INfiltration Role of Large Soil Pores:

A Channel System Concept*

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Infiltration rates for a given soil vary over a wide range depending on prevailing conditions. Conditions reportedly influencing infiltration include soil texture, soil structure, soil layering, soil water content, pore size distribution, soil temperature, water temperature, water quality, soil porosity, soil depth and surface slope (9); however, these conditions are often masked by the overriding influence of the immediate soil surface. Duley and Russell (4) noted that surface sealing affects infiltration more than does soil type, slope, moisture content and profile characteristics. Free, Browning and Musgrave (5), in a study of 68 soil sites scattered over the United States, found a definite association of infiltration with all indices of large pores or with those indices affecting pore size. Dixon (1) showed that large open pores, representing a negligible part of the total surface area, contribute greatly to infiltration.

For water to infiltrate, soil air must be displaced. Wilson and Luthin (11) observed soil air pressures up to 14 cm of H₂O in homogeneous soil columns vented to the atmosphere and up to 110 cm in unvented columns. They indicated that soil air pressure reduces the number of large pores active in transmitting water. In a column experiment Horton (7) showed that an entrapped air pressure of only 2.5 cm nearly halved the final infiltration rate.

Large soil pores, a form of soil heterogeneity in the horizontal plane, surprisingly have received little attention by researchers in view of their marked effect on infiltration. This lack of interest can be attributed to the inherent nature of large pore systems. Owing to the large dimensions and infrequent spatial repetition of large pores, an adequate-sized sample is often too cumbersome for laboratory work. In addition, an adequate description of large pore geometry is impossible because the physical and biological processes creating this geometry are poorly understood. Further, the infiltration potential of large pores in cultivated soils was seldom realized before the advent of minimum and no-tillage practices, since tillage for weed control usually blocked these pores at the soil surface. The role of large pores also has been neglected because this form of soil variability is overwhelming mathematically. Flow equations for hydraulically homogeneous soils with uniform initial water distribution have been difficult to solve. Solution of equations adequately describing water movement in the field where permeability, moisture and temperature typically vary continuously in both time

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and space appears improbable. Transient pneumatic potential is another complicating factor that is usually important in natural soils but is commonly excluded from mathematical analyses by simplifying assumptions (11).

THEORETICAL CONSIDERATIONS

The large infiltration contribution of large pores would be expected since volume flow according to Poiseuille's equation increases with the 4th power of a cylindrical tube diameter. Thus, theoretically, a pore 1 mm in diameter conducts downward 10,000 times as much water as a 0.1 mm pore. Volume flow in a plane crack increases with the cube of the crack width. Furthermore pore tortuosity (flow path length) decreases and pore continuity increases with increasing pore size. The tendency for large pores to fill with displaced soil air and thereby block infiltration paths would also be expected. Jurin's equation indicates that capillarity decreases with increasing pore diameter (or diameter of curvature in air-water interface) and is < 3 cm of H₂O for pores > 1 mm in diameter. Hence a displaced air pressure of only 3 cm can eliminate the otherwise large infiltration contribution of soil 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 in depth that initially contains 10% air. Consequently, air pressures > 3 cm of H₂O are probably common under natural field conditions during wetting. The need for large pores to be open and exposed to free surface water before they can contribute to infiltration is implied by Darcy's equation which indicates that water moves only in the direction of decreasing hydraulic head. Hydraulic head always increases in the direction of a large pore isolated from free water by a surface seal.

CHANNEL SYSTEM CONCEPT

Dixon and Peterson (2, 3) recently described the role of large pores in soil water movement in a new infiltration concept designated the channel system concept. This concept originally was developed to provide a basis for interpreting the large infiltration variations commonly observed in the field. It may also be useful in the solution of many infiltration-related problems.

The channel system concept assumes that large soil pores and soil air pressure are commonly encountered under field conditions; that they have a profound influence on rate and route of water infiltration; and that this influence is controlled by soil surface conditions. It contends that a network of large soil pores or a channel system can function as a subterranean arterial system for rapidly distributing free surface water to locations within the soil mass (or matrix) and for exhausting soil air displaced from this mass. Such a role is depicted diagrammatically by the U-shaped channel, a water intake-air exhaust circuit, shown in Fig. 1. The soil mass surrounding the channel serves as a water storage sink and is termed the capillary system.

