

Macropore flow as a groundwater component in hydrologic simulation: modelling, applications and results

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Macropore flow carries water from the soil surface to deeper profile or groundwater, bypassing the intermediate soil profile. The phenomenon is ubiquitous and not rare. A theoretical framework of this flow has not been perfected so far, but ignoring this process may lead to incomplete conceptualization of soil-water flow. The macropore flow has been modelled based on observed data on morphometry, macropore size distribution and fractal dimensions of soil voids and stain patterns, and incorporated in the Watershed Processes Simulation (WAPROS) model. The performance of WAPROS model was evaluated to be good (NSE – hourly; daily = 0.8578; 0.9020), when applied to a real watershed. The sensitivity of macropore flow sub-model showed that the adjustment factor was linearly related to macropore flow. Simulations were performed for five types of soil, namely sandy loam, sandy clay loam, sandy clay, clay loam and silty clay loam (A, B, C, D and E respectively). The values of macroporosity factors and fractal dimensions generated for the five types of soil have been presented. The model generated data for A, B, C, D and E soil types were: the number of macropores: 379, 3074, 3412, 153 and 0; the macropore flow (mm): 1.5121, 9.3667, 15.1728, 4.4055 and 0; the average pore flow (mm/pore): 0.0040, 0.0030, 0.0044, 0.0287 and 0; and the macropore flow to base flow ratio: 0.0055, 0.0474, 0.1908, 0.2759 and 0. The modelling methodology gives encouraging results. The model can be updated as and when better equations are made available.

Keywords: Groundwater, hydrologic simulation, macropore flow model, sensitivity, soil types.

MACROPORE flow can be categorized as a flow phenomenon that is initiated from the soil surface and terminated at the deeper profile or groundwater, bypassing the intermediate soil profile. The carriers of macropore flow are: connected and disconnected macropores, soil pipes, soil cracks, random holes formed by soil fauna and desiccated roots. The macropore flow is classified as a part of

the ‘preferential flow’ that is pervasive and not exceptional¹.

The macropore flow results in: (i) recharge of groundwater even before the soil is completely wetted; (ii) availability of less moisture for crop growth as the root zone is not wetted; (iii) enhanced and immediate recharge of groundwater as the soil matrix is bypassed; (iv) more and longer baseflow from the watershed; (v) unhindered movement of pollutants or chemicals applied at the soil surface to groundwater, and (vi) less run-off and soil erosion².

Macropore flow occurs not only in humid environments, but also in semi-arid regions³. As its consequences are wide-ranging, ignoring this flow component in soil water, hydrologic or groundwater studies or models, will lead to incomplete conceptualization or description of the above-mentioned models. Hence, it becomes obligatory to include macropore flow component in a watershed model⁴.

Four decades of research on macropore flow could only explore the vast alternatives to study the phenomenon better. The random nature of distribution of macropores below ground, and different types of soil and land management practices hinder the formulation of a complete theory for macropore flow⁴⁻⁶. It has been pointed out that knowledge about preferential flow processes in the soil is still in its infancy⁷, and that even partial success in this justifies good effort⁸.

These considerations make modelling of macropore flow for universal application more difficult, but it cannot be neglected^{3,9}. Hence, a modest attempt has been made to model the macropore flow component for incorporation in the Watershed Processes Simulation (WAPROS) model.

In this article, the allied subjects like preferential flow, macroporosity and morphometry have been briefly explained. The distinct features of macropore flow, discharge of old water and the factors governing the flow have been described. The importance of soil structure and the methods of quantifying it have also been dealt in this article. The approach towards modelling macropore flow component in a hydrologic model has been described. The results of simulation are presented for both hydrologic model and macropore flow component.

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Preferential flow

It is a conventionally held view that infiltration and percolation carry water from the soil surface to the sub-surface and groundwater through the soil matrix. When the quantity of water transported to the groundwater storage far exceeds the known rates of these processes, there is a lesser known unconventional flow phenomenon known as preferential flow that is ubiquitous¹⁰. The infiltration flow is characterized as uniform, stable and in equilibrium, while the preferential flow as non-uniform, unstable and in non-equilibrium¹¹, and both occur simultaneously.

Preferential flow is an umbrella term that includes all types of unconventional flow, each assuming a specific pattern of pathways, bypassing the soil matrix. The soil matrix offers maximum resistance to the flow and it is bypassed by the preferential flow to take the path of least resistance below the soil surface. This causes water to move faster in some parts of the soil profile than in others, resulting in irregular wetting of the soil profile. The preferential flow has gained more prominence for its negative implication that it could carry solutes and contaminants to greater depths, limiting the storage, filter, and buffer functions of soils^{10,12}.

The fine-textured soils containing proportionately more clay and silt are more prone to the formation of aggregates and structural patterns and hence are called structured soils. The coarse-textured soils contain more sand and are not amenable to the formation of structures and aggregates; these are called structure-less soils. The preferential flows occur more in structured soils than in structure-less soils. The soil texture could explain the dynamics of uniform and equilibrium flows, but not the non-equilibrium flows. The soil structure plays a predominant role in non-equilibrium flows, but it is only described qualitatively as granular, blocky, crumbly, prismatic, angular, sub-angular, etc. As the measurement of soil structure is not fully quantified, the complete dynamics of non-equilibrium flows cannot be quantitatively described. This feature of macropore flow makes it difficult to model this flow process.

