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Macropores and Water Flow in Soils

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This paper reviews the importance of large continuous openings (macropores) on water flow in soils. The presence of macropores may lead to spatial concentrations of water flow through unsaturated soil that will not be described well by a Darcy approach to flow through porous media. This has important implications for the rapid movement of solutes and pollutants through soils. Difficulties in defining what constitutes a macropore and the limitations of current nomenclature are reviewed. The influence of macropores on infiltration and subsurface storm flow is discussed on the basis of both experimental evidence and theoretical studies. The limitations of models that treat macropores and matrix porosity as separate flow domains is stressed. Little-understood areas are discussed as promising lines for future research. In particular, there is a need for a coherent theory of flow through structured soils that would make the macropore domain concept redundant.

INTRODUCTION

There has long been speculation that large continuous openings in field soils (which we will call macropores) may be very important in the movement of water—at least under certain conditions. Such voids are readily visible, and it is known that they may be continuous for distances of at least several meters in both vertical and lateral directions. The idea that these voids will allow rapid movement of water, solutes, and pollutants through the soil is an attractive one and dates back at least to *Schumacher* [1864], who wrote:

> the permeability of a soil during infiltration is mainly controlled by big pores, in which the water is not held under the influence of capillary forces.

Similar ideas were also being expressed at Rothamsted in England by *Lawes et al.* [1882], who reported, on the basis of early plot drainage experiments, that

> The drainage water of a soil may thus be of two kinds: it may consist (1) of rainwater that has passed with but little change in composition down the open channels of the soil; or (2) of the water discharged from the pores of a saturated soil.

Hursh [1944], in pointing out that subsurface flows may make an important contribution to flood hydrographs in areas of high infiltration capacity, noted that for natural soil profiles with strongly differentiated soil horizons there may be

> a tremendous increase in lateral transmission-rate as the water table approaches the soil surface...in considering flow through upper soil horizons, the formulas of soil mechanics do not generally apply. Here porosity is not a factor of individual soil particle size but rather of structure determined by soil aggregates which form a three-dimensional lattice pattern. This structure is permeated throughout by biological channels which in themselves also function as hydraulic pathways. A single dead-root channel, worm-hole or insect burrow may govern both the draining of water and escape of air through a considerable block of soil.

Even *Horton* [1942] noted that runoff may take place

> through a thick matting of grass or mulch cover; through a layer of plant roots close to the soil surface and under forest litter; or even, in some cases, through a network of suncracks in the soil surface.

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However, Horton suggested that such flows would be mostly turbulent, while true groundwater flow is mostly laminar, and he coined the term 'concealed surface runoff' for such rapid flows through these macropores.

There is no doubt that water will move through large voids under saturated conditions and that they have a very important influence on the saturated hydraulic conductivity of soils, even though they may contribute only a very small amount to the total porosity of a soil. However, there remain some major questions concerning their role in water flow through soils. In particular: When does water flow through macropores in the soil? How does water flow through macropores in the soil? How does water in a macropore interact with water in the surrounding soil? How important are macropores in terms of volumes of flow at the hill slope or catchment scale? What are the implications of macropores for movement of solutes and chemical interactions in the soil?

Work on all of these questions has been proceeding very rapidly in the last few years, and this review is a timely opportunity to assess what has been achieved and what remains to be done.

THE OCCURRENCE OF MACROPORES IN SOILS

Definitions: When Is a Pore a Macropore?

At the microscopic scale, the storage and flow of water in any particular void of the porosity of a soil is related to the size of that void and also to its generally irregular geometry. In particular, flow rates will be controlled by the void of smallest size in any single continuous flow path (called pore necks). Thus we should expect a complex relationship between void geometry and flow characteristics at some macroscopic scale of interest. This has led to a number of indirect ways of classifying pore space.

The method most commonly used has been to interpret the soil moisture retention curve in terms of pore size classes, where a measure of effective pore size is related to capillary potential through the Laplace equation for capillary pressure [e.g., *Bear*, 1972]. This involves an analogy between the macroscopic retention characteristics of the soil and the microscopic concepts of the behavior of a bundle of capillary tubes. This technique cannot provide an unequivocal defini-

TABLE 1. Some Definitions of Macropores and Macroporosity

Reference	Capillary Potential, kPa	Equivalent Diameter, μm
Nelson and Baver [1940]	>−3.0	
Marshall [1959]	>−10.0	>30
Brewer [1964]		
Coarse macropores		5,000
Medium macropores		2,000–5,000
Fine macropores		1,000–5,000
Very fine macropores		75–1,000
McDonald [1967]	>−6.0	
Webster [1974]		
[quoted in *Mosley*, 1979]	>−5.0	
Ranken [1974]	>−1.0	
Bullock and Thomasson [1979]	>−5.0	>60
Reeves [1980]		
Enlarged macrofissures		2,000–10,000
Macrofissures		200–2,000
Luxmoore [1981]	>−0.3	>1,000
Beven and Germann [1981]	>−0.1	>3,000

tion of a macropore. The choice of an effective size to delimit macropores is necessarily arbitrary and is often related more to details of experimental technique than to considerations of flow processes. In addition, the capillary tube analogy becomes increasingly tenuous as pore size increases. Some of the definitions of macroporosity used are shown in Table 1.

Porosity may also be classified with respect to the hydraulic conductivity of the soil, where data on the change of conductivity with soil moisture are available. Thus volumetric fractions of the pore space can be directly related to incremental contributions to hydraulic conductivity. This approach is, however, necessarily restricted to cases where hydraulic gradients can be properly defined. It can be argued that this is not always the case for soils with individual macropores that are long in relation to their width. Under these conditions the traditional porous media concept that a unique pressure gradient can be specified for some macroscopic 'representative elementary volume' [e.g., *Bear*, 1972] of the soild may not be appropriate. When the structural pores are large in relation to those in the surrounding soil, the movement of water through the macropores, once initiated, may be much faster than the equilibration of potentials in a representative volume of the soil matrix. If this is so, the potential gradients associated with the two systems will be different. This is not a new idea, and Lawes et al. noted that

> In a heavy soil, channel drainage will in most cases precede general drainage; a portion of the water escaping by the open channels before the body of the soil has become saturated; this will especially be the case if the rain fell rapidly, and water accumulates on the surface.

The possibility of such discontinuous behavior will increase as the size and connectivity of the macropores increases and the effects of capillary tension within the macropores become smaller. However, it must be stressed that size alone is not a sufficient criterion for the definition of a macropore in this sense. Pore structure is also of crucial importance [see discussion of *Luxmoore*, 1981, by *Bouma*, 1981; *Skopp*, 1981; *Beven*, 1981]. Other terms, such as preferential pathways or macrochannels, have been suggested to emphasize the importance of structure on flow dynamics. We wish to make quite clear that in using the word macropore we are implying structures that permit the type of nonequilibrium channeling flow described above (hereafter referred to simply as channeling)—whatever their size. We recognize that not all large voids are macropores in this sense and that the present nonmenclature is unsatisfactory. However, we feel that considerable further work remains to be done before an acceptable set of flow concepts, rigorously based in an understanding of the dynamics of flow through structured porous media, is available.

Types of Macropore

Several standard soil survey procedures include statements on voids and other structural properties of the soil [see, for example, *USDA*, 1975; *Avery*, 1973; *Thomasson*, 1978]. Thus, from a morphological point of view, the readily visible macropores are a well-established feature of soils. However, the characteristics of macropores recorded by morphological surveys may bear only a complex relationship with the hydraulic properties of interest to the hydrologist. On the basis of morphology the macropores may be grouped as follows:

Pores formed by the soil fauna. These are primarily tubular in shape but may range in size from less than 1 mm to over 50 mm in diameter for holes formed by burrowing animals such as moles, gophers, and wombats. Macropores formed by soil fauna are often concentrated close to the soil surface. *Omoti and Wild* [1979] report that for earthworm channels (2–10 mm diameter, 100 channels/m^2) in a loam soil in southern England nearly all were continuous to 0.14-m depth, with 10% continuous to 0.7 m. *Ehlers* [1975] reports that the number of earthworm channels increased with depth down to 0.6 m in both tilled and untilled soil. *Green and Askew* [1965] describe the activities of ants in producing macropore networks (2–50 mm diameter) to a depth of at least 1 m. This study is particularly interesting since it is related to the earlier hydrological work of *Childs et al.* [1957], in which the saturated hydraulic conductivities of the clay soils were reported as having magnitudes more usually associated with gravels. *Williams and Allman* [1969] found cylindrical macropores in a loess profile down to a depth of at least 10 m. The pores had a diameter of 5–10 mm and ranged in frequency from 100/m^2 close to the surface to 50/m^2 at a depth of 8 m. They were not certain in this case if the pores were formed by plants or animals. Moisture conditions and *p*H of a soil influence the composition of soil fauna. In acid soils the insects tend to dominate, whereas earthworms prefer low acid to neutral soils. They avoid alkaline soils almost completely [*Sapkarev*, 1979]. A comprehensive review of the activities of animals in soils is given by *Hole* [1981].