The channel system includes the space immediately above the soil surface and that within a subsurface network of large pores which fills
and drains largely by gravity during and after soil surface exposure to free or ponded water. Specifically, it includes microtopographical features and large pores or channels produced by clay shrinkage, tillage, earthworms, insects, roots, internal erosion, ice lenses, pebble dissolution, and entrapped air. In contrast, the capillary system includes the space within and between individual soil aggregates (textural and structural pores or simple and compound packing voids) that fills and drains largely by capillarity. Thus during rapid wetting of an initially dry soil, the channel and capillary systems contain water at pressures of near atmospheric and below atmospheric, respectively.

Fig. 1. Bimodal Porous Soil Containing a Channel and a Capillary System. Symbol definitions are: A = plant residue cover on soil surface; B = free water surface; C = microdepression in soil surface; D = water intake port of channel; E = microelevation in soil surface; F = soil air exhaust port of channel; G = channel space; H = channel wall; and I = capillary space. From Dixon and Peterson (2).

Fig. 2. Channel System States and Associated U-shaped Channel for Water Infiltration into Bimodal Porous Soils. States A, B and C represent rough soil surfaces with open, constricted (unstable) and closed channels, respectively; whereas states D, E and F represent plane or smooth surfaces with open, constricted and closed channels. Refer to Fig. 1 for symbol definitions. From Dixon and Peterson (2).

The two systems share a common porous boundary at the soil surface and along subterranean channel walls, thus intersystem flow of water and displaced air occurs. Rate and route of system and intersystem fluid flux are controlled primarily by surface roughness and openness — physical properties related to the degree of soil surface microrelief and the de-
gree of channel continuity with the soil surface, respectively. These properties determine the extent of hydraulic and pneumatic continuity between the soil surface and underlying channels and thereby regulate fluid flux in the channel system. At present the channel system concept embodies six channel system states representing two degrees of soil surface roughness and three degrees of channel openness (Fig. 2). Channels are U-shaped to show the dual function of the channel system; i.e., to let in free surface water and to vent displaced soil air. By definition, states A, B, and C represent rough surfaces with open, constricted (unstable) and closed channel ports, respectively. States D, E, and F represent plane or smooth surfaces with open, constricted (unstable) and closed channel ports. Since these states encompass the complete range of naturally occurring surface openness and roughness, they can guide practical field application of the channel system concept.

State A symbolizes a highly functional channel system that rapidly transfers and distributes free surface water to subsurface borders of the capillary system and that readily exhausts displaced soil air. Steep hydraulic gradients exist across a large border area between the two systems, causing rapid movement of water into the storage space of the capillary system. A soil with this type of channel system would have numerous stable open channel ports exposed to free water and some nearby open to the atmosphere. This means that the soil surface would be rough, open, and covered. The roughness provides microdepressions for water intake ports and microelevations for air exhaust ports, whereas the cover helps to stabilize these ports. These soil surface conditions introduce a high degree of lateral hydraulic imbalance in the channel system. This imbalance and the high conductivity of the channel system produce the rapid rates and direct routes of water entering an A surface. Such surfaces are hydraulically anisotropic. Cultural practices such as stover and stubble mulch tillage, that stabilize the soil surface in a rough open condition, create the A surface.

State B is similar to state A except that the channel ports are unstable and constrict when exposed to free water. These constrictions impede water entry and air exit; consequently, channel system B contributes less to infiltration than system A. Extent of channel port constriction depends partly on the water source. For instance an intense rainstorm may completely close channel ports, whereas basin and border irrigation may cause only minor constriction. State B is created with tillage and planting implements that produce a rough but exposed surface such as moldboard plows, listers, and plow planters.

State C differs from state B in that channel ports are completely closed initially; i.e., the channel system is physically discontinuous at the soil surface. Consequently, subsurface channels are hydraulically and pneumatically disconnected from the soil surface. Infiltrating water cannot enter such channels until the bordering regions of the capillary system become saturated, and not even then, if channel air pressure is above atmospheric. These closed channels function primarily as reservoirs for entrapped air, and thus as barriers to water movement within the capillary system. However, some free water may enter the terminal ends of subsurface channels in the region beneath microdepressions where the capillary system first becomes saturated. Infiltration rates under state C are lower than under state B since nearly all water entering the soil
must now take the high resistance path of the capillary system — of those small tortuous capillaries exposed to free water only along the rough soil surface. Buildup in soil air pressure further limits infiltration under state C by blocking water flow in the larger structural pores of the capillary system. State C is typical of plowed, listed and plow-planted fields having unprotected surfaces sealed previously by intense rainfall or sprinkler irrigation.

