two interrelated and interacting properties of the soil surface have

yet to be characterized directly in a way which accurately reflect their infiltration roles. Such characterization presents a formidable task because of the great rapidity and intensity of physical and biotic structure-forming processes at the soil surface. This problem can be circumvented by 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 h_w and h_a on the performance of the U-shaped water-intake air-exhaust circuits or the macropore systems (Dixon, 1975b). This new parameter, referred to as the *effective surface head* h_s, is defined by the equation: $h_s = h_w - h_a$. It usually has a narrow range of only a few centimeters of water surrounding the reference zero taken as ambient atmospheric pressure. The h_s is commonly less than zero where a large surface area becomes saturated as occurs during intense rainfall, and basin and border irrigation.

Studies of h_a build-up under border-irrigated alfalfa (Dixon and Linden, 1972) led to the definition of h_s by showing that h_a affects infiltration by opposing the downward force of h_w within the macropore system. Whenever h_a exceeded the sum of h_w and the soil bubbling pressure, macropores would exhaust soil air rather than infiltrate surface water head, as evidenced by streams of bubbles emanating from the surface openings of macropores. Thus 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 h_a, and the resulting negative h_s that is common during natural infiltration. Consequently, the h_w and h_s associated with these devices are essentially identical and always greater than zero. Several unique infiltrometers, referred to as *closed-top infiltrometers* (Dixon, 1975a), 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 h_a can be simulated by imposing an equivalent negative air pressure above a ponded-water surface.*

Data from the closed-top infiltrometers indicated that infiltration is highly dependent on h_s in a narrow range surrounding zero (Dixon, 1975a) 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 (1958) suggested about a 2% theoretical infiltration increase per cm of surface head at small times. In field studies, Horton (1940) and Lewis and Powers (1939) 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, h_s, was a major step forward in quantifying the *AEI*

concept. From this assumption and the *AEI* concept, it may be concluded that h_s controls infiltration--a conclusion consistent with the view of Childs (1969) 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 (1939), Horton (1940), and Holtan (1961) 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 (1973), 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 h_a rise and thus h_s. In reverse, h_s controls the extent to which the underlying macropore system can become saturated, thereby controlling the hydraulic conductivity (and infiltration) contribution of this system. The h_s is the only component of the surface gradient that is highly responsive to cultural practices and thus, easily controlled by them.

Algebraic Equation Selection. The next step in quantifying the *AEI* concept was to select a suitable infiltration equation from those reported in the literature and then mathematically and physically interpret it relative to the *AEI* concept. The criteria serving as a basis for equation selection were:

(1) parameter number is limited to two;

(2) infiltration volume I_V is expressed as an explicit function of time T;

(3) equation parameters are sensitive to *AEI* conditions, especially surface microroughness, surface macroporosity and h_s;

(4) zero I_V is approached as T approaches zero;

(5) zero infiltration rate I_R is approached as T approaches infinity or as the unfilled profile storage space approaches zero;

(6) infinite I_R is approached as T approaches zero;

(7) equation is general enough to account for the net infiltration effect of diverse interacting infiltration processes or factors that are affected by *AEI* conditions;

(8) equation is general enough to give a consistently accurate fit of data collected under a wide range in surface microroughness, surface macroporosity, and h_s;

(9) equation fitting always yields positive-valued parameters;

(10) equation form is such that positive-valued parameters can yield rates that can either decelerate, or remain constant, or accelerate with increasing T;

(11) parameters have general mathematical and physical interpretations applicable to a wide range of *AEI* conditions;

(12) equation form facilitates data interpretation, summarization, extrapolation, and interpolation;

(13) equation has simple first and second derivative forms for determining infiltration rates and rate changes;

(14) equation is easily least-square fitted to infiltrometer data to obtain parameter estimates;

(15) infiltration is easily calculated using equation and parameter estimates; and

(16) equation should have the simplest form possible.

The first two criteria limited the possible choices to the following four equations:

$I_V = AT^B$ Kostiakov (1932)

$I_V = A_P T^{\frac{1}{2}} + B_P T$ Philip (1957)

$I_V = A_O T^{\frac{1}{2}} + (B_O)$ Ostashev (1936)

$I_V = A_D T + (B_D)$ Darcy (1856)

These equations can be easily linearized to permit use of simple regression-least square fitting procedures to evaluate parameters A and B. The equations of Ostashev and Darcy were modified slightly by adding a constant as shown in parentheses to improve their fitting ability and to make them more comparable with the other two equations.

