A model for calculating the effects of macropores on runoff generation

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Abstract

In clay soil the massive network of cracks in the upper part of soil profile is in a dynamic process of evolution and collapsing due to the alternative processes of drying and wetting in summer time, and in some places, freezing and thawing in winter time. Water moves by gravity only in cracks of the soil and other minuets interstitial system and can transport water and chemicals at velocities much faster than predicted with the conventional solute transport models. A method has been developed to calculate that part of rainwater, which bypasses directly through the macropores to the drains and does not react with soil solution or with the soil solid particles. Drain flow records, surface runoff, evapotranspiration and rainfall measurements over a considerable period of time, have been used in our research to produce a structurally sound model that enables us to calculate bypass flow in clay soil. Physical characteristic of the soil that determines water flow is lumped in one parameter called a retardation factor ($K$). In addition, another parameter ($F$) was used to describe water entrapment in cracks and other macropores. The overall agreement between calculated and measured results has indicated that the model can be a useful tool in determining bypass flow in clay soil.

1 Introduction

The basic problem in clay soil is the massive networks of cracks and other macropores that are built up caused by the dynamic processes of shrinking and expansion, and the alternating processes of freezing and thawing that prevail...
under sub-zero climates. Over the last decades, numerous investigations on macropore flow and solute transport have been performed [1,2,3,4,5,6,7,8]. They all pointed out that only the macropore flow of the soil is significant due to the extremely low permeability of clay soil. Accordingly, water moves by gravity only in cracks of the soil and other minuets interstitial system and can transport water and chemicals at velocities much faster than predicted with the conventional solute transport models. The rapid transport of water and solutes through cracks to subsoil and to groundwater, determines water and nutrient shortage to crops. It also determines the pollution impact on the fragile ecosystem where agricultural activities are intensified in terms of high doses of pesticides, herbicides and the liquid manure fertilisers.

Soil physical properties after thawing, do not completely return towards their original conditions [9]. Formation of random macropore cracks due to the freezing action, create large variations of water outflow and therefor, the conventional physical laws may become obsolete for calculating the bypass flow in clay soils.

In order to calculate the bypass flow, an experiment was conducted using Methylene blue staining patterns of five undisturbed unsaturated soil cores of 200 mm long and 200 mm in diameter from a well-structured clay soil [10]. Based on that experiment, an empirical equation was developed which relates the total amount of outflow from a soil core to the volume fraction of stained parts. However, the equation may become questionable if it is applied on field scale particularly because water entrapment in discontinuous cracks and the seasonal changes in the macropores physical characteristic were both not considered.

The objective of this study was to develop a methodology for calculating that part of rainwater that, bypasses directly through the macropores to the drains and it does not react with soil solution or with the soil solid particles. The research project included field measurements of drain flow, surface runoff, rainfall and some other hydrological investigations.

2 Experimental Set-up

The experimental field is located about 35km Southeast of Helsinki (lat. 60° N). The area of the field is about 3.2 hectares drained with a network of subsurface drainage pipes. The topography is hilly with slop of about 5%. Topsoil is silty clay soil of 30 cm in depth overlaying a clay soil layer of a depth of more than 2.5 m. The details can be found in [11].

Field investigations have shown that soil moisture does not vary in time very much particularly at depth below 30cm. Those macropore conduits and other fractures could have permanent structures that do not necessarily change during the year. However, the upper part of the conduit (aperture) is presumably evolving and collapsing according to the wetting conditions of the soil surface. Field investigations have shown that, the considerable water movement occurs only in the upper ploughed layer (0-30cm) where the rainwater flows
rainwater flows towards the permeable backfill of the existing drainage system. Most of the rainwater is passed to the drains in spite of the fact that soil profile has not yet reach the field capacity. Figure 1 shows a schematic representation for the macropores in clay soil and the flow mode in the region. The topsoil is highly porous in spring due to macropores expansion caused by soil water freezing during winter. In early spring after the thawing period, ice lenses disappear leaving behind macropores of a considerable size. This argument is supported by the hydrographic analysis, which was carried out to understand the hydrologic behaviour of the area. The results have shown that in early spring, a considerable amount of water stored in soil than for instance in summer [11]. In summer time plants cover topsoil and infiltration is minimal. The phenomenon of shrinking and expansion in clay soil begins in summer to play a role in the development of macropore flow. In August or September, cracks may become well developed and some of the rainwater bypasses to the drains through soil cracks and other macropores, and probably some of it even goes deeper below the drain levels causing less drain flow than in spring time. It was found that vertical cracks in soil profile might trap 10% to 90% from rainwater, which can be regarded as deep percolation losses. This amount of losses depends mainly on soil moisture conditions of the topsoil during the period that precedes the rainfall event. Disregarding the deep percolation losses from the water and solute balance equation may lead to overestimating the impact of agricultural activities on the ecosystem. Therefore, simulating subsurface flow by using the conventional physical equations may not be the right approach to calculate the subsurface flow in the region. Instead, we are intending to establish a stochastic method to calculate the bypass flow of water, which takes in consideration the macropore configuration and the antecedent soil water conditions.