State D differs from state A only by soil surface roughness, but this profoundly affects system and intersystem flow since the flat surface of state D favors lateral hydraulic balance. Under intense rainfall on sloping land, a thin relatively uniform layer of water would accumulate on the D surface. Hence, there would be no optimal sites for either channel intake or exhaust ports. Ports would receive too little water for rapid water intake and too much for low-pressure exhausting of displaced air. Channel ports would probably take in water and exhaust air intermittently since simultaneous flow in opposite directions would be unlikely except for wide soil cracks or large animal burrows. Because of this inefficient port action, system D would contribute less to infiltration than system A. Mean infiltration rates under states D and B for the first hour would probably be comparable. System D would have lower initial infiltration rates than system B owing to greater lateral hydraulic balance, but the rates would fall off more slowly because of greater surface stability. State D is found often under turfgrass, and under grass and legume crops.

State E is like D except that the soil surface lacks cover and is therefore unstable. As in state B, channel ports constrict on exposure to free water. These constrictions reduce the infiltration contribution of system E well below that of system D. Mean first hour intake rates under states E and C would be similar. Relative to system C, system E would have higher initial intake rates attributable to greater channel openness, but the rates would fall off more rapidly because of less surface stability. State E is represented well by freshly prepared alfalfa and grass seedbeds.

Sealing an E soil surface converts it to state F. The smooth, closed F surface is hydraulically and pneumatically disconnected from subsurface channels, i.e., it is hydraulically isotropic. Under state F infiltration is the lowest of all states since all infiltrating water must enter the flat surface border (a minimal surface area) of the capillary system and must move along the small tortuous pathways of this system against increasing displaced air pressure. Surface F possesses the highest degree of lateral hydraulic balance of all surfaces and is approximated by smooth water-sealed seedbeds.

The channel system concept may be conveniently summarized by ranking the six surface states with respect to their definitive and deductive properties. By definition soil surface roughness and depression storage rank in the order A=B=C>D=E=F, whereas channel port openness and physical continuity of soil surface and subsurface channels rank A=D>B=E>C=F.

Hydraulic and pneumatic continuity of soil surface and subsurface channels; hydraulic anisotropy of soil surface; border area of channel system wetted with high pressure water; water infiltration, interflow,
and deep percolation rate; mean vertical and horizontal hydraulic conductivity and gradient; soil-water pressure and content; air permeability of soil surface and exhausting rate of displaced air; entrapped air pressure; and internal soil erosion probably rank in the order $A > B = D > C = E > F$. Surface runoff; tortuosity of main flow routes for water penetration and air displacement; exhaust pressure of displaced air (surface bubbling pressure) and maximum displaced air pressure; displaced air pressure rise per unit infiltration; entrapped air volume; and time required to attain steady state infiltration probably rank $A < B = D < C = E < F$.

By inference, 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 would rank $A > B = D > C = E > F$. Conversely, flash flooding; surface erosion and pollution of surface waters; downward movement of soil solutes per unit infiltration and pollution of groundwater with these solutes; surface evaporation of soil water from brief intense rainstorms; and soil-water evaporation during the constant rate period would rank $A < B = D < C = E < F$.

The six physical models of the channel system concept appear useful in designing cultural practices to either raise or lower infiltration relative to the existing level. A mathematical model for an initially dry soil could possibly be developed by evaluating the two parameters of Kostiakov's equation (8) as functions of soil surface roughness and openness. First, however, methods are needed for measuring these two surface conditions which reliably reflect their infiltration roles.

Holtan (6) reported a mathematical model for watershed infiltration having a physical basis somewhat similar to that of the channel system concept except that the direct infiltration roles of surface roughness and soil air pressure are not considered. His parameter "a" (percent basal area of vegetation) corresponds closely to the openness parameter of the channel system concept.

CONCEPT TESTING

A series of field experiments were conducted to test the performance of selected channel system states and to thereby evaluate the potential of the channel system concept as a practical scheme for controlling infiltration (3, 10). Widely diverse vegetal, edaphic and climatic conditions were represented. Results indicated that standard channel system states 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 states were imposed, since the infiltration capacity of state A increased while the capacity of F decreased. Observed increases under state A were attributed largely to earthworm activity at the soil surface. Such activity not only improves the surface continuity of the channel system but increases its subsurface continuity and extent. Fungal and bacterial activity probably plays an important role in stabilizing channel ports. Observed decreases under state F reflected the absence (or low level) of surficial biological activity and the resulting decreases in channel system continuity at the soil surface.
Fig. 3. Total Infiltration Under Imposed Channel System States A and F and Naturally Occurring State D or E. The curve labeled S represents total water applied by infiltrometer spray nozzle. Numbers near curves at 1- and 2-hour times denote infiltration rates at cm hr⁻¹ for these times. From Dixon and Peterson (3).