The four equations were fit to data from (1) *AEI*, h_u and h_a experiments; (2) border irrigation infiltrometers; (3) wet and dry infiltrometer runs; (4) sprinkled-water infiltrometers; and (5) ponded-water infiltrometers with both open and closed tops. Thus a wide diversity of water source and infiltration system conditions were represented in this equation-fitting study, the results of which will be detailed in a subsequent paper. The conclusion was, however, that Kostiakov's equation best satisfied criterion No. 8 by being the only equation giving a consistently accurate fit regardless of the data source. The four equations were ranked as to their ability to satisfy the preceding criteria. Kostiakov's equation ranked equal to or better than each of the other equations for all of the 16 criteria; consequently it was selected for modeling the *AEI* concept of infiltration.

The I_R and its rate of deceleration I_D are given by the first and second derivative forms of Kostiakov's equation which are:

$$I_R = ABT^{B-1}$$

$$I_D = -AB(B-1)T^{B-2}$$

The integral and derivative forms of Kostiakov's equation indicate that where $0 < B < 1$:

(1) $I_V = 0$ and I_D are undefined for $T = 0$;

(2) $I_V \to 0$, $I_R \to \infty$ and $I_D \to \infty$; as $T \to 0$; and

(3) $I_V \to \infty$, $I_R \to 0$ and $I_D \to 0$ as $T \to \infty$.

Thus, I_V increases at a decreasing rate monotonically with increasing T; and I_R and I_D decrease at a decreasing rate approaching zero asymptotically at large T.

The condition $0 < B < 1$ holds for most data sets from natural infiltration systems; however infrequently the condition $B > 1$ prevails indicating that I_R is increasing with T. For the special cases $B = \frac{1}{2}$ and $B = 1$, Kostiakov's equation becomes identical to Ostashev's and Darcy's equation, respectively. The form of Philip's equation is obtained by combining the forms of Darcy's and Ostashev's equations. All three of these equations assume that infiltration varies either directly with T, the $T^{\frac{1}{2}}$, or a combination of the two. These assumptions are appropriate for very simple porous media systems having simple initial and boundary conditions. Such constraining assumptions apparently limit the generality and utility of these three equations as indicated by their inability to consistently fit field infiltration data accurately.

The mathematical interpretation of the parameters in the integral and derivative forms of Kostiakov's equation is readily apparent. If the unit for T is hours, then parameter A may be interpreted as either first-hour I_V or the mean first-hour I_R; the parameter product AB is the instantaneous I_R at the end of the first hour or at $T = 1$, parameter B is first-hour end I_R divided by the mean I_R or $B = I_R/\bar{I}_R$ for $T = 1$, and the time coefficient $[-AB(B-1)]$ is the I_D at $T = 1$. Thus sets of infiltration data may be conveniently and meaningfully summarized in terms of the A and B parameters and the time period upon which they are based. Such summarizations give the first-hour infiltration and its abatement ratio and permit calculation of I_V, I_R, and I_D for any selected time. Parameter A usually ranges from 0 to 20 (assuming I_V is in cm) and gives the integral curve its magnitude; whereas parameter B usually ranges from 0 to 1 and gives the integral curve its shape.

The A and B parameters may be quickly estimated from infiltration data since $A = I_V$ and $AB = I_R$ at $T = 1$; however, better estimates are usually obtained by linearizing the integral form to obtain the equation:

$$\ln I = \ln A + B \ln T,$$

which can be least-square fitted to infiltration data. Such fits are easily

performed with inexpensive hand calculators programmed for simple linear regression analyses.

A physical interpretation of the Kostiakov equation and its parameters relative to the *AEI* concept is possible, although not as readily apparent as the preceding mathematical interpretation. The *AEI* concept assumes that all infiltrating surface water is subsequently stored in the soil profile. Thus, I_V becomes the storage volume of infiltrated water, I_R is the storage rate, I_D is the deceleration in the storage rate, T is the elapsed time (after incipient ponding of the microdepressions) 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 dimensionless ratio of AB and A which reflects the degree of storage rate abatement during the first hour, with $B = 1$ indicating no abatement and $B = 0$ indicating complete abatement.