Pores formed by plant roots. Pores in this category are also of tubular shape. Macropores may be associated with either live or decayed roots, and the distinction may often be hard to make, as there is a tendency for new roots to follow the channels of previous roots. The bark of tree roots sometimes resists decay longer than the xylem, and a hose type macropore is formed, partially sealed by the bark [*Gaiser*, 1952; *Aubertin*, 1971; Figure 1, this paper]. The lumen is frequently filled with loosely packed organic matter primarily derived from the decaying root itself. Such macropores may comprise up to at least 35% of the volume of a forest soil, but this may be expected to decrease rapidly with depth [*Aubertin*, 1971]. The structure of macropore systems derived from roots will be dependent on the plant species and the conditions of growth. They may be very effective in channeling water through the soil, even through unsaturated soils [Aubertin, 1971; *Beasley*, 1976; *Mosley*, 1979, 1982]. The hollows resulting from decaying tree stumps and windblown trees may act as a funneling system, channeling water into a network of macropores formed by the decaying roots. Former grass roots on the other hand may yield a system of more equally sized macropores.

Cracks and fissures. These macropores are formed either by shrinkage resulting from dessication of clay soils [e.g., *Blake et al.*, 1973; *Lewis*, 1977] or by chemical weathering of bedrock material [e.g., *Reeves*, 1980]. Freeze/thaw cycles may also produce cracks and fissures, as will cultivation techniques such as the drawing of mole drains and subsoiling. Shrinking and swelling of clay soils is subject to seasonal variation, depending on changes in soil moisture conditions. Once a crack is formed, it may recur at the same location through a series of wetting and drying cycles. In fact, in drained heavy clay soils, cracks between structural peds may not close, even after prolonged wetting [*Beven*, 1980]. Interpedal macropores may be utilized by roots and soil fauna, and *Reeve et al.* [1980] have demonstrated how soil cracking can be influenced by the pattern of moisture extractions by roots.

Natural soil pipes. Natural soil pipes may form because of the erosive action of subsurface flows, where the forces imposed on individual soil particles caused by the flow exceed the structural competence of the soil [e.g., *Zaslavsky and Kassif*, 1965]. Such conditions generally occur only in highly permeable, relatively noncohesive materials that are subjected to high hydraulic gradients.

A second type of piping has been reported from peaty gleyed podsols in upland Wales [*Jones*, 1971; *Gilman and Newson*, 1980]. These underground drainage networks are of two types. The first exists in former bedrock channels, the peat having grown sufficiently to cover the channel. These pipes may be up to 1-m diameter. The second type occurs extensively on the hill slopes and exhibit complex and irregular networks of pipes within the peaty topsoil of the order of 50-mm diameter. These pipes are thought to be formed as a result of dessication cracking during uncommon dry summers (of the order of 1 year in 20) but have been shown to survive over long periods of time and to conduct considerable amounts of runoff during storms [*Gilman and Newson*, 1980].

Experimental Determination of Macroporosity.

Any experimental technique used to determine soil macroporosity should distinguish between two types of large voids: voids that are hydrologically effective in terms of channeling flow through the soil (our macropores) and those that are not. The concept of hydrological effectiveness in this sense is a somewhat nebulous one, since it has been shown that different numbers and sizes of macropores may be effective under different conditions [e.g., *Bouma et al.*, 1977]. However, channeling implies a degree of continuity and/or connectivity with other macropores that will not be true of all large pores. Techniques that are based on pore size alone, such as the impregnation and sectioning techniques of *Wilkins et al.* [1977] and *Hewitt and Dexter* [1980] will yield an estimate of total macroporosity that is not necessarily closely related to channeling macroporosity. *Bullock and Thomasson* [1979], for example, show that total macroporosity measured from thin sections is poorly correlated to macroporosity measured from equilibrium suction measurements. This is because during the suction measurements, only the pores effectively connected to the sample surface by pore pathways with an equilibrium tension or air entry tension less than the imposed tension will drain, often via a rather tortuous path. Thus the suction plate method may be a better indicator of channeling macroporosity.

Fig. 1. Root channel macropore lined with remains of root bark at a depth of 25 cm, Observatory Hill, Charlottesville, Virginia. In this profile there were at least 12 such channels, mostly vertical, with diameters 3–12 mm, within 5 cm of the face of a 1-m-wide pit.

However, this method also has drawbacks. Since we are implicitly dealing with very low soil tensions, and the sample must have a finite length for the effects of continuity to be apparent, it is often difficult to establish a suitable equilibrium tension throughout the sample. Second, equilibrium measurements can only give an indirect measure of macropores, without any indication of the nature of flow in them.

There is morphological evidence of flow channeling in macropores. Cutans of dislocated and redeposited fine silt and clay particles are often seen around the edges of macropores in thin section [see, for instance, *Banse and Graff*, 1968]. Such cutans frequently have a layered structure and are an indication that water has flowed with sufficient force to redistribute fine particles of sediment. Such particles may have been translocated over considerable distances through macropores. In a study reported by *Pilgrim et al.* [1978] the sediment carried was all in the narrow size range of 4–8 μm and was thought to be derived from material detached by rain splash at the soil surface. The distribution of cutans in the profile may be interpreted in terms of connectivity and ability of the macropores to conduct water [*Fedoroff et al.*, 1981].

Mottling along the edges of macropores may also be interpreted in terms of fast water flow within the macropores. These mottles have been described by *Germann* [1981] along channels of former roots in the B_t horizon of a silt loam soil that receives water from precipitation only and in which no water table occurs (Pseudogley). When the macropores conduct water, lateral infiltration takes place into the surrounding matrix. The infiltration may be sufficient to saturate the matrix in the immediate vacinity for hours, or perhaps days. During this period, anaerobic conditions become established in the saturated fringe, and the iron and manganese sesquioxides are mobilized and transported laterally away from the macropore, leaving a pale zone. After a certain distance, aerobic conditions occur, the sesquioxides are reoxidized and deposited to form a reddish fringe. This process was simulated under laboratory conditions by *Verpraskas and Bouma* [1976].

Several studies have used dyes as tracers to make the preferential pathways of infiltrating water visible. *Ehlers* [1975], for example, described the macropore system produced by worms in this way. *Kissel et al.* [1973] and *Omoti and Wild* [1979] used fluorescent dyes and ultraviolet photography to demonstrate the effective macropores at the profile scale. *Bouma and Dekker* [1978], *Bouma and Wosten* [1979], and *Bouma et al.* [1977, 1979] have gone a stage further in producing thin sections of undisturbed soil cores after applying different amounts of dyed water. A method for the quantitative interpretation of the number, size, shape, volume, and connectivity of the macropores was developed.

All the morphological and tracing experiments described so far are essentially small-scale techniques, suited at best to the study of soil cores. The hydrologist is interested in the hydrological effectiveness of macropores in channeling water flow at the plot, hillslope, and catchment scale. Integrating the information from small-scale experiments over the larger volume of area of interest can be used to estimate the desired information. However, there is evidence that estimates obtained in this way may neglect some large-scale variability. *Murphy and Banfield* [1978] have demonstrated considerable sampling variability of macroporosity estimated from thin sections. *Aubertin* [1971] reported large-scale variability in soil macroporosity in 6-inch cubes taken from 6-foot by 6-foot profiles through a forest soil in Ohio.

A number of different operational definitions of macroporosity have also been used in the past. *Burger* [1922] saturated core samples, weighed them, let them drain for 24 hours on a gravel bed while preventing evaporation, and weighed them again. The volume of the drained water was called the 'air capacity' of the soil. This air capacity will be closely related to effective macroporosity as discussed by *German and Beven* [1981*b*]. This type of drainage procedure has been greatly refined by *Germann and Beven* [1981*a*] in a more controlled experiment using large undisturbed soil samples. Soil moisture tension profiles during drainage were used to differentiate the total effective macroporosity on the basis of capillary potential and to estimate the flow characteristics of the macropore system at different degrees of saturation.