Fig. 1: Schematic representation of macropore water flow regime in Sjokulla Research Field
3 Method of Calculation

In calculating the bypass flow, the net input rainfall is reduced to a bypass flow by subtraction of losses (water entrapped by discontinuous cracks), and then the bypass flow is transformed into rapid response drain flow by cylinder storage model. The loss term is obtained by calculating the amount of water that is lost by being entrapped inside the discontinuous vertical and the sheet-like cracks. This part of water is termed "losses" since it is not contributing to the drain flow. The loss rate is not constant and it is a function of the total rainfall that has fallen prior to the beginning of the storm event under consideration. The variable loss rate concept is based on the assumption of a limited capacity for the thin topsoil to absorb water and to allow the water to be directed to the lower part of the cracks. This is based on the fact that width of the fracture aperture depends on the wetting conditions of the topsoil. The loss rate could be as high as 90% of the total rainfall during the early minutes of the event and diminishes gradually with time due to the expansion that occurs in soil, which ultimately, reduces the aperture width. It should be emphasise here that although such a concept is clearly important on small homogenous areas, the loss rate approach is less relevant at catchment scale. Vegetation, soil inhomogeneity and topographic slope all influence the extent to which rainfall is lost as far as the generation of rapid response drain flow is concerned. In particular, the loss rate approach makes no allowance for the fact that much of the runoff may be arising from only part of a catchment.

Rainfall data and drain outflow records were both used to derive a simple conceptual model similar in essence to the linear reservoir concept which is defined as the reaction in outflow to the instantaneous input of unit volume [11]. The model concept represents the whole soil continuum as a reservoir of which the storage is directly proportional to outflow. The notable feature of the model is that a linear relationship is assumed between bypass flow and rapid response drain flow. This assumption of linearity does not mean that the overall model structure is necessarily linear [11]. The model reads:

\[ Q_{t+1} = Q_t e^{-1/\kappa} + (1 - \frac{\Gamma}{100})R_{t+1} (1 - e^{-1/\kappa}) \]  

where, \( \kappa \) is the retardation factor (T) and \( Q \) is the outflow (L/T), \( R \) is the net (routed) rainfall rate (L/T) and \( \Gamma \) is the water entrapment coefficient (%).

Equation 1 in fact, represents a non-linear reservoir concept for rainfall-runoff calculations. The presence of a non-linearity in the model ensures that the model output possesses an extended recession after the rainfall input and a preceding recession from previous event.

The water entrapment coefficient is determined by a polynomial function, which is based on data fitting of historical storm events:
\[
\Gamma = 80.1447 - 0.543782 S_r + 0.086013 S_r^2 - 0.0091204 S_r^3 + 0.0002754 S_r^4 - 3.72047E-006 S_r^5 + 2.37499E-008 S_r^6 - 5.84985E-011 S_r^7
\]
\[
\Gamma = 97.5883 + 2.95992 S_r^2 - 0.672998 S_r^3 + 0.038822 S_r^4 + 0.00107757 S_r^5 + 5.37647E-010 S_r^7 - 3.94961E-013 S_r^8 - 2.25459E-015 S_r^9
\]

where, \( S_r \) is the accumulated total rainfall during the previous time steps (mm).

Under the Scandinavian weather conditions, Equation 2 is applicable during wet months i.e. early spring and autumn, whereas equation 3 is applicable to dry months i.e. during the period from June to August.