According to Darcy-based infiltration theory, $B = \frac{1}{2}$ is appropriate for capillary-induced flow into an initially dry infiltration system where only the abatement in the capillary pressure gradient (resulting from the advancing wetting front) causes the decreasing infiltration rate. Similarly, $B = 1$ applies to gravity-induced flow into near-saturated soils where the gravitational gradient is constant and there is no abatement in infiltration rates. Thus Ostashev's equation applies to horizontal flow where the gravitational force can be ignored and Darcy's equation applies to vertical flow in saturated porous media where capillarity can be ignored. Philip's equation applies to vertical infiltration into an initially dry soil where both capillary and gravitational forces are driving the process but only the decreasing capillary gradient (resulting from the deepening wetting front) causes infiltration abatement. The first and second term of Philip's equation give the infiltration contributions of the capillary and gravitational forces, respectively. The time dependencies assumed in Darcy-based theory are appropriate only for the very simple infiltration systems upon which such theory is based.

Infiltration has long been recognized as a process reflecting the net effect of numerous concurrent decay or abatement factors (Horton, 1940) which cause the decreasing infiltration rates with increasing elapsed T after the onset of the process. In natural soils, under complex initial and boundary conditions, the abatement of capillary pressure gradient (the justification for the $T^{\frac{1}{2}}$ dependency) is often relatively unimportant compared with other infiltration abatement factors, some of which are infiltration-related abatement processes. These factors include (1) capillary pressure head reduction at the wetting front resulting from increasing moisture content with depth, (2) surface crusting or sealing, (3) soil subsidence or settling, (4) h_a build-up and air entrapment, (5) clay mineral hydration, (6) eluviation and illuviation, (7) h_w dissipation, (8) decreasing water phase continuity in the macropore system through air entrainment and entrapment, (9) macroporosity extent and continuity reduction with depth in the profile, and (10) anaerobic slime formation. Some other soil conditions, which will be referred to here as infiltration augmentation factors, tend to offset (and infrequently reverse) the normal

abatement in infiltration rates. Such conditions include (1) increasing flow dimensionality with time, (2) increasing wettability with depth, (3) decreasing moisture content (or increasing air porosity) with depth, (4) decreasing water repellency with depth, (5) eluviation (micropiping) that increases surface macroporosity and subsurface macropore continuity, (6) increasing h_w, (7) increasing surface area ponded, and (8) increasing water phase continuity in the macropore system through air displacement and absorption.

The magnitude of parameter *B* in Kostiakov's equation thus reflects the net interacting effect of the preceding abatement and augmentation factors on the time course of infiltration, with the magnitude being inversely related to the number and intensity of infiltration abatement factors and directly related to the number and intensity of augmentation factors that are active in a given infiltration system. Values for *B* near zero, near one, and above one, indicate the dominance of abatement factors, little dominance of either abatement or augmentation factors, and dominance of augmentation factors, respectively. Since most of the abatement and augmentation factors are greatly affected by *AEI* conditions, parameter *B* may be regarded as a function of such conditions, especially where unfilled profile storage space is large enough to not dominate infiltration abatement. Parameter *B* is expected to be relatively large where h_s and surface microroughness and macroporosity are relatively large and relatively small where these *AEI* conditions are relatively small.

Darcy-based flow theory for simple infiltration systems can also be useful in physical interpretation of parameter *A* in Kostiakov's equation. The coefficient in Darcy's equation is given by the product of the hydraulic conductivity and hydraulic gradient for a near-saturated stabile porous soil. For such soils both the conductivity and gradient are relatively constant. However, for unsaturated soils, the conductivity and gradient are not constant, but are interdependent variables with the gradient decreasing and the conductivity increasing as the soil wets by infiltration. Thus, in accordance with Darcy's equation and the view of surface infiltration presented by Childs (1969), parameter *A* may be regarded as the product of the first-hour time-weighted means for hydraulic conductivity and hydraulic gradient at the soil surface. As discussed previously, the surface hydraulic gradient and conductivity are greatly affected by the surface microroughness and macroporosity and their hydraulic counterpart, h_s. Consequently, parameter *A* is also a function of these *AEI* conditions. Parameter *A* is expected to be relatively large where h_s and surface microroughness and macroporosity are relatively large and relatively small where these *AEI* conditions are relatively small.

In conclusion, the preceding mathematical and physical interpretations are in agreement that parameters *A* and *B* are interrelated. The physical interpretation indicates that both parameters depend on *AEI* conditions.