The preferential flows are variously classified based on different considerations, as: (i) type of flow – macropore flow, fingering flow and funnel flow¹³; (ii) operational scale of flow – pore scale, Darcian scale and areal scale¹¹; (iii) direction of movement of flow – vertical, horizontal and both¹⁴. The horizontal flow is often called as lateral flow or interflow; this is not dealt in this article. In case of vertical flows, macropore flow is dominant and incorporated in the WAPROS model.

Macroporosity

The porosity defined by the distribution of soil primary particles, sand, silt and clay is referred to as textural

porosity. Similarly, the voids between soil aggregates are called macropores and their distribution is referred to as structural porosity¹⁵ or macroporosity or inter-aggregate porosity. In the WAPROS model, textural porosity and macroporosity are considered to coexist and are independently treated to model matrix flow and macropore flow. The values of macroporosity (%) have been reported to vary from: 0.2 to 1.5 (ref. 3); 3.6 to 22.9 (ref. 16); 2.18 to 3.8 (ref. 17); 0.22 to 2.25 (ref. 18) and 2.0 to 4.0 (ref. 19).

The reported data on macroporosity vary widely, because a macropore has been defined differently by different researchers and estimated by different methods¹⁸. The low macroporosity (%) data reported were: 0.0005–0.002 (ref. 18); 0.35–0.77 (ref. 20); 0.31–0.51 (ref. 21) and 0.028–0.061 (ref. 22).

Size of macropores

The sizes of macropores vary widely, depending more upon the types of pores. The average diameters (μm) of various biological pores reported were: root hairs: 5 to 10; lateral roots of cereals: 20 to 100; taproots of di-cotyledons: 300 to 10,000; wormholes: 500 to 11,000; ant nests and channels: 500 to 50,000 (ref. 23).

Soil pores have been classified differently by soil physicists and hydrologists. Different approaches have been used for the classification of pores^{15,22–24} as follows: (i) Brewer classification based on sizes – cryptovoid, ultramicro-void, micro-void, meso-void and macro-void, with equivalent cylindrical diameter (ECD) (μm) intervals at 0.1, 5, 30, 75 and >75 respectively; (ii) International Union of Pure and Applied Chemistry (IUPAC) classification – micropores, mesopores and macropores, with ECD (μm) intervals at 0.005, 0.1 and 5000 respectively; (iii) Greenland classification based on functionality – bonding pore, residual pore, storage pore, transmission pore and fissure, with ECD (μm) intervals at 0.005, 0.5, 50, 500 and >500 respectively; (iv) Luxmoore classification based on pore size (equivalent diameter in μm) – micro <10 ; meso 10–1000; macro >1000 , and (v) Luxmoore classification based on capillary potential (kPa) pressure gradient pore, gravitational pore and channel-flow pore, with pressure intervals at -30 , -0.3 and less than -0.3 respectively.

There are different types of pore classification, and different ranges in class limits to describe macro, meso, and micro pores, which itself is an indication of the arbitrary nature of most classifications; thus it is pointless to search for a single universal classification of pore sizes²³.

Generally, macropores include all soil pores of size 1 mm or more in equivalent diameter that drain at field capacity, which adhere to Luxmoore limit²⁴. Macropores of diameter larger than 0.5 mm are also characterized by relatively large length (high continuity) and low

tortuosity¹⁹. As Luxmoore classification of pores prescribing ECD >1000 μm for macropore is found to be reasonable, the same has been adopted in the WAPROS model.

Morphometry of macropores

A study that investigated the geometry of macropore networks reported that cylindrical biopores larger than 1 mm in diameter were present in sandy loam soil under grass. More than 13,000 branching networks/ m^3 of soil, contributing to macroporosities between 2% and 4% were identified. The networks had a mean volume of 50 mm^3 , tortuosity between 1.2 and 1.3, and modal length of 40 mm (ref. 24).

Numerical density is the number of macropores per unit volume, regardless of their size or shape. It varies from soil to soil. The number of macropores/ m^2 was reported to vary from 228 to 698 (ref. 20). In another study, the size distribution of root channels was estimated as follows: 68% of pores was between 0.5 and 2.5 mm in diameter, and 8% was larger than 4.5 mm in diameter²⁵.

The pore size distribution shows the number of pores in the respective pore size in a unit area. A typical pore size distribution at 30 cm depth of soil has been reported as: 76.3%, 14.5%, 4.8%, 1.9%, 1.3% and 1.08% for pore sizes 0–1, 1–2, 2–3, 3–4, 4–5 and >5 mm respectively²⁶. The number of pores was found to be inversely proportional to pore diameter. The pore size distribution was also reported to follow exponential distribution^{27,28}.

It has been observed that pores greater than 2 mm diameter constitute only 2% of total macropores²⁹, and those pores greater than 3 mm in diameter represent no more than 2% or 3% of the total porosity²³, or 0.004% of macroporosity. However, as wetness of the soil increases, the pores coalesce and the number of active macropores increases, contributing to more macropore flow and higher hydraulic conductivity²¹.