Results of soil air pressure studies support the channel system concept by showing that small pressures greatly reduce infiltration (Dixon and Linden, unpublished manuscript). For instance, a pressure of only 18 cm H₂O (0.25 psi) reduced border irrigation infiltration totals by about one-third.

CONCEPT UTILITY

The channel system concept clarifies the physical nature of infiltration phenomena as they occur in the field where soils are never hydraulically isotropic either vertically or horizontally. It describes the major infiltration roles of the two sources of soil surface anisotropy, microtopographical roughness and channel openness. Both of these parameters are influenced greatly by numerous physical and biological processes occurring often at accelerated rates at or just beneath the soil surface. In turn, cultural practices are known to alter the rates of these processes. Cultural practices maximizing biological activity at the soil surface favor the open-channel conditions of states A and D, whereas practices minimizing this activity favor the closed-channel condition of states C and F. Tillage plus wetting of the soil surface creates the constricted channel condition of states B and E (unstable intermediate states). States B and E then trend toward states A and D if the soil surface is biologically active or to C and F if it is inactive. Intense biological activity at the soil surface tends not only to stabilize soil surface roughness but also to augment this roughness through the excavating activities of such organisms as earthworms and ants.

The air-exhausting function of the channel system becomes unimportant where soil air permeability and soil air volume are large enough to prevent measurable soil air compression by the wetting front. However, in most soils one or both of these variables are small enough to effect a rise in soil air pressure. Common profile features that restrict downward
flow of displaced air include wet plow soles and clay pans, wet fine-textured B horizons, cemented and rocky horizons, and water tables.

The major significance of the channel system concept lies in its potential for practical field application (10). Since soil surface conditions control the rate and route of water movement into, within and through the soil, soil and water management practices which alter this surface can be used to control various cropping hazards. Management practices can be directed to changing the existing channel system state into the desired state by means of the transformation processes shown in Fig. 4. For example, state A is changed to state F by the exposing-smoothing-sealing sequence of processes. Although these transformation processes often occur naturally, their direction and rate may be controlled by appropriate cultural practices. For instance, exposing of the soil surface may occur slowly through biological decomposition of vegetal residue or very rapidly via cultural practices such as burning and moldboard plowing. Conversely, covering of a barren soil in a semiarid region may be achieved rapidly by combining cultural practices such as irrigation, fertilization and mulching. A field guide for applying the channel system concept can be developed from Fig. 4 by determining the channel system states 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. For example, covering can be accomplished by various means including crop canopies, crop residues, rocks, clods, plastic film, crude oil, asphalt, and concrete; however, the effectiveness and economic feasibility of these materials in creating and maintaining open stable channel orifices vary widely.

![Fig. 4. Channel System Cycles and Transformation Processes. From Peterson and Dixon (10).](image-url)
The channel system concept appears applicable to a wide range of cropland problems which are related to rate and route of water infiltration. To control runoff, erosion and pollution of surface waters, the existing channel system state could be transformed to state A. This could raise intake rates above the intensity of 50-year storms, thereby eliminating runoff. Upland flooding of much of interior United States often occurs when the storage space of the topsoil is just partially filled. Accessibility of this storage space (even beneath water repellent surfaces) to free surface water is greatly increased by the short circuits of the A system.

This concept also appears useful in controlling soil leaching and groundwater pollution. State F would give the most efficient leaching of soluble salts (when evaporation is small relative to infiltration) because infiltrating water would move slowly via long, small, tortuous routes through the soil. Thus diffusion distance would be minimized and diffusion time would be maximized. However, if pollution of ground or drainage water is of major concern then state A should be used, since here infiltrating water initially bypasses the soil mass and hence the salts. Thus net downward movement of salt per unit of water applied would be reduced greatly. However, when the pollutants are on the soil surface or in the water source (rather than in the soluim) state F would minimize the pollution of groundwater as more of the pollutants would be deposited in the soil and/or removed in surface runoff.

The channel system concept could be used to control lateral distribution of soil water replenished by surface or sprinkler irrigation and rainfall. To achieve greater distribution uniformity, inherent lateral variability (due to soil texture, slope, etc.) could be minimized by imposing the appropriate channel system state A through F. More uniform lateral distribution of soil water would lead to more efficient irrigation and crop use of the resource.

State A could be imposed to augment aeration, drainage, and groundwater recharge. State A may 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 rainfall since some of the surface storage space would be bypassed. Water held deeper in the profile is less subject to evaporation. For regions where annual precipitation is insufficient to support a complete crop cover, efficient runoff-irrigation practices could be developed by imposing and maintaining alternate contour strips of states A and F.