Concept Parameters Versus Equation Parameters. The last step in quantifying the *AEI* concept was to relate its two parameters to the two parameters

in Kostiakov's equation. The families of I_V curves, discussed previously (Figs. 3 and 6), were used for this purpose. Parameters A and B were determined by least-square fitting of Kostiakov's equation to the family of curves which were generated by varying surface roughness and openness at the *AEI*. Parameter means and the coefficients and exponents of the first and second derivative forms were then plotted as functions of the *AEI* condition (Fig. 7). The four *AEI* conditions, representing a broad range in surface roughness and openness, were assigned the equivalent effective surface head h_{es} values that would be expected under intense rainfall of large areal extent. This assignment of estimated numerical values expedited subsequent linear regression analyses and facilitated comparison with the curves presented in Fig. 8.

The family of curves generated by varying the h_s (Fig. 6), were analyzed similarly to produce Fig. 8. The close correspondence of the shape and magnitude of the curves in Figs. 7 and 8 is consistent with the hypotheses that h_s is the hydraulic manifestation of surface roughness and openness and that the closed-top infiltrometer may be used on uncrusted soils to determine infiltration effects of these two interacting and interrelated physical conditions. Linear regression analyses indicated that parameter A

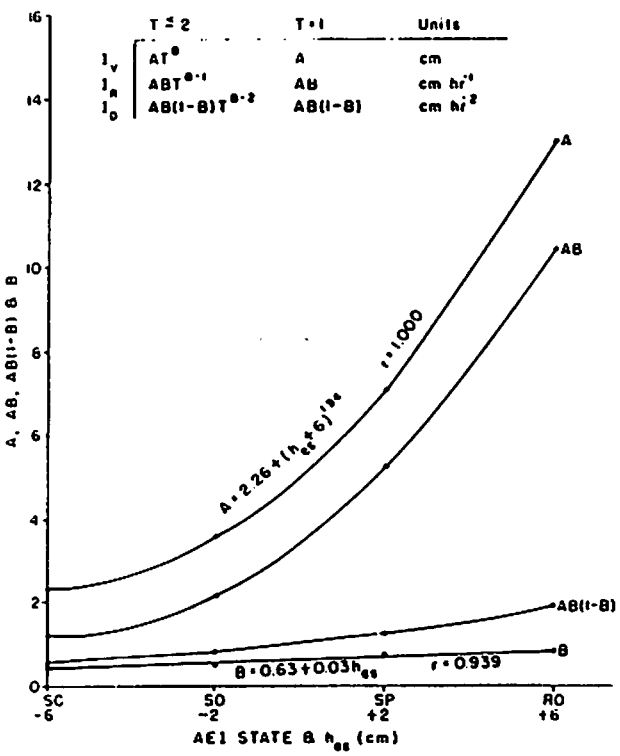

Fig. 7. Parameters for the integral and first and second derivative forms of Kostiakov's equation as functions of the *AEI* physical state and the estimated equivalent effective surface head h_{es}.

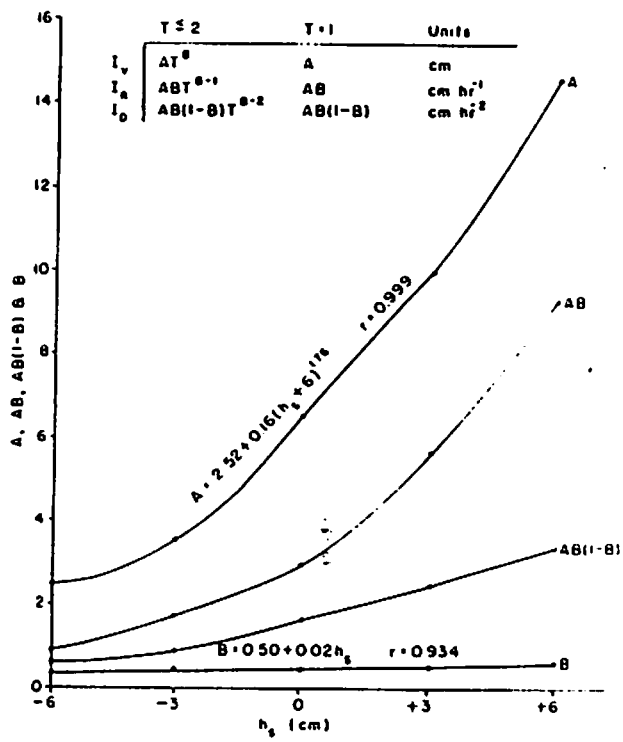

Fig. 8. Parameters for the integral and first and second derivative forms of Kostiakov's equation as functions of effective surface head h_s.