Dynamics of Macroporosity.

Most soils contain macropores of some sort. The volume and structure of the macropore system will represent a dynamic balance between constructive and destructive processes. Any change in the soil-plant-animal community and in external conditions, such as the pattern of weather, will affect that balance.

Weather may have a great effect on the macropore system of a given soil in a number of ways. Drought will cause a clay soil to crack, sometimes to considerable depth, and may cause soil animals to dig deeper to maintain a favorable environment. Extreme soil freezing and frost heave may deepen soil crack but may also reduce the population of soil animals. Surface sealing of silt soils by intense rainfalls is a common occurrence [e.g., *Horton*, 1941; *Morin et al.*, 1981] and will tend to seal the entrance to macropores. Transport of sediment into the macropores may result in partial or complete filling, resulting in reduced hydrological effectiveness. Longer-term climatic changes will also affect the macropore system through its effect on the soil-plant-animal community.

Long-term ecological changes may also have an important effect on soil macropores. The decreasing population of birds of prey and foxes in central Europe over several decades has resulted in an increasing population of rodents, mainly mice. The earthworm population appears to be steadily increasing in the mid western United States [*Hole*, 1981]. There is evidence that earthworms colonizing a virgin soil can spread at rates of 4–10 m/yr [*Van Rhee*, 1969]. In Australia, native and introduced species of earthworms have been widely found, particularly in garden plots, in areas where populations were thought to be negligible [*Abbot and Parker*, 1980].

However, perhaps the most important changes in macroporosity are due to land use. Plowing a soil once or twice a year produces many cracks in the plow layer. Many of these will disappear during the growing season, depending on the mechanical stability of the soil clods. Plowing also cuts the natural macropores and may account for vertical discontinuities in the macropore network. *Ehlers* [1975] found that the number of earthworm channels in the surface layer of a tilled soil was much less than in a comparable untilled area, whereas at 0.6 m the numbers were equivalent. The use of heavy machinery tends to increase the density of the upper soil layers and to destroy macropores. Compaction by grazing animals may also destroy macropores close to the surface and affect infiltration rates [e.g., *Langlands and Bennett*, 1973]. *Slater and Hopp* [1947] reported that protecting soil animals from frost helped to maintain infiltration rates.

The question arises as to how long it takes for a macropore system to develop and how long it might last. Laminar flow theory [*Childs*, 1969] and experimental evidence [e.g., *Germann and Beven*, 1981*b*] suggests that even a small amount of macroporosity can increase the flux density of saturated soil by more than 1 order of magnitude in soils of low to moderate matrix conductivity. Assuming a macroporosity of 0.01, extending to a depth of 0.5 m, then the total volume of macropores would be equivalent to a depth of soil of 5 mm. This may be compared with *Darwin*'s [1881] estimates for an English soil of an annual rate of transport of 5 mm of earthworm casts to the soil surface during a period of 10 to 20 years following a distinct reduction in land use intensity. *Graff and Makeschin* [1979] calculated an accumulation rate of 25 kg m^{-2} a^{-1} (about 15 to 20 mm a^{-1}) of fine soil materials at the surface of a meadow in north Germany as a result of soil animals. *Stöckli* [1928] estimated an annual accumulation of 5 mm/yr transported by earthworms in Switzerland. Other estimates for accumulation by earthworms have ranged up to 26.8 kg m^{-2} a^{-1} [see *Edwards and Lofty*, 1977. p. 144]. Russian investigators have reported between 1 and 12 mm/yr, mainly due to moles (*Talpa europea*) [*Abaturov*, 1968; *Voronov*, 1968; quoted by *Graff and Makeschin*, 1979]. For a clay soil, *Nemec* [1976] reported that the apparent hydraulic conductivity continued to increase for several years following the laying of pipe drainage.

Several observations and estimates of the age of macropore networks are reported. *Green and Askew* [1965] for example considered the age of ant-developed macropore systems to be one of several hundreds of years. *Mellanby* [1971] suggested that where food is readily available mole runs may be hundreds of years old and may not be apparent from the soil surface. Our own observations suggest that macropores formed from the roots of trees may last at least 50–100 years in a soil containing about 30% clay. The effective lifetime of macropores may be assumed to increase with stability of the soil structure, which is in itself a function of soil texture and the composition of organic matter.

Thus it is possible that macropore systems may be produced, at least under favorable circumstances, within 1 to 2 years and may last for considerable periods of time. On the other hand the effectiveness of the macropores can be destroyed within one rainstorm by the in washing of material detached by rain splash. We may assume that, under comparable conditions, the most effective macropore systems will occur at relatively undisturbed, usually forested, sites and that intensive land use may show the lowest macroporosity.

MACROPORES AND INFILTRATION

Experimental Evidence

The presence of macropores close to the surface of the soil may be particularly important in the process of infiltration of rainfall and solutes into the soil. Figure 2 offers one simplified view. Three stages of flow may be expected.

$$P(t) < I_1(t)$$

All water arriving at the surface is absorbed by micropores connected to the surface.

$$I_1(t) < P(t) < I_1(t) + S_1(t)$$

During this period, surface runoff on small scale may take place. Both macropores and micropores open to the soil surface take up water simultaneously. As soon as there is a significant flow into the macropores, flow down the walls will also start ($S_2(t) > 0$) and lateral infiltration into the matrix will be initiated ($I_2(t) > 0$). These lateral losses will temporarily reduce the macropore flow S_2 and the depth of penetration of water along the walls of the macropore. The flow of water in the macropores can greatly increase the surface area available for infiltration into the matrix in this way.

$$P(t) > I_1(t) + S_1(t)$$

Significant amounts of water will begin to be stored at the soil surface, and overland flow will start on a large scale ($O(t) > 0$). Note that all the symbols represent volume flux densities.

Direct infiltration into the macropores can be neglected during the first stage, since they contribute very little to total surface area. The second and third stages, on the other hand, suggest a process that will not be adequately described by approaches to infiltration based on Darcy's law, since assumptions of homogeneity of hydraulic properties of the soil over some representative cross-sectional area will no longer be valid. Water fluxes may vary several orders of magnitude over distances of only a few centimeters, and hydraulic gradients may no longer be properly defined for the soil as a whole. Any flow concept based on an 'average' hydraulic gradient may be expected to fail. There is some justification for this view from comparisons of the results of mathematical models based on Richards' equation with experimental data [e.g., *Rogowski and Weinrich*, 1981]. *DeVries and Chow* [1978] reported that the potential field during infiltration into a highly porous forest soil in British Columbia developed so irregularly that it could not be used for calculations of Darcy-type infiltration. However, during redistribution and drainage, this irregular pattern of hydraulic potentials changed gradually toward a more regular one. *Bouma et al.* [1980] found similar results in a cracked heavy clay soil in Holland, where predicting the height of the water table in the profile with unlined auger holes failed completely. They concluded that the response of the water table in the auger holes was governed primarily by flows in the cracks, whereas the tensiometers indicated hydraulic potentials within the rather impermeable clay peds.

Heterogeneity of flow has also been observed during and shortly after infiltration of heavy storms into the soil of a large weighing lysimeter [*Germann*, 1981]. It was found that fast-moving water required between 1 and 2 days to reach the bottom of the lysimeter at a depth of 220 cm, whereas based on isotope measurements, slower-moving water had a residence time of about 6 months. The velocity ratio of the modes of flow was between 100:1 and 400:1. *Ligon et al.* [1977] also found that two peaked tritium profiles developed during long-term studies of vertical water translocation in soils in South Carolina, a result they interpreted in terms of the effects of macropore flows. *Blume et al.* [1966] and *Blake et al.* [1973] also used tritium to trace infiltrating water. Both

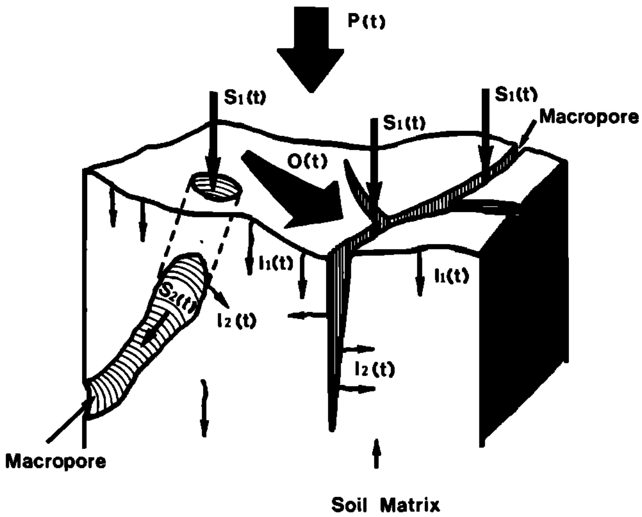

Fig. 2. Definition diagram for water flows during infiltration into a block of soil with macropores. $P(t)$, overall input (precipitation, irrigation); $I_1(t)$, infiltration into the matrix from the surface; $I_2(t)$, infiltration into the matrix from the walls of the macropores; $S_1(t)$, seepage into the macropores at the soil surface; $S_2(t)$, flow within the macropores; $O(t)$, overland flow [after *Germann*, 1980].