In analysing the macropore flow, the parameter \( \kappa \) of Equation 1, represents the physical properties of the clay soil continuum, namely, the accessibility "well being" of the cracks and other macropore conduits for transporting water. It is termed here as a retardation factor since its value reflects the retardation of soil continuum to water flow. The dimension of the retardation factor \( \kappa \) is day. Its optimum value, which ensures an accurate prediction, appeared to vary from one storm event to another. It has been found a systematic relationship between values of \( \kappa \) and the dryness of the soil, in other words, the shape of the calculated hydrograph depends primarily upon the dryness/wetness of upper soil layer. Higher values of \( \kappa \) of 0.6 to 0.8 are characteristic of the macropores in early spring soon after the thawing period whereas values of 0.06 to 0.2 represents the very dry summer conditions.

4 Results And Discussion

The model was first calibrated by using the event series of 1995-97. The calibration was necessary in order to determine the two parameters required for operating the model.

Model applications for combined storm events during summer 98, are presented in Figure 2. The input rainfall (being the total rainfall minus runoff and evapotranspiration), water losses due to entrapment in discontinuous fractures, and the actual and simulated drain outflow are all presented. All dimensional units are expressed as depths over the basin for convenience. The model calculates first the volume reduction component of rainfall and secondly, determines the shape transformation component of the bypass water.
Figure 2. Comparison of calculated (solid lines) and measured (dots) drain discharge in Sjökulla research field for two storm events in June and August.

Figure 2 shows that the model predicts higher drain flow (less water entrapment) than the actual one during the very beginning of the storm event. Admittedly, the coefficient (F) is not sufficiently expressing the entrapment mechanism. Value of (F) is varying within the storm and applied to all ordinates of the net rainfall hyetograph to reduce them to those of the bypass flow. The malfunctioning of (F) can be improved to a certain degree by incorporating other parameters such as the geometric configuration of the macropores in soil continuum and the physical characteristics of the soil surface.

The model performs better when the soil surface is covered by plant canopy, which keeps the moisture content of topsoil constant and relatively wet.
(event 18-20.8). When the soil surface is relatively bare (event 17-26.6), then few sunny hours could be enough to dry up the top soil promoting an unstable conditions by widening the apertures and allowing more rainwater to be entrapped in the fractures. The aperture may become critically unstable particularly under the conditions of intermittent heavy showers.

The simulation results indicated that the exponent parameter $\kappa$ in the non-linear reservoir Equation 1 has proved its suitability for closely fitting the curvature of the majority of recession curves from the selected storm events. The results also indicated the non-linearity of the model ensures that the output from the model for a typical isolated storm event possesses both an extended recession after the rainfall input and a preceding recession from a previous event. The optimum value of $\kappa$ for each event ascertained to vary from event to another. More than this, the results indicated that $\kappa$ is not even constant during a selected storm, rather, its value is fluctuating around the selected seasonal value. This could be attributed to the fact that the "well being" of the macropore channels and other fractures are also effected by the extended storm events such as the one in Figure 2 (17-26.6).

Measured and predicted data are regressed in Figure 2. The figure shows the deviation of their regression line from the optimum 45° line. The overall performance of the model is expressed by the root mean square residual (RMSR) that is a measure of the deviation of the predicted value from the measured value. The errors have been considered within the accepted limit.

5 Conclusion

The processes of freezing and thawing, and swelling and shrinkage in clay soils both have significant consequences represented by the flow of water through cracks to subsoil and ultimately to groundwater creating what is known as bypass flow. Determination of the bypass flow is a key issue in defining nutrient deficiency to crops and alternatively it quantifies the impact of agricultural activities on the ecosystem.

A method has been developed to determine the bypass flow in agricultural clay soil. The relation between rainfall and bypass flow is modelled by storage routing technique. A proportional loss method of rainfall separation has been adopted which is linked to the soil wetness represented by the rainfall volume that has fallen prior to the simulated time step. The variable loss rate concept is based on the assumption that macropores conduits in the topsoil offers a limited corridor for the passage of rainwater into the discontinuous fractures prevail in clay soil continuum. This corridor (aperture) diminishes considerably as the soil expands due to the wetting process. The second parameter $\kappa$ named the retardation coefficient reflects the status of the macropores conduits and their geometric configuration in soil continuum. Analysing several hourly rainfall-outflow data, derives seasonal values of the parameters $\Gamma$ and $\kappa$. In the derivation of the model parameters equations, consideration has been given to easing problems encountered in characteristic abstraction and application under