is accurately described as a power function of the numerical estimates of the *AEI* condition and h_s, whereas parameter *B* is linearly related to the *AEI* condition and h_s. Parameter *A* increases at an increasing rate with increasing surface roughness and openness and with increasing h_s as indicated by power function exponents of 1.94 and 1.76. The coefficients *AB* and *AB(1-B)* corresponding to the instantaneous I_R and I_D at $T = 1$, respectively, increase at an increasing rate with increasing time. If the ranges in *AEI* condition and h_s were extended upward, the curves for parameter *A* would probably go through inflection points and become S-shaped; however such an extension would be unrealistic,considering the small areal scale to which the *AEI* concept pertains and assuming that macroscale surface drainage is unimpeded.

Although the curves in Fig. 7 and 8 exhibit surprisingly close correspondences, the small differences that do exist may be attributed to (1) error in estimating the numerical range for the *AEI* conditions, (2) differences in soil texture, and (3) differences in water source. The *RO* interface would probably have an h_s slightly below the estimated 6 cm. The soils represented by the curves shown in Fig. 7 have a mean texture slightly finer than that of the soil represented in Fig. 8. The curves of Fig. 7 are derived from sprayed-water infiltration, whereas those of Fig. 8 are from ponded-water infiltration. The effect of soil texture would probably be relatively small compared to water source. Inherent to the sprayed-water source is the infiltration augmentation factor of increasing ponded area and depth with time. This factor may largely account for the differences in magnitude and shape of corresponding curves for the *A* and *B* parameters.

The functional relationships for the *A* and *B* parameters as given graphically and mathematically in Figs . 7 and 8 can provide a practical approach for quantifying the *AEI* concept. Further research is needed, however, before absolute infiltration prediction for all soils may be achieved by this approach. This includes development of better methods for characterizing surface roughness and openness, evaluation of natural h_s under diverse *AEI* and water-source conditions, and correlation of the measured h_s and corresponding surface roughness and openness. The curves in Figs. 7 and 8 are appropriate for medium-textured soils that are initially dry and well-structured. With the aid of closed-top infiltrometers, similar sets of curves need to be developed for coarse and fine-textured soils. Methods which facilitate correcting for the infiltration effect of antecedent moisture and single grain soil structure need to be developed.

AEI CONCEPT VERSUS DARCY THEORY

The *AEI* concept, although contrasting sharply with classical Darcy-based infiltration theory, is not only consistent with such theory but represents an extension of it. The theories differ with respect to the purposes and the physical systems for which they were developed. Darcy-based theory was developed for predicting infiltration into homogeneous

micropore systems based on a knowledge of internal soil and hydraulic properties such as soil texture, soil moisture content, h_p and hydraulic conductivity. In the derivation and testing of this theory, upper boundary conditions were simplified as much as possible by assuming a smooth microporous surface having a porosity and texture identical to that underneath and having a uniform layer of free water ponded above. The effect of h_a build-up was (and is) often ignored by assuming that air escapes unimpeded from the system. Experimentally, this ideal is approximated by side and bottom venting of laboratory columns.

The *AEI* concept was developed to (1) improve the understanding of natural infiltration processes involving the flow rates and pathways of two fluids in macropore and micropore systems as affected by two interacting and interrelated physical conditions of the air-earth interface, (2) predict infiltration into natural soils based on the knowlege of dynamic physical and hydraulic properties of the soil surface that are easily controlled externally through cultural practices, and (3) achieve wide-range point infiltration, runoff and erosion control through management of surface macroporosity and microroughness.

Thus, Darcy-based infiltration theory is concerned chiefly with internal and not easily controllable conditions that affect infiltration in micropore systems, whereas the *AEI* concept is concerned with external and easily manageable conditions that not only greatly affect infiltration in macropore systems but also tend to mask the relatively small effect that the internal conditions have on infiltration in the micropore system.

The spatial scale to which Darcy theory applies is several orders of magnitude smaller than that of the *AEI* concept because of the constraints imposed by unrealistic simplifications of the *AEI* and the soil itself. These simplifying assumptions are satisfied reasonably well only by the interface model having the *SC* surface

The *AEI* concept is consistent with Darcy's Law as interpreted by Childs (1969) for infiltration at the soil surface. Darcy's law implies that the I_R of a given soil is the *product of hydraulic conductivity and hydraulic gradient for a given time;* 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 consistent with each other, 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 *RO* 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 an h_a rise, produce a positive hydraulic gradient in the direction of macropores, thereby preventing 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 general belief that a soil has a final infiltration rate closely approximating the saturated hydraulic conductivity of the profile. Both initial and final infiltration rates decrease with decreasing surface roughness and openness, and the consequent decreasing degree of attainable soil saturation.