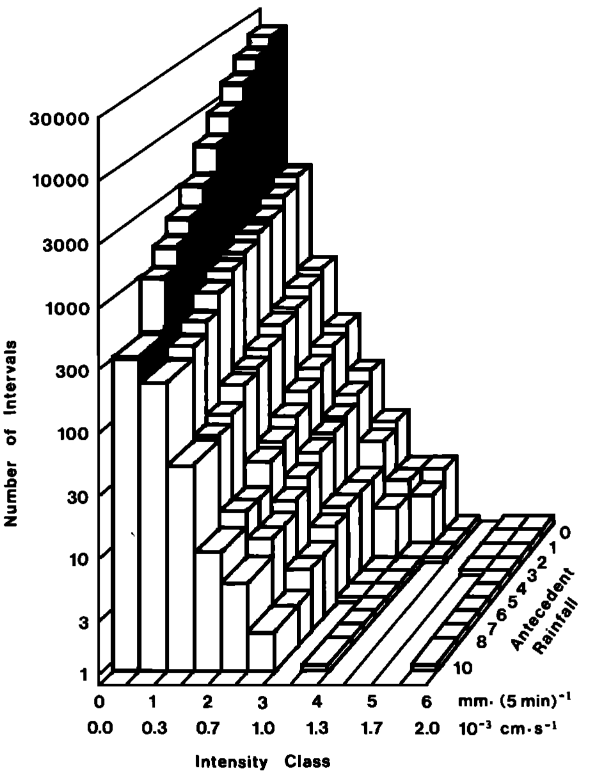

Fig. 3. Cumulative frequency distributions of 5-min rainfall intensities for different classes of antecedent rainfall in the preceding 2 hours. Derived from all 5-min intervals with rainfall from December 1975 to December 1979, Rietholzbach experimental basin, Switzerland [after *Germann*, 1981].

studies concluded that some water was channelled along macropores, since the experimental results differed markedly from Darcian theory.

Laboratory-measured breakthrough curves of undisturbed soil columns show these effects particularly clearly [*Kissel et al.*, 1973; *McMahon and Thomas*, 1974; *Anderson and Bouma*, 1977*a*, *b*; *Kanchanasut et al.*, 1978]. *Miller et al.* [1965] showed that intermittent applications of water were more efficient in removing chloride from a Panoche clay loam than an equal amount of water applied by continuous ponding. This can be explained by the more continuous flow through macropores that would be generated by ponding and that would bypass most of the soil volume. An essential contribution of macropores to infiltration was also concluded by *Wild and Babiker* [1976], based on assymetric nitrate and chloride concentration profiles observed after irrigation of agricultural soils in England. The ions were transported deeper and faster along macropores than could be explained by miscible displacement theories. This has also been demonstrated by *Tyler and Thomas* [1978] in lysimeter pans inserted in otherwise undisturbed soils in Kentucky. Similarly, in leaching experiments in the drainage gauges at Rothamsted, U.K., *Addiscott et al.* [1978] showed that added chloride was sorbed mainly in the soil matrix but transported substantially in the macropores.

Dyes and salts have also been used to stain pores and mark the pathways of water movement during infiltration. *Bouma and Wösten* [1979], for example, interpreted stained pores in thin sections to indicate the macropores contributing to flow under different application rates. Fluorescent dyes have been used to show that root channels in forest soils are important pathways for infiltrating water, as demonstrated by *Áubertin* [1971] in Ohio. Similarly, *Reynolds* [1966] in England showed that, close to trees, stem flow would infiltrate preferentially along both living and dead root channels. In an agricultural soil, *Omoti and Wild* [1979] concluded, on the basis of cross sections of dyed soil photographed under ultraviolet light, that there may be preferential movement of channeling of flows through pores much smaller than what would normally be considered as a macropore. We have been involved in recent experiments using alizarin red dye and potassium bromide to trace infiltrating water in a nontilled cornfield soil. Decaying corn roots were shown to be important channels for water movement. The same study also demonstrated that for some macropores Br^- concentrations were higher near the macropore/matrix interface than the average concentration of the whole soil layer, whereas in other cases the opposite was found. This suggests that the latter macropores may not have been as effective in contributing to flow.

Less information is available on the precipitation rate at which water flow in macropores may be initiated. Omoti and Wild suggest that

> . . . there is more movement down large channels under irrigation (application rates 5 to 8 mm.h^{-1}) than under winter rainfall (mean rate during rain of 0.7 to 1.5 mm.h^{-1})

Topp and Davis [1981] used time-domain reflectometry to measure changes of soil moisture in thin layers parallel to cracks of heavy clay soils and demonstrated clearly that water contents increased much faster close to the crack than at some distance from it. They also concluded that '...more than 1 cm of rainfall at rates greater than 0.1 cm.h^{-1} contributed water to the soil cracks.'

These data would suggest, therefore, that rainfall intensities of 1–10 mm h^{-1} may be sufficient to initiate macropore flows, depending on the antecedent precipitation. We may use this information to estimate the frequency of natural rainfalls that produce macropore flows. As an example, *Germann* [1981] analyzed a total of about 30,000 5-min time intervals with rainfall recorded in the Rietholzbach catchment in Switzerland. The data are summarized in Figure 3 in terms of number of intervals with a given intensity and antecedent rainfall in the previous 2 hours. Applying a simple threshold for macropore flow of 1.5 10^{-6} m s^{-1}(5 mm h^{-1}) from the limit given by Omoti and Wild, all the unshaded classes in Figure 3 might be expected to generate macropore flow (about 3% of the total). Depending on the antecedent precipitation, many of the shaded intervals may also generate macropore flows. The rapid change in number of intervals with antecedent rainfall in this (shaded) region would suggest a great sensitivity in the frequency of macropore flow to rainfall intensity and antecedent rainfall totals. A rigorous frequency analysis must await more information on the conditions under which macropore flows are generated for a given soil.

Macropores may make up only a small portion of the total soil voids but may dominate vertical flow rates during infiltration under some conditions. A theoretical relationship between saturated flow rates and macroporosity may be derived by assuming that macropore flow is analogous to laminar Poiseuille flow through vertical tubes [e.g., *Childs*, 1969] such that

$$Q_s \ \alpha \ E_{ma}^2$$

where Q_s is the saturated flux density of the macropores and E_{ma} is the porosity of the macropore system.

Germann and Beven [1981*b*] showed that this relationship adequately described the data on macropore flows of *Burger* [1940] and *Ehlers* [1975] but that the constant of proportionality varied over a large range (0.033 to 40 m s^{-1}). *Ranken*'s [1974] data for forest soils in Oregon would suggest that the exponent may also deviate significantly from 2. Thus it appears that this relationship will be of little predictive value. One extreme value of macropore flux has been reported by *Peterson and Dixon* [1971], where they measured, for a single macropore of 6-mm diameter, an average flux of 0.5 m s^{-1} with a corresponding Reynolds number of about 3000, suggesting turbulent flow. These authors also reported that the opening of a single macropore increased the infiltration capacity of a particular 1.35 m^2 plot from 1.7 to 2.8 10^{-5} m s^{-1} (6 to 10 cm h^{-1}), even though the pore space available for infiltration increased by only 0.002%. Ehlers' observations showed that infiltration rates into single worm holes were in the range of 0.001 to 3.033 m s^{-1}. The increase in infiltration rates with sample size, described by *Ritchie et al.* [1971] and *Kissel et al.* [1973], emphasizes the importance of the connectivity of the macropore system over large soil volumes on the effectiveness of the macropores during infiltration.