Macropore flow

Macropores represent only a small part of the total pore volume, but their flow accounts for the bulk of water movement³⁰. The contribution of macropore flow to groundwater was reported to vary between 81% and 93% in brown soils¹² and thus it becomes an unavoidable hydrologic process.

By definition, macropore flow is a non-equilibrium process whereby water at pressures close to atmosphere rapidly bypasses a dry soil matrix. There is less likelihood of macropore flow generation at potentials smaller than –10 cm, i.e. at high negative pressure¹⁹.

Macropores can be continuous or non-continuous based on the nature of aggregates. It has been observed that pores opening at the surface are often found to be closed at the base²³. When water flows through discon-

tinuous macropores, it will accumulate at some depth and start infiltrating from there. This process of obstruction or stagnation of macropore flow is called ‘internal catchment’³¹. The macropores which are not directly connected to a water source or not connected to one another become active as wetness increases and these disconnected macropores self-organize the flow into an efficient network²¹.

The method of initiation of macropore flow, whether from above or below the soil surface is still debated. It was earlier prescribed that surface ponding as a threshold storage depth needed to be exceeded to allow water into macropores³¹. Different threshold values were reported to initiate macropore flow, such as rainfall of 55 mm, rainfall intensity of 12 mm/h (ref. 6), 26.6 mm/h (ref. 3) and soil moisture content of 50% saturation capacity¹². However, it is found to be practical to go by the recommendation that surface soil does not have to be completely saturated or ponded to initiate macropore flow²⁸.

After macropore flow is initiated, the pore faces are reported to absorb a part of the flow and transmit it to the soil matrix depending on soil wetness. Water flows down the macropore walls as a thin film, soaking into the walls as it moves, and the rate of advance is controlled by the lateral infiltration rate when the soil is initially dry and by flow resistance when the macropore walls are initially wet³². However, the cumulative horizontal absorption is observed as only a small fraction, which ranges from 0.7% for sandy loam to 0.3% for clay³¹. As the estimated lateral absorption during macropore flow is always less than 1%, it is affirmed that lateral absorption is not an important parameter. It has been also reasoned that organic and inorganic linings in biotic macropores and aggregate coatings restrict lateral mass transfer, enhancing non-equilibrium water flow and solute transport¹⁹.

Old water from macropore flow

Macropore flow is often dominated by ‘old’ or ‘pre-event’ water³³. This causes a fast subsurface response accompanied by pre-event mixed chemical concentrations. This phenomenon has been suggested as a double paradox of hillslope hydrology³⁴.

Many theories have been put forth to explain the discharge of old water through macropores. It has been explained that macropore flow causes perching of water at the soil–bedrock interface, which moves upward into the depleting soil matrix that is later conveyed through large soil pipes with a rapid response of well-mixed old water³⁵. The pre-event water is considered to be stored in the discontinuities in the preferential flow network and displaced into downstream flow pathways, causing changes in chemical characteristics⁵. Another interpretation is that pre-event water enters the preferential flow path either after mixing in the surface soil, or getting transported from saturated depressions or after interacting with the soil

matrix³⁶. There is unanimity on the delivery of pre-event water, but there is no consensus on its mechanism.

Fractal approach

The quantification of macropore flow is thwarted by non-quantifiable nature of the soil structure. Soil physicists have advanced fractal concepts to measure soil structure through indirect measurement of aggregates and voids. Fractal is defined as an object which appears self-similar under varying degrees of magnification, with each small part replicating the structure of the whole³⁷. The fractal dimension is usually a non-integer dimension greater than its topological dimension, and less than its Euclidean dimension. The fractal dimension provides a means of predicting behaviour at one scale from the information obtained at another scale³⁸.

A fractal appears the same, regardless of the scale of observation³⁹. The properties of fractals can be described by a scale-invariant power law characterized by an exponent termed the 'fractal dimension' (FD)¹⁹.

Soil aggregation is hierarchical⁴⁰, such that aggregates of a given size consist of smaller sub-units, which in turn comprise of even smaller aggregates. The lower the order in the hierarchy, more denser and stronger will be the aggregates. Larger aggregates are associated with larger inter-aggregate voids causing stronger non-equilibrium flow and transport. As the soil bulk density increases, aggregation, porosity and pore size decrease. These characteristics help quantify soil structural porosity.

The perimeter FD (D_{pe}) and the surface area FD (D_s) are useful for studying staining patterns of macropore flow¹⁶. The mass fractal dimension (D_m) is reported to contain more information on the processes that influence the flow pathways, than the less sensitive 'perimeter' or 'surface' fractal dimension⁴¹.

The fractal approach provides a unifying framework to predict the effects of structure on transport processes³⁸. Fractal power laws are used to describe aggregate and macropore size distribution, and larger values of the exponent imply better hierarchy of structure. As macroporosity displays characters of fractal geometry, the fractal concepts are used to describe macropore flow and transport¹⁷.

Macropore flow equations and models

Over the years, different approaches have been used to represent water flow in macropores. Various types of flow equations have been used in previous studies such as: the Darcy–Richards equation^{42–44}, Hagen–Poiseuille's equation^{18,23}, Green and Ampt infiltration model⁴³ and kinematic wave equation^{7,45}.