AEI CONCEPT APPLICATION

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 h_w in macroporous soils; relatively small and unpredictible infiltration effect of soil texture, bulk density, and moisture content; runoff and erosion acceleration resulting from clean cultivation; infiltration acceleration associated with grass cover and litter development; erosion control effectiveness of mulching and minimum tillage practices; interflow in sloping forest lands while the main soil body is relatively dry; flash flooding of upland watersheds before the topsoil is nearing saturation; faster infiltration into some clayey soils than into sandy soils; and desertification of semiarid regions in the absence of drought.

The major significance of the *AEI* concept lies in its potential for practical field application (Peterson and Dixon, 1971). 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 Fig. 9. For example, the *RO* interface is changed to *SC* by the *exposing-smoothing-sealing* sequence of processes. Although the transformation processes often occur naturally, their rates and pathways may be controlled by appropriate cultural practices. For instance, *exposing* of the soil surface may occur slowly through grazing and biological decomposition of plant material, 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 irrigation, fertilization, mulching, and grass seeding. The transformation processes are general processes which include many specific processes including physical, chemical, and biological processes, and man-imposed processes (cultural practices). A field guide for applying

the *AEI* concept can be developed from Fig. 9 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 altern-

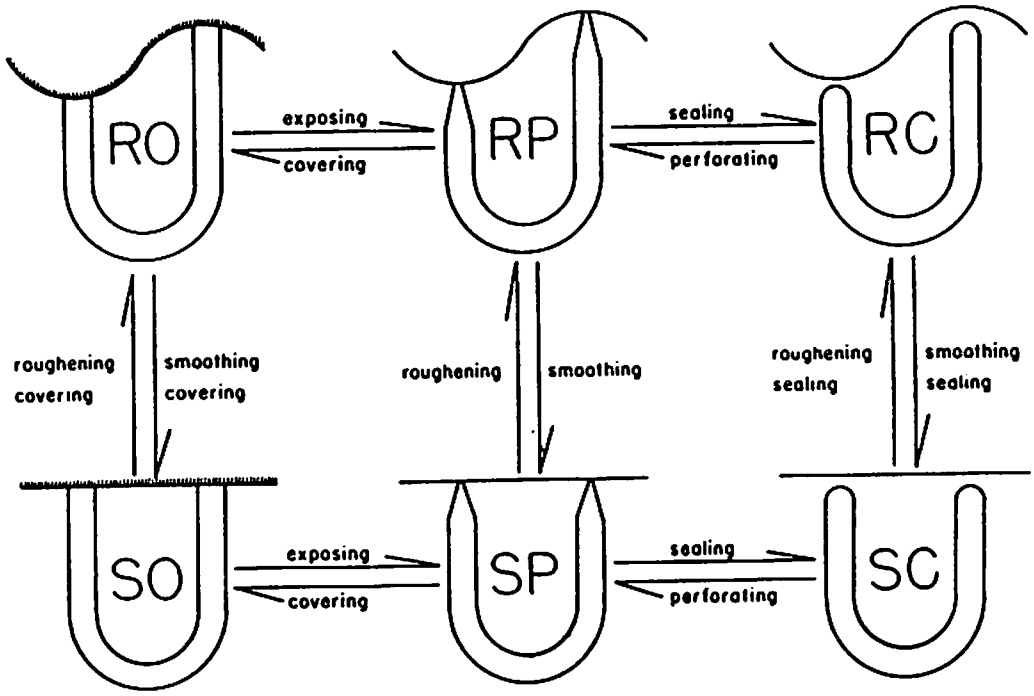

Fig. 9. *AEI* cycles and transformation processes. Infiltration control can be achieved by selecting cultural practices which effect the appropriate interface transformation. From Peterson and Dixon (1971).

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 the *RO* interface. This could raise intake rates well above the intensity of 50-year storms, thereby essentially eliminating runoff. Upland flooding of much of interior United States 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. The *SC* interface 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, the *RO* interface 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 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 an appropriate interface. More uniform lateral distribution of soil water would lead to more efficiency in irrigation and in crop use of the resource.