Not all the effects of macropores on infiltration are included in Figure 2. Where high input rates are applied over large areas of soil, air entrapment under ponding may exert a considerable influence on infiltration rates. *Dixon and Linden* [1972] and *Linden and Dixon* [1973] reported that an internal air pressure of about 2.0 kPa (20 mbar) decreased infiltration rates by a factor of 3. *Linden and Dixon* [1976] found an even more drastic reduction in infiltration rates, from 1.1 10^{-4} to 8.3 10^{-6} ms^{-1} (40 to 3 cm h^{-1}), as a result of an internal air pressure of only 0.5 kPa (5 mbar). In such cases, macropores may provide important pathways for the escape of air. This idea has been stressed in the 'channel concept' of infiltration of *Dixon and Peterson* [1971]. They cite both the connectivity of the macropore network with the soil surface and the roughness of the surface in controlling infiltration rates.

One consequence of the concepts summarized in Figure 2 is that the same volume of water applied at a higher intensity may run deeper into the profile along the macropores. There is some indirect evidence to support this. *Anderson and Bouma* [1977*a*, *b*], for example, demonstrated that the apparent dispersion coefficient of infiltrated chloride solution was decreased drastically when the infiltration rate was reduced from unlimited (8–11 cm d^{-1}) to about 10^{-7} ms^{-1} (1 cm d^{-1}). Higher initial moisture contents in the soil may also allow deeper penetration along the macropores by reducing the lateral losses (I_2). *Quisenberry and Phillips* [1976] showed that higher initial moisture contents resulted in infiltrated water reaching much greater depths in the soil profile, a result that they interpreted as being due to flow through large pores.

Some attempts have been made to relate soil hydrological properties to morphometric information on soil voids, macropores in particular, from soil thin sections. The saturated hydraulic conductivity of the soil was estimated from such data by *Anderson and Bouma* [1973], *Bouma and Wösten* [1979], and *Bouma et al.* [1979] for different soils in the U.S. and The Netherlands. *Bouma and Denning* [1974] related morphometric data with the hydraulic conductivity/water content relationship by interpreting the size distribution of active pores under different flow conditions. The movement and dispersion of salts measured from breakthrough curves have also been related to morphometric data by *Anderson and Bouma* [1977] and *Bouma and Wösten* [1979]. Such methods may be very important to understanding the flow of water through macropores at the microscale. However, the problems of sampling would suggest that they may be of limited use in predicting the effects of macropores on infiltration at the field scale.

Theoretical Studies

The experimental evidence cited above strongly suggests that theories of soil water flow that treat the soil as a relatively homogeneous porous medium conforming to Darcian principles may not adequately describe the infiltration and redistribution of water where the soil contains macropores. Thus we may expect that predictions based on Darcy's law may be significantly in error when the macropores conduct significant amounts of water. However, any improved theoretical structure cannot reject traditional approaches, since models based on Darcy's law have been well proven in the past [see, for example, *Haverkamp et al.*, 1977; *Zaradny et al.*, 1978; *Bresler et al.*, 1979].

This suggests the introduction of a domain concept to model combined macropore/matrix systems, with the matrix as one domain that can be described by hydraulic principles based on Darcy's law and the macropores as a second domain. A description of interaction between the domains would then complete the model. The use of a domain concept to model large/small pore systems is not new and dates back at least to *Muskat* [1946], who discussed saturated flow in fissured limestone. More recently, domain concepts have been applied to flows through snow [e.g., *Wakahama,* 1974], flow through saturated rocks and soil with fractures or macropores [e.g., *Duguid and Lee,* 1977; *Scotter,* 1978], and flows through aggregated porous media [e.g., *Phillip,* 1968].

The important feature of domain models in the current context is that as well as allowing different flow characteristics for the two domains, different potential gradients can also be specified. Of course, there is nothing special about two domains. One can envisage a further level of complexity in which macropores interact with both interaggregate capillary pores and intraaggregate porosity. Interacting flows of water and air could also be included. However, increasing the number of domains increases the complexity of the interactions that must be specified and is, as yet, not justified by the experimental data available for field soils.

Returning to a two-domain macropore/matrix model, there are a number of important components to be specified in a complete model. The models available to date differ in the handling of each component, and some general discussion is in order before a detailed comparison is made. The following components can be identified:

1. *The nature of flows in the matrix domain.* Flow in the matrix may be modeled to a good approximation by Richards' equation based on Darcy's Law [*Richards,* 1931]. However, in soils with macropores, continuity of the matrix space cannot necessarily be assumed, so that boundary conditions for the flow equation may be extremely complex. All domain models have necessarily relied on extreme simplifications of the geometry of the aggregate, fracture or macropore systems to specify the boundary conditions.

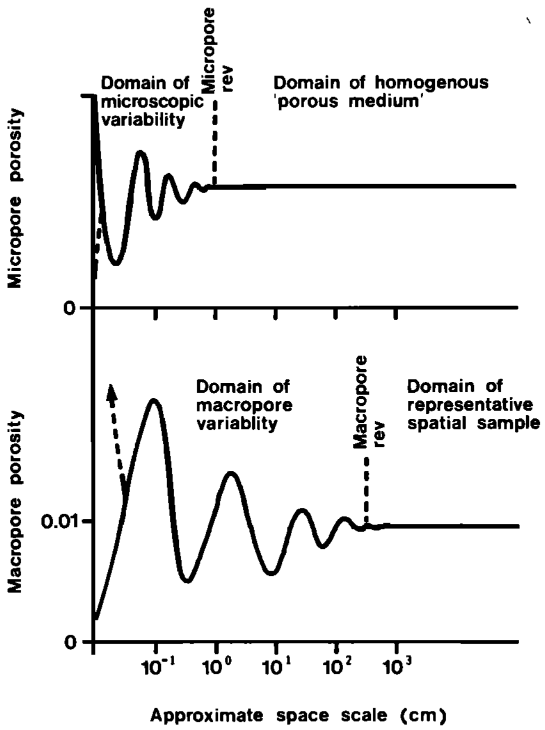

Fig. 4. The variation of porosity with spatial scale and the definition of representative elementary volume (rev) [after *Beven and Germann,* 1981].

Choosing a representative geometry will depend on what type of macroporosity is important (e.g., root channels or dessication cracks) and may require some detailed experimental work. Flow in the matrix may be subject to hysteresis and air pressure effects that are often ignored.

2. *The nature of flows in the macropore system.* Little is known about the hydraulics of flow in either single macropores or macropore networks. It is known that macropores may conduct considerable quantities of water without being saturated [e.g., *Bouma and Dekker,* 1978] and that unsaturated flows may take place as discrete 'rivulets' along the sides of the macropores [*Bouma et al.,* 1977]. Staining experiments have shown that not all large voids conduct water, even under essentially saturated conditions [e.g., *Bouma et al.,* 1977]. Flow may often be laminar in macropores, but they are not generally smooth sided, and this will tend to channel flows under unsaturated conditions and hasten the transition of quasi-turbulent or turbulent flow conditions. Flows in irregular macropore networks may be subject to 'necking' effects [*Bouma et al.,* 1977] and may be under high input rates to air pressure effects [*Linden and Dixon,* 1976].

3. *The spatial and temporal characteristics of the macropore network.* Any theoretical analysis of flow in macropore systems must provide some means of handling the inherent spatial variability of macropore networks. In any field soil there is likely to be a distribution of macropore sizes with varying degrees of irregularity and connectivity. Any useful model must then, in some way, integrate the effects of the macropore system as a whole. Exploration of conditions around a single macropore will yield insight but will not ultimately prove useful as a predictive model, except for some very simple network geometries. This need for integration gives rise to scale problems in that if we wish to apply a continuum approach to the macropore network, the scale of lateral variability (or 'representative elementary volume') for the macropores may be much larger than for the intervening micropores (see Figure 4). The additional temporal variability of the macropore network gives rise to problems about which there is very little information (see section on experimental determination of macroporosity). Some types of macropores will change size and shape on a time scale of minutes or hours, there will certainly be important seasonal effects in many soils; while some biotic channels may be relatively stable for many years [e.g., *Green and Askew,* 1965; *Mellanby,* 1971].

4. *Interaction between the domains.* Interaction between the domains will depend on the supply of water within the macropores and the hydraulic conditions within the matrix. Water may move either from the macropores to the matrix or, if the matrix is saturated and the macropores not, in the opposite direction. The surfaces and hydraulic gradients involved in the interaction process will depend on the structural geometry of the combined system, the time available for interaction, and the flow geometry in the macropores, since under unsaturated conditions, not all the macropore surfaces may be wetted.