The rapid transport and heterogeneous movement of water through the unsaturated zone make macropore flow a difficult process to describe⁴⁶. It occurs often as turbu-

lent flow under gravitational and inertial forces, which contravenes the assumptions of Darcy's law; thus it has been advised to dispense with the use of Darcy's law for macropore flow¹⁹.

The use of Richards equation for representing macropore flow is criticized as misuse of physics⁵, because it cannot adequately characterize flow processes in a heterogeneous unsaturated soil matrix⁴¹.

A study reported weak and negative correlation between saturated hydraulic conductivity and macropore flow¹². Few studies reported contradictory correlation results in macropore flow. Correlation between macropore flow and bulk density of soil was reported to be: negative⁴⁷, positive⁴⁸, and oscillatory with a maximum at an intermediate level of bulk density or compaction⁴⁹.

As macropore flow is influenced more by soil structure and aggregates, which are not satisfactorily represented quantitatively, a generally acceptable model is not yet available⁵⁰. The incomplete understanding of macropore flow in a laboratory setting is still confounded, when applied at landscape or catchment scale^{1,4}.

Macropore flow modelling in WAPROS

Macropores increase overall permeability of the soil and tend to reduce overland flow generation²⁰. The contribution of macropore flow to groundwater was reported to vary between 81% and 93% in brown soils¹². These facts show the potential role of macropore flow, which cannot be avoided in a hydrologic model.

The macropore flow process modelling is proposed to be built from morphometric data and approximations, and linked to an adjustment factor to get the expected output. Once the static part of the macropore flow component is fine-tuned, the WAPROS model will make use of this part to simulate other hourly hydrologic outputs. Macropore flow is modelled in WAPROS from diagnostic principles, drawing inferences from its observations and phenomena. The process modelling envisages exclusion of unimportant features, and incorporation of important relationships. As pointed out by Think Tank Group IV, the conceptual model is approached to be simple and uncomplicated to guard against over-developing model complexity¹⁰. In WAPROS modelling, more importance is given to algorithms that are sensitive to changes in soil type rather than those that are insensitive to changes in soil type.

As lateral absorption during bypass flow is reported to be less than 1% and considered as not important³¹, macropores are treated as vertical pores in the WAPROS model that connect soil surface and groundwater. As surface ponding is not a prerequisite to initiate macropore flow¹⁹, threshold surface detention storage as a prerequisite to initiate macropore flow is not considered. The possible flow rate of macropore has been estimated as 360–2520 mm/h, for a low macropore density of 100/m² (ref. 27). This discharge capacity is far greater than

normally observed rainfall intensity, implying that all the rainfall reaching the pores will be conveyed efficiently without any constraint.

The dual permeability concept adopted in the MACRO model was reported to give promising results^{2,19}. The dual permeability approach has been modified to suit the conceptual approach in WAPROS. The flows from surface to subsurface zone have been treated independently as (i) infiltration through soil matrix, and (ii) macropore flow through macropores.

Radii and number of macropores

A statistical approach was suggested for macropore flow, using the equation $R = [(-2\sigma)/(\psi\rho g)]$, where R is the macropore radius, σ the surface tension at the air–water interface, ψ the capillary potential in units of length, ρ the density of water and g is the acceleration due to gravity⁵¹. As pore radius (R) corresponding to a capillary potential (ψ) of zero was undefined, an arbitrary value of $\psi = -1.0$ cm was chosen in the study as the boundary between macropores and micropores, and the equivalent diameter was estimated as 3.0 mm.

In another study, the Hagen–Poiseuille equation was adopted assuming laminar flow through a capillary tube to determine upper bound for the number of effective macropores per unit area and the minimum value for macroporosity¹⁸. As uniform and steady-state assumptions were used for flow to get soil-invariant data, the procedure has not been used here. The pore-scale physical laws have been found to be unsuitable, as macropores rarely flow at full saturation⁴⁶.

As capillary potential differs from soil to soil, the assumption of an arbitrary constant value of -1.0 cm may not hold good under all circumstances. Hence, air-entry value or bubbling pressure (h_b ; absolute value) employed in the Brooks–Corey model for soil water retention has been used for estimating radius of pore as⁵²: $r = (0.148/h_b)$. The value of r thus obtained represents the average value of the pores, including that of micropores. Hence, such estimated value of r , needs to be up-scaled to get the average value of radius of macropore. Such simplification of macropore morphologies is unavoidable due to lack of information on macropore network within the soil mass⁹.

In the WAPROS model, the following form of modified Poiseuille's equation has been used to estimate the average value of radius r (ref. 53):

$$r = \left(\frac{2\sigma \cos \alpha}{\rho g h_b} \right), \quad (1)$$

where α is the contact angle. The value of bubbling pressure (h_b) is estimated using pedotransfer function recommended for Brooks–Corey soil water retention model. This estimate of r is multiplied by a constant k_p , ($k_p > 1$) to get the minimum value of radius of macropore (R_1).

Now, macropores are considered as a bundle of pores of different sizes, with radius R_1 , R_2 , R_3 , R_4 and R_5 (equal to R , $2R$, $3R$, $4R$ and $5R$) following a pore size distribution of 80%, 10%, 5%, 3% and 2% respectively. In the WAPROS model, Luxmoore limit of $ECD > 1.0$ mm for macropore is adopted and pores having radius less than 0.5 mm are ignored. The cross-sectional area of each class of macropore, based on its radius is estimated as a_1 , a_2 , a_3 , a_4 and a_5 .