The *RO* interface could be imposed to augment aeration, drainage, and groundwater recharge. This interface 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 *RO* and *SC* interfaces. Runoff-irrigated seedbeds could be similarly created to assure seed germination and seedling establishment in the revegetation of barren land areas.

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 stabilize and thereby 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.

The *AEI* concept can help reverse the desertification process--a process driven by short term droughts, excessive cultivation, and overgrazing of arid and semiarid lands. This excessive exploitation leads to increased land barrenness, decreased surface roughness and openness, decreased infiltration, and increased runoff and surface evaporation. The little water that does infiltrate, penetrates the soil so superficially that it is quickly lost by surface evaporation.

A unique tillage implement, the land imprinter, has recently been developed for practical application of the *AEI* concept to large land areas (Dixon, 1977; Dixon and Simanton, 1977). By a crushing, shearing, compressing action, the land imprinter molds plant and soil materials into intricate geometric patterns for wide-range infiltration control (Fig. 10). Runoff-irrigated seedbeds, as discussed above, can be efficiently created by this implement. Interconnected geometries for enhancing both runoff and infiltration are imprinted simultaneously. The land imprinter is expected to be useful for controlling infiltration in bulldozer-leveled strip-mined lands. Besides being a practical method for applying the *AEI* concept, the land imprinter should be useful in further testing and refining of this concept.

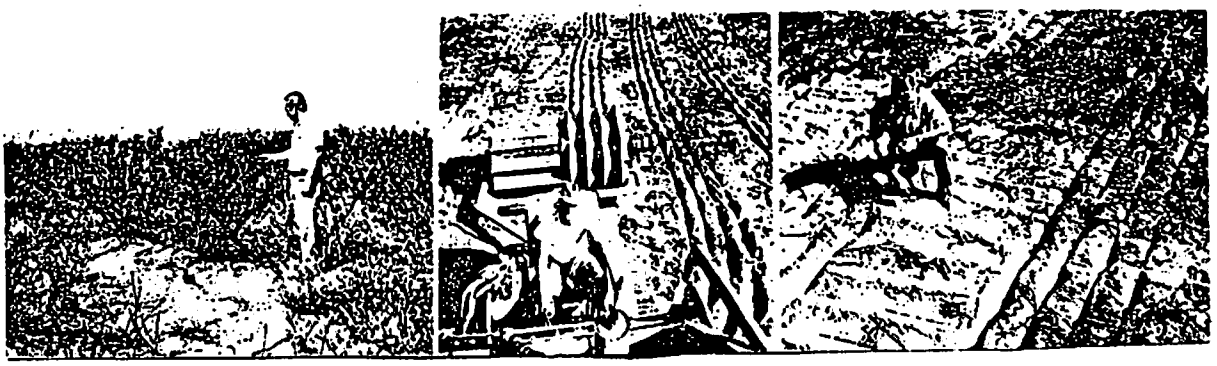

Fig. 10. Desert shrubland prior to, during, and following land imprinting. By pairing ten unique imprint capsules in as many ways as possible, 45 different geometric patterns can be created for various applications of the *AEI* concept. Assembled as shown, the land imprinter is forming rainwater-irrigated seedbeds for establishing forage grasses.

SUMMATION

The *AEI* concept is based on assumptions that are realistic and in agreement with the reported physical behavior of natural soil infiltration systems in addition to the behavior of the simple idealized systems previously discussed. The essential characteristics of natural infiltration systems are incorporated in the physical models of the *AEI* concept so that model behavior is sufficiently similar to that of real systems to make possible accurate relative prediction of natural infiltration and a simplified explanation for a great diversity of natural infiltration phenomena. An infiltrating system, as envisioned by the *AEI* concept, involves *flow rates and routes of two fluids in two pore systems as affected by the two AEI conditions, surface roughness and openness.*

Fig. 11 illustrates the mechanisms by which surface roughness and openness (and the resulting h_s) control infiltration in accordance with the *AEI* concept. A *RO* surface is associated with positive mean h_s having maximal areal variability, whereas a *SC* surface is associated with negative mean h_s having minimal areal variability. The h_s, by determining the hydraulic gradient at the surface openings of macropores, controls fluid flux into (or out of) and within the macropores. This includes both the transmission of free surface water downward and soil air upward. In general, water will flow downward displacing the soil air ahead of it when the h_s is positive. In contrast, when h_s is negative, macropores serve to vent the soil air upward that is being displaced by water infiltrating the bordering microporosity. When the h_s is near zero, a condition approaching static equilibrium may be approached between the counteracting hydraulic and pneumatic forces at the macropore openings. Thus, h_s and the resultant