5. *Initiation of flows in the macropores.* Initiation and maintenance of flows in the macropore system requires a supply of water exceeding all losses to the matrix. During infiltration, this will most commonly occur at the soil surface, when the infiltration capacity of the matrix is exceeded. Note that not all macropores may be connected directly to the surface and that, particularly under vegetation canopies, the local variability of supply to the surface caused by stem flow and drip may be important in generating local 'infiltration excess' [e.g., *Horton,* 1919; *Specht,* 1957]. Even then, the initiation of macropore flow may, in a similar manner to surface runoff, be very dependent on local surface roughness such that some storage at the soil surface must be filled before macropore flow starts. Indeed, positive pressure in the soil matrix above a wetting front may serve to supply water to macropores by means of subsurface interaction. These are all factors that will lead to a dependence of macropore flow on antecedent precipitation.

There are four models of infiltration currently available that take account of the effect of macropores. None of them are entirely satisfactory on all five criteria discussed above. The model of *Kutilec and Novak* [1976] does not consider the nature of flows in the macropores, only the way in which their volume and surface area may influence infiltration rates. The model of *Edwards et al.* [1979] considers only the effect of single cylindrical macropores on the infiltration rate into small vertical cylinders of soil and uses a very simplified characterization of the progress of wetting in the macropore. The model of *Hoogmoed and Bouma* [1980] includes an important innovation whereby the way in which the wetted surface area in the macropores changes over time is accounted for. The relationships for surface wetting used in the model were based on the detailed experimental work of *Bouma and Dekker* [1978]. However, this model still uses only a simplified accounting procedure for the calculation of flows within the macropores. The model of *Beven and Germann* [1981] uses laminar film flow assumptions to derive a relationship between moisture content and flow characteristics in a distribution of vertical macropores. This

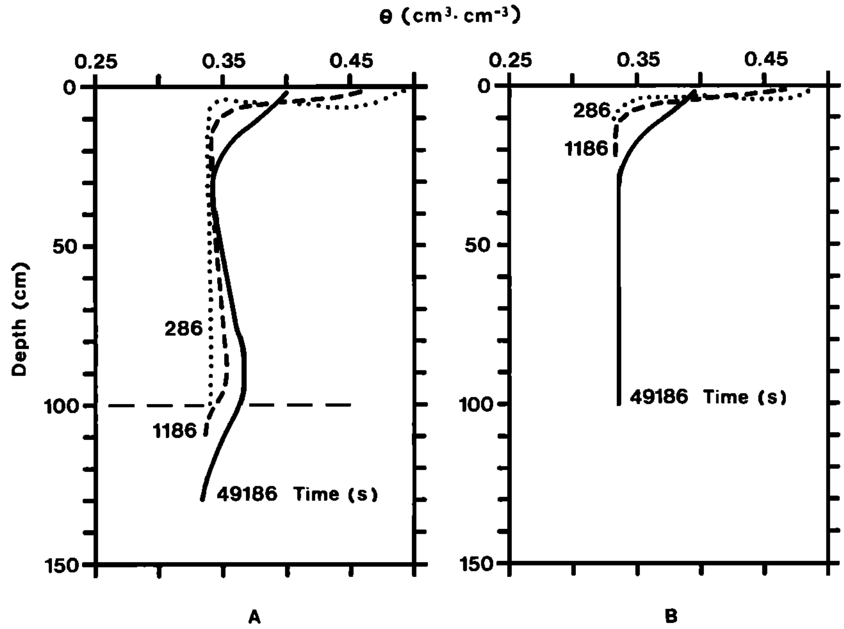

Fig. 5. Results of numerical simulations of infiltration, resulting from a storm of 2.5 x 10^{-4} ms^{-1} for 266 s; A, with macropores; B, without macropores [after *Beven and Germann,* 1981].

mode, however, uses a very simple description of the interaction between macropores and matrix. Only one of these models (that of Hoogmoed and Bouma) has been compared with experimental data, and that in only a simple way. The model predicted combined macropore/matrix drainage at the base of a 0.2-m profile with reasonable accuracy in three experiments.

The results of the model simulations suggest that the presence of macropores at the soil surface always serves to increase infiltration rates because additional surfaces are made available for infiltration into the matrix at depth. The effect of the macropores is dependent on the spacing between large pores, the pattern of rainfall intensities, and the hydraulic characteristics of the matrix. The effect will be greatest in soils with hydraulic conductivities of the matrix somewhat lower than average rainfall intensities. With higher conductivities, all the rainfall infiltrates anyway. With low conductivities, little water infiltrates into the micropores, and the main effect of the macropores is to increase the volume of storage that must be filled before surface runoff is initiated *[Beven and Germann,* 1981]. If the macropores fill with water above a depth of which flow rates become limited, then characteristic water content profiles showing a bulge at depth may develop (Figure 5). There is some experimental evidence to support the simulations in this respect (Figure 6 at time t_1, between depths of 1.0 to 1.2 m).

A number of problems remain to be solved in defining, calibrating, and validating an adequate model of a combined macropore/matrix system. The attempts at modeling made so far have served to highlight the lack of experimental data on the nature of macropore flows, the structure of macropore systems, and the interactions between macropores and the matrix. Until such data become available, both for single macropores and for complete networks, such models cannot be considered as more than exploratory hypotheses, nor, more importantly, can they be validated.

MACROPORES AND SUBSURFACE STORMFLOW

Experimental Evidence

It is now commonly accepted that in many catchments the magnitude and shape of the storm hydrograph is dominantly controlled by subsurface flows. Evidence for this comes from areas where little or no overland flow is observed [e.g., *Hursh and Brater,* 1941; *Roessel,* 1950; *Hewlett and Hibbert,* 1963, 1967; *Mosley,* 1979] and from hydrograph separation techniques based on the chemical characteristics of rain, soil, and groundwater that suggest that prestorm water may make up a significant proportion of the hydrograph peak [e.g., *Pinder and Jones,* 1969; *Martinec,* 1975; *Sklash and Farvolden,* 1979, *Herrmann and Stichler,* 1980]. Of course it is not necessary that all the prestorm water reaches the stream by subsurface routes. Some may exfiltrate in areas of surface saturation as return flow and flow to the stream over the soil surface [*Dunne and Black,* 1970; *Dunne,* 1978].

If macropores are effective in transmitting flow to the stream channel, they may do so at velocities of the same order as overland flows. This is, however, only one of the mechanisms that might account for a rapid subsurface flow response to storm rainfall. *Hewlett and Hibbert* [1967] suggested the term 'translatory flow' to describe a mechanism by which new water entering the saturated zone on a hill slope causes a displacement of old water at the base of the slope. This is due to rapid, wavelike transmission of the pressure changes at the boundary of the saturated zone. Air pressure effects beneath an advancing wetting front have also been quoted as causing a rapid response of the saturated zone and restricting infiltration into larger pores [*Linden and Dixon,* 1973, 1975; *Dixon and Linden,* 1972]. However, this mechanism requires that no open pathways be available for the escape of air to the soil surface. It is therefore necessary that the input of water at the surface be sufficient to saturate the surface over distances of perhaps tens of meters in

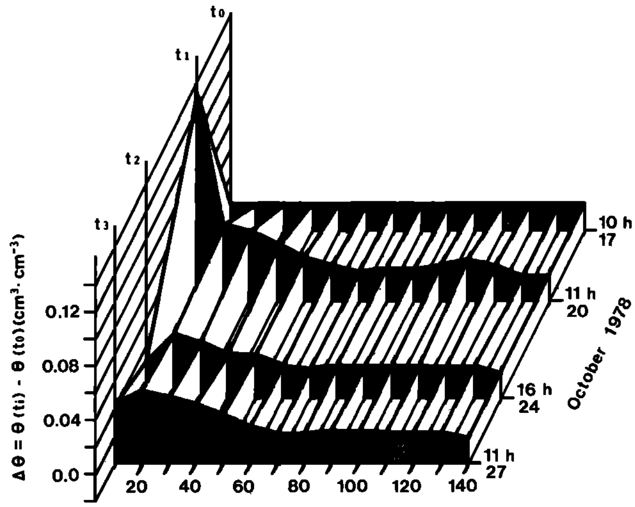

Fig. 6. Changes in water content of the upper 140 cm of a weighing lysimeter (t_0 = 1000, 17.10.78) [after *Germann*, 1981].

horizontal extent. The importance of this process in the field under natural rainfalls has yet to be assessed properly.