Macroporosity was quantified in a study by its relative cross-sectional area, defined as the macropore cross-sectional area divided by the total soil cross-sectional area⁴³. Following this analogy, a horizontal cross-section of 1×1 m, consisting of soil particles and soil pores, is considered in the soil profile and this unit area is denoted as A . The following assumptions have been made based on the normal (modal) values reported by different authors for different macropore characteristics: (i) macroporosity (θ_m) is 0.04; (ii) non-vertical pores constitute 25% (p_1); (iii) pores not connected to the soil surface constitute 25% (p_2); (iv) pores disconnected (having internal catchments) constitute 25% (p_3); and (v) tortuosity averages 15% in vertical cross-section (p_4).

The total cross-sectional area of macropores in the soil profile of unit sectional area is A_{mp} ($= A\theta_m$) and the proportion of active, vertical and connected macropores is $\beta = 1.0 - (p_1 + p_2 + p_3 + p_4)$, where $(p_1 + p_2 + p_3 + p_4) < 1.0$. The pore size distribution is superimposed on the cross sectional area of macropores to get the effective macropore area EA_{mp} ($= A_{mp}\beta$). The representative areas occupied by different pore size classes have been estimated as: $RA_i = EA_{mp} \cdot p_i$, for $i = 1$ to 5. From this, the number of pores of different sizes (N_{mpi}) is estimated as $N_{mpi} = (RA_i/a_i)$. Thus using this procedure, the number of pores and area occupied by different classes of pores are estimated.

Then, the composition of bundle of macropores across a section in the profile is estimated. These pores are treated as vertical pipes connected to the soil surface. Conveyance of each pore is characterized as non-limiting for the rainfall received. Then, the proportion of rainfall that would reach the macropores is estimated.

In the WAPROS model, each macropore opening at the soil surface is assumed to have an independent catchment area that is circular in shape with radius equal to $4R_i$, and the catchment area of each macropore $CA_i = 16a_i$. Then the catchment area of all macropores in that class $CA_{mpi} = N_{mpi} \cdot CA_i$. The total catchment area of all macropores $CA_{mp} = \sum CA_{mpi}$, and the proportion of geographical area (CA_{mp}/A) would receive proportionate rainfall directly.

As bubbling pressure is dependent on the soil type, the values of CA_{mp} would vary from soil to soil. As macropore flow is also dependent on land management and soil structure, suitable modifiers have been proposed to get final macropore flow factor.

Effect of land use

Land uses have a definite bearing on the formation and modification of macropores^{1,47}. PTFs were formulated to estimate macroporosity factor A (ref. 54). In the WAPROS model, factor A is used as a modifier to macroporosity. The prediction equation of A for undisturbed forestland, A_{fo} is

$$A_{fo} = \exp(2.82 - 0.099*SD + 1.94*BD), \quad (2)$$

and A for agricultural areas, A_{ag} is given as:

$$A_{ag} = \exp(0.96 - 0.032*SD + 0.04*CL - 0.032*BD), \quad (3)$$

where SD, CL are percentage contents of sand and clay, and BD is bulk density of soil (g/cm^3). BD is considered as the value unadjusted for coarse aggregates and organic matter contents of soil. In the WAPROS model, land uses such as grazing, barren or fallow lands coming under neither forest nor agriculture, are classified under other uses and their A value, A_{ot} is taken as an average of A_{fo} and A_{ag} . Intermediate status has been given to grasslands, as moderately wet grassland soils can efficiently promote macropore flow¹².

The macroporosity factors A_j are weighted with the respective areas under three land uses LU_j , to get weighted average value of macroporosity factor as $LU_w = [(\sum A_j LU_j)/A_T]$, where A_T is the total area of the watershed. The modified catchment area of macropores (MCA1) is then obtained as: $MCA1 = (CA_{mp} \cdot LU_w)$ (subscripts $j=1$ for forest, 2 for agriculture and 3 for other types of land uses (LU); w represents watershed).

Fractal dimension of soil parameters

The structure of soil plays a dominant role in shaping the size and shape of macropores, but there is no reliable method of quantifying soil structure⁵⁰. Soil physicists have come forward with fractal dimension as a solution to characterize soil structure and thus macropore flow. However, estimation or measurement of fractal dimensions is a laborious task and it is highly improbable to find their effective values for a watershed, given spatial heterogeneity of soil characteristics. Hence, recourse is made to estimate these fractal dimensions through indirect methods, using published equations and relationships. There are also arguments that such equations cannot be transferred validly outside the area of study¹⁹. In the WAPROS model, such equations for fractal dimensions are used despite reservations, as these are the only ones available to satisfactorily describe soil structure and macropore flow. The fractal dimension values have been used in WAPROS as modifiers to MCA1.