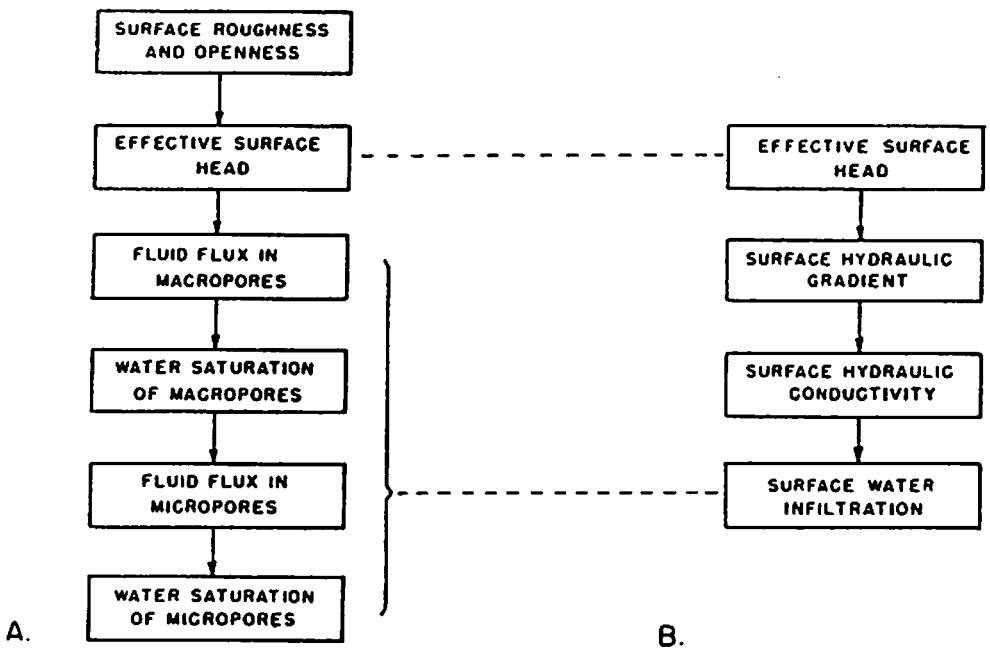

Fig. 11. A: Mechanisms by which surface roughness and openness control surface water transmission into a soil and subsequent storage of this water within soil pores. B: mechanism by which effective surface head h_s controls infiltration. Modified from Dixon (1975b).

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 border, water saturation of macropores regulates water flow into micropores and this flux in turn determines the degree of water saturation of this pore space. By the foregoing mechanism, surface roughness and openness control the effective hydraulic gradient and conductivity within the soil profile. The four lower blocks in Fig. 10a 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 in the micropore system.

The block diagrams in Fig. 11 indicate the theoretical basis for relative infiltration control at the *AEI*. Kostiakov's equation can be used in absolute infiltration control by interpreting the coefficient A as a function of h_s, with large A values being associated with *RO* surfaces and positive h_s and small A values with *SC* surfaces and negative h_s. Exponent B may be viewed as a function of infiltration abatement-augmentation factors with values near zero, near 1, and above 1, indicating the dominance of abatement factors, little dominance of either the abatement or augmentation factors and dominance of augmentation factors, respectively. Since many of the abatement and augmentation factors affect h_s and vice versa, parameters A and B are interdependent. Further theoretical and experimental research is needed to determine the independent effect of various infiltration abatement and augmentation processes on the parameters of Kostiakov's equation. The study of water infiltration as affected by dynamic surface boundary conditions is a fertile field for major theoretical advances.

SYMBOLS

AEI = air-earth interface
RC = rough closed
RO = rough open
RP = rough partly open
SC = smooth closed
SO = smooth open
SP = smooth partly open

A = coefficient of T in Kostiakov's equation, L/T^B
B = exponent of T in Kostiakov's equation, dimensionless
h_a = pressure head of soil air, L
h_{es} = equivalent effective pressure head at soil surface, L
h_p = pressure head of soil water, L
h_s = effective pressure head at soil surface, L
h_w = pressure head of ponded surface water, L

I_D = deceleration in infiltration rate, L/T^2
I_R = infiltration rate, L/T
I_V = infiltration volume (depth), L
T = time elapsed after incipient ponding in microdepressions, T

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