The response of the subsurface flow system as a whole will also depend on the lag in the unsaturated zone. If the saturated flow is close to the surface, this lag will be short. If macropores are effective in transmitting water rapidly to depth, this lag will be short. The lag may be short in some soils because where a significant capillary fringe has developed over a water table prior to the onset of rainfall, only very small additions of water are required to convert the capillary fringe to a zone of positive pressure, with consequent rapid changes in the boundary conditions of the saturated zone. In this case the velocity of the leading edge of the wetting front, or the flow of small quantities of water in macropores, may assume particular importance. This mechanism of rapid response has been stressed by Sklash and Farvolden as an important factor in the generation of subsurface stormflow in some catchments.

For purposes of the present discussion we shall divide studies of subsurface stormflow reported in the literature into two broad categories. In the first, explanations have been largely based on traditional concepts of soil water movement. Responses may be very rapid [e.g., *Hursh and Brater,* 1941; *Roessel,* 1950; *Ragan,* 1968; *Harr,* 1977; *Sklash and Farvolden,* 1979; *O'Brien,* 1980] or very slow [e.g., *Hewlett and Hibbert,* 1961, 1967; *Weyman,* 1970, 1973; *Anderson and Burt,* 1978], depending on the soil characteristics, antecedent moisture conditions, and depth to the water table or a relatively impermeable horizon. There is a second category in which the authors have cited flow through soil macropores as being important in the generation of subsurface stormflow. This has either been inferred from the extreme rapidity of the subsurface response or directly from observations of flow in large pores. This group of studies will be discussed in more detail and are summarized in Table 2. Note that these two categories cannot be considered mutually exclusive. Responses involving macropores may also involve any of the other mechanisms discussed in the previous section. Responses explained by traditional Darcian concepts may also involve flow through macropores—at least in the saturated zone.

There are two important ways in which the presence of macropores may give rise to responses that differ from predictions based on Darcian principles. The first is when they conduct water rapidly through unsaturated soil ahead of the wetting front in the soil matrix. The second is when flow in the macropores is quasi- or fully turbulent in either the saturated or unsaturated zones.

The role of macropores in vertical infiltration has already been discussed above. There is ample evidence, however, that macropores may also conduct water laterally downslope through otherwise unsaturated soils. For this to be an important mechanism in the supply of water to streams and consequently in the generation of subsurface stormflow, there must be a supply of water to the macropores in excess of lateral losses to the surrounding soil, as discussed above for the infiltration case. In addition, the macropore system must have a sufficient degree of connectivity to transmit water for some distance downslope or at least to a saturated zone that contributes to streamflow. The movement of water in macropores through unsaturated soil has been observed to take place over considerable distances and at high velocities [e.g., *Aubertin,* 1971; *Beasley,* 1977; *Mosley,* 1979, 1982].

Perhaps the most comprehensive study of flow rates through macropores on hill slopes has been reported by *Mosley* [1982]. He carried out a series of experiments at 51 sites in South Island, New Zealand, At each site a trench was dug along the contour down to bedrock (1–1.5 m), within which a collecting trough was built. A l-m length of perforated gutter was placed 1 m directly upslope of the pit and was used as a line source for the input of water. The aim was to

TABLE 2. Studies of Subsurface Stormflow, Quoting Macropore Flows

Area	Reference	Type of Experiment and Macropores
Japan	*Tsukamota* [1961]	plot, artificial rain
Ohio, USA	*Whipkey* [1965, 1967] *Aubertin* [1971]	plots, artificial rain, root channels, cracks, macroorganism pathways
British Columbia	*Chamberlin* [1972] *Feller and Kimmins* [1979]	catchment response, natural rains, forest floor, root channels
Canada	*DeVries and Chow* [1975] *Utting* [1979]	plots, artificial and natural rainfall, forest floor
Powys, Wales	*Jones* [1971, 1978] *Gilman and Newson* [1980]	hill slopes, natural rainfalls, natural pipes in peat
Somerset, England	*Weyman* [1974]	small catchment, natural rainfalls, natural pipes in peat
Yorkshire, England	*Arnett* [1974]	hill slope, natural rainfalls, bracken rhizomes
Mississippi, USA	*Beasley* [1977]	hill slope plots, natural rains, root channels.
California, USA	*Pilgrim et al.* [1978]	plot, natural and artificial rain, root and animal channels
New Zealand	*Mosley* [1979, 1982]	plot and catchment response, natural rain and ponded infiltration, root channels
Oxford, England	*Beven* [1980]	large plot, natural rain and sprinkling, cracks in heavy clay soil

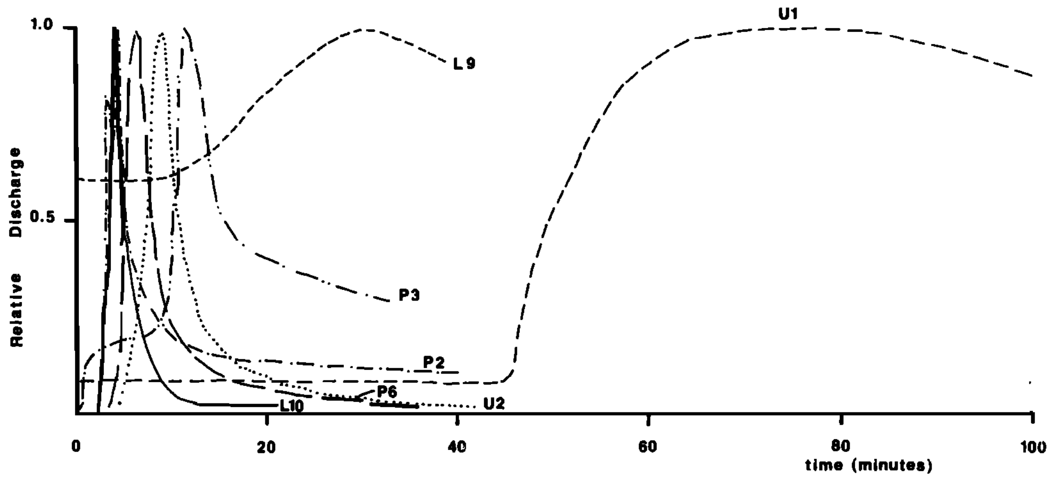

Fig. 7. Results of tracing experiments in forest soils with macropores (see text for details) [after *Mosley*, 1982].

determine the velocity of water moving downslope rather than the rate of infiltration over the 1-m^2 area upslope of the pit. Some representative outflow hydrographs are shown in Figure 7, and flow velocities are compared with other estimates in Table 3. The ratio of outflow volume to input volume ranged from 0 to 0.49. For purely subsurface responses where some water was collected, the time lag between the centroids of input and output ranged from 0.8 to 30.5 min.

Mosley notes that some of the variability in response was due to different durations of water application but that there remains a high degree of variability between sites with similar cover conditions. There was little or no relationship between outflows and soil depth, slope angle, bulk density, and antecedent precipitation. He suggests that

> assuming that the vertical faces are acceptable samples of the whole soil profiles, the observations show that there are preferred pathways for flow along cracks and holes in the soil and roots, both live and dead. Some features from which water flowed are 3-4 mm in diameter, but most were on the order of a few tenths of a millimeter.

It is clear that under these experimental conditions water can move downslope through macropores very rapidly, under both saturated and unsaturated conditions. Mosley demonstrates that saturated flows, generally at the base of the soil profile will be most important in the generation of subsurface stormflows. He suggests that because of large spatial variability in soil depth and antecedent moisture conditions, local saturated wedges may develop soon after the onset of rainfall in some areas. Similar variability in flow rates and observations of preferred pathways have been noted by *Weyman* [1970] under natural rainfall conditions at the base of a brown earth profile in the East Twin catchment in England.

In summary, it is likely that a variable zone of saturation at the base of the soil profile, or above a relatively impermeable horizon, will dominate lateral macropore flows through unsaturated soil in generating subsurface stormflows. However, the time delay in the unsaturated zone may dominate the timing of the subsurface hydrograph. A lot more experimental work is required to specify the conditions under which macropore flow is important in the unsaturated zone.

While a number of studies reviewed here reported macropore flow through unsaturated soil under natural rainfall conditions, the majority of studies have utilized relatively high artificial rainfall rates or a line source input. Some caution in interpretation of the results is therefore in order. High application rates must increase the probabiltiy of macropore flow and consequent fast responses.