Fractal dimensions of stained flow patterns have been used in a study to estimate cumulative macropore flow⁵⁵. Among others, the surface fractal dimension D_s has been suggested as the best parameter to quantify staining patterns⁵⁶. The fractal dimension of stained surface is found to be correlated with porosity, particle size and λ values, and three regression equations for estimating fractal dimensions have been recommended as follows⁴¹

$$D_s = 0.0525(2 - \lambda) + 0.677\varphi - 0.095d + 0.960, \quad (4)$$

$$D_s = 0.0745(2 - \lambda) + 0.732\varphi + 0.893, \quad (5)$$

$$D_s = 0.830(2 - \lambda) + 0.134, \quad (6)$$

where D_s is the surface fractal dimension, λ an exponent for pore size distribution in Brooks–Corey water retention model, φ the porosity, and d is the average particle size. It is further reported that preferential flow increases with increase in fractal dimension, with a threshold value at $D_s = 1.30$.

In the WAPROS model, the geometric mean (FD_s) of three D_s values is found and a multiplying factor $FD1 = (FD_s/1.30)$ is estimated.

The mass fractal dimension increases with clay content and decreases with sand content, showing positive correlation with macropore flow⁵⁷. The relationships between mass fractal dimension and soil texture have been studied in detail and the following equations were proposed to estimate the mass fractal dimensions⁵⁸

$$D_{m1} = 2.2712 + 0.1669 \ln (CL + 1.0), \quad (7)$$

$$D_{m2} = 2.9419 - 0.0045 SD. \quad (8)$$

The geometric mean of these two values is represented as D_{mH} .

As aggregate formation and its stability are more dependent on sand, clay and organic matter, stable macropores are formed in loamy soil than in sandy or clayey soils.

The D_m values for various soils have been estimated as: loamy sand = 2.489; loam = 2.720; silt loam = 2.776; clay loam = 2.840; and clay = 2.896 (ref. 58). In this model, D_m of 2.70 for loamy soil is taken as the optimum value for high macropore flow, and the absolute deviation of the estimated D_m value from the datum 2.70 is found as $DD_m = \text{abs}(2.70 - D_m)$. A higher value of DD_m is interpreted to reduce macropore flow. A multiplying factor for the D_m value, similar to $FD1$, is developed as $FD2 = (1.20 - DD_m)$, allowing that soil with $D_m = 2.70$ will have 1.20 times macropore flow as maximum and $FD2$ will be smaller when D_m deviates from 2.70. Then, an average value $FD_{av} = [(FD1 + FD2)/2]$ is estimated.

The catchment area $MCA1$ is multiplied by FD_{av} to get $MCA2$. Then $MCA2$ is multiplied by macropore flow

Table 1. Macroporosity and fractal dimension data for different types of soil

	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
Details of model inputs and outputs	A	B	C	D	E
Inputs					
Sand content of soil: (% kg/kg)	60.0000	60.0000	55.0000	30.0000	10.0000
Silt content of soil: (% kg/kg)	30.0000	15.0000	10.0000	35.0000	55.0000
Clay content of soil: (% kg/kg)	10.0000	25.0000	35.0000	35.0000	35.0000
Coarse fragments content: (% kg/kg)	1.2300	1.2300	1.2300	1.2300	1.2300
Organic matter content: (% kg/kg)	1.4500	1.4500	1.4500	1.4500	1.4500
Outputs					
Macroporosity factor – A					
Rawls–macroporosity factor – A_{Forest}	0.9015	0.7647	1.1279	13.5141	99.4744
Rawls–macroporosity factor – $A_{\text{Agriculture}}$	0.5435	0.9930	1.7415	3.8751	7.3471
Surface fractal dimension–dye stain: D_s					
Ds–fractal dimension–Ogawa I	1.3546	1.3907	1.4106	1.4124	1.4127
Ds–fractal Dimension–Ogawa II	1.3643	1.3993	1.4181	1.4173	1.4165
Ds–fractal Dimension–Ogawa III	1.5843	1.6663	1.6924	1.6852	1.6819
FDs–GM–surface fractal dimension	1.4255	1.4743	1.4955	1.4937	1.4926
Mass fractal dimension: D_m					
Dm–mass fractal dimension–Huang I	2.6714	2.8150	2.8693	2.8693	2.8693
Dm–mass fractal dimension–Huang II	2.6719	2.6719	2.6944	2.8069	2.8969
DmH–GM–mass fractal dimension–Huang	2.6717	2.7425	2.7805	2.8379	2.8831

adjusting factor (AJ6) to get MCA. The MCA is represented as macropore flow factor for watershed (MPFF) and it is given as input to the WAPROS model. The macropore flow has been treated as an independent rainfall abstraction component in the WAPROS model, similar to impervious area, to get initiated with rainfall and terminated with cessation of rainfall.

Modelling results

The WAPROS model has been programmed with six parameters to be calibrated, and seven adjustable factors to be given as inputs by experimenters or experts. The model simulates elemental processes, which when summed up give the values of the respective lumped hydrologic processes. As the hydrologic simulation and water balance component are unified in the WAPROS model, the water balance data are also simultaneously generated with simulation data for the hydrologic processes.

The results are presented in two phases: performance of the WAPROS model as a whole, and performance of macropore flow as a component. By varying the values of macropore flow-adjusting factors, the sensitivity of the factor has been studied. By changing the sand, silt and clay contents of soil in the input data, the predicted changes in the macropore data and flow are discussed.