This concept may permit greater latitude in the design of surface and sprinkler irrigation systems as it facilitates infiltration control by cultural means. Existing irrigation systems could be made more efficient by converting the prevailing channel system state into one giving an appropriate infiltration capacity.

In many cropland situations the channel system concept can be applied by merely altering tillage practices to effect the appropriate change in soil surface roughness and openness. Both roughness and openness are functions of tillage implement type and setting, crop residue placement, and soil conditions. Crop residue placed at the soil surface helps to maintain the roughness and openness created by the tillage implement.
Although cropland applications have been stressed, the channel system concept is general enough to apply to other land areas as well.

**CHANNEL SYSTEM FORMATION**

Soil surface conditions of roughness and openness not only reflect subsurface channel development but affect it as well. For instance a rough open surface by favoring rapid air and water flow in existing channels causes enlargement and extension of these channels. Steep hydraulic gradients under state A produce erosive channel velocities and increase the likelihood of ruptures in the soil fabric. Such ruptures may improve continuity of the subsurface channel net by linking isolated channel segments.

The author has observed rapid development of subsurface channels after a flat bare surface was roughened and covered. Physical and biological processes (and their interactions) contribute to this development. A rough surface condition favors maximal steepness in hydraulic gradients at the soil surface, particularly within microdepressions. Both surface head and relatively low pneumatic back pressure add to this steepness. Such gradients, through rapid saturating and weakening of the soil fabric, produce ruptures and the downward mass flow of a water-soil slurry. This flow tends to follow the path of least resistance or through large soil voids and the weakest areas of the soil fabric. By decreasing splash erosion and velocity of overland flow, soil surface cover reduces the sediment load of water entering the rupture, and thereby reduces the chance that the newly-formed channel will become plugged or filled with sediment. Low sediment water also has a greater capacity for internal erosion. Such erosion may prevent complete closing of shrinkage cracks on rehydration of clay minerals. A rough soil surface also favors nonuniform wetting and drying stresses which in turn may cause surface cracking, especially at the juncture of microelevations and depressions.

For water to attain maximum velocity in channels, soil air must be vented at a minimum pressure. This can be accomplished by the channels terminating at the crest of microelevations located in close proximity to the microdepressions. Such a surface configuration shortens the air vent circuit and minimizes waterlogging of its outlets.

Microdepressions of a rough covered surface provide attractive feeding sites for earthworms and other soil organisms. Earthworms migrate (often via subterranean routes) rapidly to these depressions and soon perforate them with their burrows. Some species such as *Lumbricidae terrestris* form essentially vertical burrows 1- to 3-m deep and 6 to 8 mm in diameter, whereas other species tend to burrow horizontally. A criss-crossing (sometimes intersecting) net of burrows having surface continuity is thus developed. Such earthworm burrowing increased 2-hour cumulative infiltration from an initial 13 cm to 39 cm during the first year following imposition of state A (3) and to 75 cm during the second year.

Interacting physical and biological processes may also assist in channel 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 cracks are there-
by extended. Soil bacteria and fungi undoubtedly play an important role in stabilizing large pores through the cementing and water proofing effects of their metabolic products. In reverse, biotic activity may lead to channel formation by physical means. For example, after an infiltration period insect and earthworm burrows become highly efficient conduits for venting soil-water vapor. As a consequence profuse cracking often occurs along burrow walls.

**SUMMARY**

The infiltration role of large soil pores is detailed by the channel system concept. This concept may be summarized by the following points:

1. Large-pore or channel systems commonly occur in both virgin and cultivated soils.

2. These systems, together with soil air pressure, can profoundly influence rate and route of free surface water movement into, within and out of soil profiles.

3. Degree of this influence is controlled by the two soil surface conditions of openness and roughness.

4. These two conditions determine extent of hydraulic and pneumatic continuity between soil surface and underlying channels or extent of surface hydraulic anisotropy.

5. Rough surfaces with open channel ports produce rapid rates and direct routes of water penetration, whereas smooth surfaces with closed channel ports produce slow rates and tortuous routes.

6. Surface openness and roughness not only reflect but influence the development of subsurface channel networks.

7. Water infiltration and interflow can be controlled over a wide range by cultural practices designed to control surface openness and roughness.

The channel system concept embodies six physical models representing two degrees of surface roughness and three degrees of channel openness. These models can guide practical application of the concept since they represent naturally occurring soil surface conditions that can be readily identified and easily created in the field. Further research is needed to adapt existing mathematical models to the channel system concept.

**REFERENCES**