In the saturated zone, fast response will depend on steep slopes and high hydraulic conductivities caused by macropores. The lateral connectivity of the macropore network is less important in the saturated zone, provided that in any cross section there are sufficient large pores to maintain a high saturated permeability. Where there is a high degree of connectivity, however, there may be considerable channeling within saturated flows. An example is reported in a study of the transport of the bacterium *Escherichia coli* through forest soils in Oregon by *Rahe et al.* [1978]. At some sampling locations, flow velocities in excess of 4.2 10^{-3} ms^{-1} (15 mh^{-1}) were indicated, whereas other sampling points nearer the injection site were initially bypassed and did not record the presence of the bacterium until much

TABLE 3. Recorded Macropore Flow Velocities

Reference	Maximum Velocity, ms^{-1}	Mean Velocity, ms^{-1}	Minimum Velocity, ms^{-1}
Mosley [1981] (Flow observation, excluding cases with overland flow)	0.0–0.0208	0.0–0.0098	
Aubertin [1971] (Flow observation)	0.00508		
Beven [1980] (Tracer experiment, may include some displacement)	0.005		
Pilgrim et al [1978] (Flow observation)			0.00025
Beasley [1977] (From lag time of hydrograph)	0.00925		
Whipkey [1965] (Flow observation)	0.00085		
Newson and Harrison [1978] (Tracer experiments in natural pipe)		0.06–0.2	

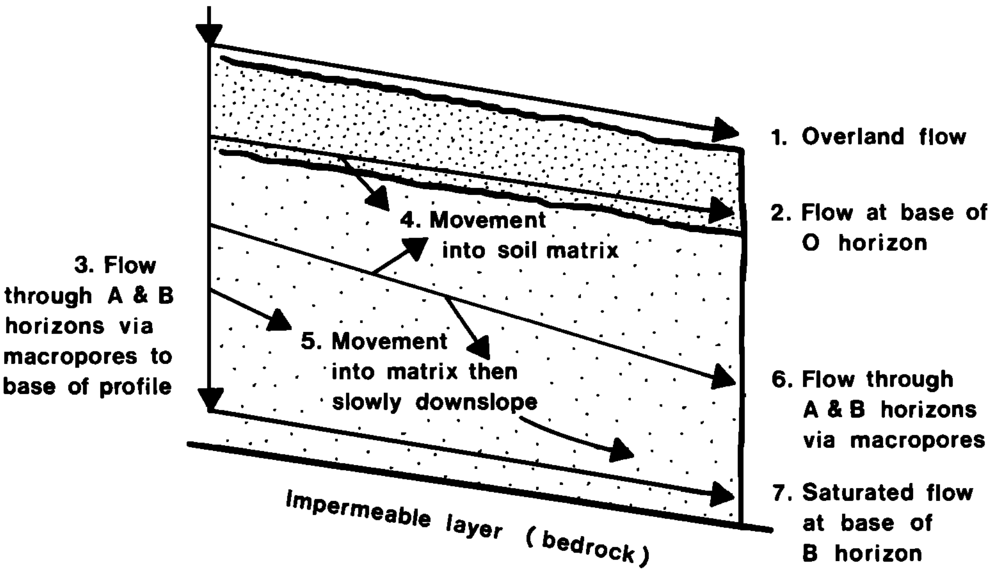

Fig. 8. Flow paths for the movement of water through a shallow forest soil with macropores (after *Mosley*, 1982].

later. On the other hand, long periods of saturation are not conducive to macropore development, except by eluviation and piping processes. Saturation inhibits the activity of animals and roots and will tend to lead to a breakdown of soil structure. Thus the role of macropores in increasing the hydraulic conductivity of the saturated zone may be largely limited to depths where saturation is an ephemeral phenomenon.

Theoretical Approaches

There have been no significant theoretical advances in modeling hill slope flows that involve macropores. It is clear from the experimental evidence that constructing such a model would not be a trivial exercise. Even using a two-domain concept similar to the infiltration case, the multiplicity of flow paths that water can take downhill (e.g., Figure 8) would make specification of interactions between macropores and matrix very complex. As a first approach it would be possible, in principle, to decouple the problem into one or more vertical unsaturated flow components similar to the combined macropore/matrix models of Hoogmoed and Bouma or Beven and Germann and one or more lateral saturated flow components. If it is assumed that both macropores and matrix must be saturated before significant lateral flow can take place, then a relatively simple model of lateral flow based on Darcian principles could be used.

In fact a very similar model with one vertical unsaturated flow component has already been used by *Colbeck* [1974] in modeling flow through a ripe snowpack overlying an impermeable bed. Colbeck assumed that capillary tension could be neglected in the unsaturated zone and used kinematic wave routing in both vertical and lateral components. *Beven* [1981] has shown that the kinematic flow equations can also be used to model saturated lateral flow through soils to a good approximation under certain conditions. However, there would be some problems in applying an extension of Colbeck's model to the case of subsurface stormflow, primarily resulting from the coupling between the vertical and lateral solutions. For the case of coarse-grained, high-conductivity, ripe snow, Colbeck was able to use an assumption of a constant effective porosity in the solution of the saturated flow component. For the case of soil on a hill slope, variations in storage deficit with depth and distance downslope must be taken into account.

At the current time, attempts at modeling subsurface stormflows involving macropores must be highly speculative. Until we have more experimental information on macropore flows, the best purpose that theorectical modeling (and this review) can serve is to point to the type of data required. However, there is no doubt that the problem of rapid subsurface flows on hill slopes have important practical implications, particularly in the geochemical interactions that take place during storm periods, and also in the spread of pollutants. The latter problem is already receiving some attention [e.g., *Steenhuis and Muck*, 1980], with the rapid flows being modeled indirectly by assuming a limited amount of interactive storage. It is likely that the nonlinear dependence of macropore flows on spatially variable antecedent moisture conditions and intensity of supply rates will mean that such indirect methods will ultimately prove of only limited usefulness.

FUTURE PROSPECTS

We have reviewed evidence to suggest that macropores play an important role in the hydrology of some field soils. We have noted that this has important implications for geochemical interactions and the movement of pollutants. We are suggesting that under some circumstances it may be necessary to add a further level of complexity to ideas and models of the movement of water through field soils. Given the current recognition of the problems posed by spatial variability of the hydraulic characteristics of soils [e.g., *Nielsen et al.*, 1973; *Sharma et al.*, 1980; *Freeze*, 1980], it is difficult enough to apply traditional models of soil hydrology without adding the further complexity of macropores—about which we have so little information.

What is needed first is experimental information. How do macropores operate hydrologically? How often do they operate? Under what conditions of macropore size and continuity is the domain concept of different potential gradients in macropores and the matrix a valid one? What do macropore structures look like at both microscopic and macroscopic scales, and can they be related to flow properties? How do macropores interact with the surrounding matrix under different flow conditions? We have only taken the first few steps toward answering these questions.

The domain concept of modeling combined macropore/matrix flows that has been discussed in this review obviously applies best when there is a distinctly bimodal pore size distribution with a high degree of continuity in the large pores (the cracked clay soils studied by Bouma and others are perhaps the best example). More generally there will be continuous pores of a wide range of (longitudinally variable) sizes. Under these conditions, macropore is a very relative term. In continuous large pores we can be sure that, given a sufficient supply of water, flow may be effectively channeled past the surrounding matrix. However, experimental evidence [e.g., *Omoti and Wild,* 1979] has shown that such channeling or bypassing may also take place within capillary-sized pores.

One important research task in the future will be to intergrate these various concepts of channeling at different scales in both capillary pores and macropores into one coherent flow theory. Such a theory would include, as a special case, the concept of a representative average tension within an elementary volume that is the basis of Darcian theory applied to unsaturated flows. In that such a theory must embody the effects of pore continuity as well as pore size, there will be a close relationship with developments in the study of three-dimensional pore structures in field soils.

If such a theory is possible, then the domain concept of distinct categories of macropores and matrix will be redundant. It is expected that the number and size of pores in which flow is being channeled will depend on the initial moisture content, the previous history of hysteretic wetting and drying, and the imposed flux rates. The difficulty then is making the link between these essentially microscopic flow processes and practical applications, such as predicting infiltration rates, subsurface stormflows, and the movement of nonpoint source pollutants. It is likely that this difficulty will not be one of theoretical development but of obtaining the experimental information to apply the theory at the field scale. It is a fascinating prospect.

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