Performance of the WAPROS model

The WAPROS model has been applied to a watershed called Ebbanad, in the Nilgiris district of Tamil Nadu,

India for evaluating the performance of the model. The total area of the watershed is 3582.0 ha. The land-use pattern in the watershed is: forest area – 1722 ha; area under agricultural crops including tea plantations – 1797 ha, and impervious area under rocks, habitations and roads – 63 ha. The average longitudinal slope of the watershed is 7.01% and the average cross-sectional slope is 32.52%. The drainage density of the channel network is 2.904 km/sq. km.

The results of evaluation of the model, with respect to hourly and daily data are: Nash–Sutcliffe's efficiency (NSE) = 0.8578; 0.9020; volume handling efficiency (VHE) = 0.9526; 0.9526; mean square error (MSE) = 0.4058; 0.2434; ratio of RMSE to standard deviation of observed flow (RSR) = 0.3771; 0.3130 and coefficient of determination: (r^2) = 0.8614; 0.9068. These values suggest that the performance of the WAPROS model can be rated as very good.

Performance of macropore flow component

Macropore flow is modelled as an elemental process in WAPROS, as a constituent of addition processes to groundwater. This arrangement helps in segregating the process values of macropore flow from the rest of the simulation data.

Effect of macropore flow adjusting factor: The macropore flow adjusting factor is incorporated at the end of the algorithm to offset the approximations. In the WAPROS model, the catchment of macropores is treated

Table 2. Macropore flow data for different types of soil

	Sandy loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam
Details of macropore and flow	A	B	C	D	E
Macropore data					
Minimum size of macropore radius (mm)	0.6685	0.5873	0.5575	0.5958	0.0000
Maximum size of macropore radius (mm)	1.6711	2.9365	2.7874	0.7447	0.0000
No. of macropores/m ² (>1 mm dia) [-]	379	3074	3412	153	0
Macropores catchment factor (m ² /m ²)	0.0128	0.0640	0.0640	0.0032	0.0000
Macropore flow factor for watershed [-]	0.0029	0.0182	0.0294	0.0085	0.0000
Hydrologic data (mm over area)					
Overland flow (surface flow)	86.6675	83.7455	81.2982	91.9035	96.2423
Base flow	276.8689	197.6620	79.5019	15.9672	11.5405
Macropore flow	1.5121	9.3667	15.1728	4.4055	0.0000

as a rainfall abstraction module, similar to impervious area and all the proportionate rainfall reaching the catchment areas of macropores will be conveyed as macropore flow. A change in the adjustment factor will only change the total catchment area of the macropores, resulting in proportionate changes in the rainfall routed. All the rainfall, without limitation on carrying capacity of flow, will be conveyed in the macropores. The internal catchment storage in disconnected pores and lateral seepage into the soil matrix are ignored. The adjustment factor bears a linear relationship with macropore flow. A parameter in a model will generally have a nonlinear, parabolic or hyperbolic relationship, requiring estimation of an optimum value. The linear relationship gives ample credence for treating this as an adjustment factor, and not as a model parameter.

Effect of soil types on macropore flow: The combination of sand, silt and clay fractions makes up 12 soil classes (few advocate 11 classes). The soil classes (or types) often encountered in the watersheds are: sandy loam, sandy clay loam, sandy clay, clay loam and silty clay loam. Hence, it has been proposed to carry out studies for these five types of soil. Based on decreasing sand content and increasing clay content, the soil types were arranged in an order and coded as A, B, C, D and E. The contents of soil constituents (% by weight) for each soil class¹⁵ span over a range. Table 1 shows the specific values of constituents (% by weight) considered for the soil type under study.

The textural contents of soil for each class were fed as inputs, and the WAPROS model was run for five soil types independently. The simulation values for hydrologic processes and water balance data were generated for the respective soil. The outputs of elemental and lumped hydrologic processes represented the effect of changes in soil types. Besides, the values of important factors and related data such as macroporosity factors, surface fractal dimension – dye stains D_s , mass fractal dimension D_m ,

pore size and number of macropores were also generated. Table 1 gives the macroporosity and fractal dimension data generated for different types of soil while Table 2 gives the macropore flow data for different types of soils.

From Table 1, it can be seen that Rawls-macroporosity factors A_f and A_{ag} increase with increase in clay content, i.e. along ABCDE (showing LH trend; L for low and H for high). The values of A_f range from 0.9015 to 99.4744 and those of A_{ag} from 0.5435 to 7.3471, showing 110 and 13 times increase. The surface fractal dimension of dye stains, D_s by Ogawa, shows increasing trend along ABEDC (showing LHL trend), with a maximum value for sandy clay soil. The mass fractal dimension, D_m by Huang shows increasing trend along ABCDE (showing LH trend), the maximum value for silty clay loam. The surface fractal dimension of dye stains, D_s shows no dependency on textural contents, but the mass fractal dimension, D_m increases with increasing clay content. As macropore flow depends on aggregate formation and density of flora and fauna, the flow would be higher among soils with good tilth. Hence soils with optimum mix of sand, silt and clay would have more and stable macropore flow. This justifies the selection of pivot values of 1.20 and 2.70 for surface fractal dimension of dye stains D_s , and mass fractal dimension D_m respectively.

In Table 2, the minimum and maximum sizes of macropores for different soil types are presented. As Luxmoore pore classification is considered in the WAPROS model, pores of diameters greater than 1.0 mm are considered as macropores and those smaller than 1.0 mm are treated as micropores associated with the soil matrix. The pore radius values estimated using Fredlund's modified Poiseuille's equation have been upscaled-based on 2R, 3R, 4R and 5R multipliers. The maximum size of pores is constrained by 5R limit. However, the maximum radius values throws some light on the number of frequency classes of macropores, being 3, 5, 5, 1 and 0 for A, B, C, D and E respectively (showing LHL trend), against the maximum possible 5. The high

clay content associated with E type of soil (silty clay loam) acts as a deterrent for macropore flow, as clayey soil is often characterized as blocky structured.

In the WAPROS model, the number of macropores has been simulated as: 379, 3074, 3412, 153 and 0 for A, B, C, D and E soil types respectively, showing LHL-trend. The silty clay loam, having more of silt and clay, and less of sand, is less suitable for aggregate formation as well as for flora and fauna, and the lack of macropores is considered justifiable.

The macropore catchment factor (CA_{mp}) [m^2/m^2] varies as 0.0128, 0.0640, 0.0640, 0.0032 and 0 for A, B, C, D and E soil types respectively, showing LHL trend. The macropore flow factor for watershed (MPFF) [-] varies as 0.0029, 0.0182, 0.0294, 0.0085 and 0 for A, B, C, D and E soil types respectively, showing LHL trend. The ratio between macropore flow factor for watershed and macropores catchment factor, gives the value of the modifier. The values of modifiers are: 0.2266, 0.2844, 0.4594, 2.6563 and 0 for A, B, C, D and E soil types respectively, indicating that the modifiers used in the WAPROS model show no-constancy and nonlinear relationship, which is more acceptable.

The macropore flow varies as: 1.5121, 9.3667, 15.1728, 4.4055 and 0 mm for A, B, C, D and E soil types respectively, showing LHL trend. The average discharge (mm/pore) for A, B, C, D and E soil types has been estimated as: 0.0040, 0.0030, 0.0044, 0.0287 and 0, showing a nonlinear relationship and a no trend.

The elemental macropore flow process values alone give an indication of direct effect of changes in soil types. The impact of macropore flow is reflected indirectly in overland flow and base flow, which are again masked with other effects. The base flow shows a decreasing trend along ABCDE, or a trend of HL. The macropore flow to base flow ratio varies as: 0.0055, 0.0474, 0.1908 and 0.2759 for A, B, C and D soil types respectively, with a LH trend. This can be interpreted as follows: the effect of macropore flow is substantial in heavy soil types, highly supplementing the low levels of base flow in such soils. In the absence of macropore flow, the base flow from heavy soil would have been very low. The absolute contribution of macropore flow in heavy soils may be less, but their relative contribution is more significant. Thus, macropore flow is found to be an important soil water phenomenon for all types of soil, when the absolute and relative contributions to groundwater are considered.

Limitations of the study

The macropore flow mechanism is shrouded with ambiguities and obscurities due to spatially and temporally varying phenomena happening below the ground. A perfect theory for macropore flow is still not available.

Macropore flow phenomenon continues to defy our ability to predict, and a fully functional perfect model remains a distant goal²⁸. All the macropores are assumed to be tubular or cylindrical, to which the cracks do not belong, and their effect on macropore flow is not quantified⁹. While modelling macropore flow, lateral flow has not been considered. Under these circumstances, this attempt to model macropore flow is aimed at bringing a new approach, with a complete understanding that it can only be approximated. There are few caveats and limitations in macropore flow modelling, especially in the use of: PTFs for a few soil properties, assumptions of normal values for macroporosity, multiplier for pore sizes, pore size distribution, pore catchment, fractal dimensions, equations for D_s and D_m , modifiers, etc. The assumed normal values are subjective, and if changed can alter the pattern of macropore simulation data. An acceptable set of normal values for different properties, if proposed, may reduce the subjectivity. The algorithms for rate processes such as chemical transport are not included in the WAPROS model.

Conclusion

Macropore flow is not amenable for modelling due to difficulties in quantifying its related processes. A modest attempt has been made to model macropore flow for use in WAPROS hydrologic model. The macropore flow has been modelled based on observed data on morphometry, macropore size distribution and fractal dimensions of soil voids and stain patterns.

The WAPROS model was tested on a real watershed and its performance was evaluated as very good (NSE – hourly; daily = 0.8578; 0.9020). The performance of macropore flow component was assessed by changing the values of adjustment factor and soil type. The adjustment factor showed a linear relationship with macropore flow. The reliability of simulated data is proposed to be evaluated by researchers familiar with the watershed, as observed data on macropore flow are not available.

The macropore flow component has been evaluated by changing the soil type. The values of macroporosity factors and fractal dimensions generated for five types of soil have been presented. For five (A, B, C, D and E) soil types, the physical data like number of macropores, macropores catchment factors and macropore flow factor for watershed were simulated.

Moreover, the hydrologic data like macropore flow (mm), average discharge (mm/pore) and the macropore flow to base flow ratio were also generated by the model. The importance of macropore flow for light and heavy types of soils has been discussed. The limitations and other pointers for improvement of macropore flow modelling are also discussed. The modelling methodology gave encouraging results. The model can be updated as and when better equations are made available.

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