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On TOPMODEL's ability to simulate groundwater dynamics

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Abstract The TOPMODEL approach has become widely used for hydrological catchment modelling. The representation of topographic effects to hydrology by a topographic index allows the simulation of distributed groundwater levels in a simple way. However, validation of spatial variations of groundwater levels (or surface wetness) simulated by TOPMODEL has not been successful in most cases. In this paper, TOPMODEL's ability to predict local groundwater levels is discussed more generally. The aim of this paper is to clarify the assumptions needed to derive the TOPMODEL theory, to investigate how reasonable the assumptions are and what errors are generated by these assumptions. Measured groundwater levels from different catchments in Sweden were used as examples. The most problematic assumptions were those of steady state flow rates and spatially uniform recharge to the groundwater, and it was concluded that these fundamental assumptions underpinning the TOPMODEL approach obstruct a correct simulation of the spatial and temporal dynamics of the groundwater table.

INTRODUCTION

In most catchments the spatial patterns of hydrological storages and fluxes are dependent on the topography. The TOPMODEL approach (Beven & Kirkby, 1979; Beven *et al.* 1995) has become widely used for hydrological catchment modelling, because it allows the consideration of topography while avoiding the complexity of fully distributed models. In contrast to other models the catchment is not divided into homogeneous units, but natural heterogeneity (i.e. topography) and its effects on hydrological processes are represented by distribution functions. Therefore, the distribution of wetness states over a catchment can be simulated in an easy way with low computational demands. This made the model very popular, especially since digital elevation models (DEMs) became easily available, not only for hydrological catchment modelling but also as a part of ecological, geomorphological or geochemical models, where information about local groundwater levels (or surface wetness) within a catchment is of importance (e.g. Robson *et al.*, 1992; Band *et al.*, 1993; White & Running, 1994; Kirkby, 1997). Furthermore, the TOPMODEL approach has been used to aggregate soil-vegetation-atmosphere transfer (SVAT) models to larger scales (e.g., Famiglietti & Wood, 1994). However, validation of spatial variations of groundwater levels (or surface wetness) simulated by TOPMODEL often has not been successful (e.g., Burt & Butcher, 1985; Iorgulescu &

Jordan, 1994; Seibert *et al.*, 1997).

The aim of this paper is to clarify the assumptions needed to derive the TOPMODEL theory, to discuss how reasonable these assumptions are and to investigate what errors are generated due to these assumptions in model applications. There seems to be a need for such a discussion since TOPMODEL's capabilities are often overrated in literature. Hinton *et al.* (1993), for instance, describe results of measurements which provide examples where the TOPMODEL assumptions are not fulfilled. Nevertheless, they concluded that modelling ".... the effect of such spatial differences in hydrological processes [....] would require distributed models such as TOPMODEL ...".

Franchini *et al.* (1996) performed a detailed analysis of the TOPMODEL approach based on applications in Italy. They concluded that the model has "surprisingly little sensitivity" to catchment topography as represented by the frequency curve of topographic index values and that TOPMODEL should be considered as a conceptual rather than a "physically based" rainfall-runoff model. Their study, however, mainly focused on the simulation of runoff and not on distributed groundwater levels. The analysis of TOPMODEL in the present study is based on experience from field experiments in till catchments in Sweden. In these catchments shallow groundwater exists, and some of the common TOPMODEL assumptions as, for instance, the decrease of hydraulic conductivity with depth have been found to be valid (e.g. Lundin, 1982; Bishop, 1991; Nyberg, 1995).

THEORY OF TOPMODEL

The topographic index of TOPMODEL (Beven & Kirkby, 1979) is defined as $I = \ln(a/\tan ß)$, where a is the local upslope catchment area per unit contour length and $ß$ is the slope angle of the ground surface. The index describes the tendency of water to accumulate (a) and to be moved downslope by gravitational forces ($ß$). For steep slopes at the edge of a catchment a is small and $ß$ is large which yields a small value for the topographic index. High index values are found in areas with a large upslope area and a small slope, e.g., valley bottoms. The TOPMODEL theory can be formulated either using local storage deficits, S [L water needed for saturation up to surface], or groundwater levels, z [L below surface]. Both formulations are directly interchangeable, therefore, only one - the formulation using groundwater levels - is shown here.

Assuming the transmissivity to decrease exponentially with increasing depth to the groundwater table, z_i [L below ground surface], the hydraulic gradient to equal the surface gradient, $\tan ß$ [-], and lateral flow in the unsaturated zone to be neglectable, the downslope flow at a certain location i is given by Eq. (1). T_i [$L^2 T^{-1}$] is the transmissivity if the groundwater level is at the ground surface and f [L^{-1}] is a shape factor describing the exponential decrease of conductivity with depth.

$$q_i = T_i \tan\beta_i \exp(-f\ z_i) \tag{1}$$

Eq. (1) provides the outflow from a certain location. Assuming steady state conditions in all locations and a spatially uniform vertical input rate R [L T^{-1}] to the saturated zone, the mass balance for each location simplifies to Eq. (2), where a_i [L] is the upslope area drained through location i per unit contour length.

$$a_i \; R = T_i \tan\beta_i \; \exp(-f \; z_i) \tag{2}$$

Eq. (2) can be rearranged to Eq. (3). It should be noted that the rearrangement is only possible if the recharge, R, is larger than zero. A mean depth to the water table, $\bar{z}$, is given by Eq. (4). The bar always denotes the mean over the catchment area, A [L^2].

$$z_i = -\frac{1}{f} \ln\left(\frac{a_i \; R}{T_i \tan\beta_i} \right) = -\frac{1}{f} \left(I_i + \ln\left(\frac{R}{T_i} \right) \right) \tag{3}$$

$$\bar{z} = \frac{1}{A} \int_A z_i \, dA = -\frac{1}{fA} \int_A I_i - \ln T_i + \ln R \; dA = -\frac{1}{f} \left(\bar{I} - \overline{\ln T} + \ln R \right) \tag{4}$$

Subtracting Eq. (4) from Eq. (3), yields a relationship between $\bar{z}$ and the local water table at each single location i (Eq. 5).

$$z_i = \bar{z} - \frac{1}{f} \left(I_i - \bar{I} - \left(\ln T_i - \overline{\ln T} \right) \right) \tag{5}$$

Due to the steady-state assumption the total specific runoff from the saturated zone, q_{GW} [L T^{-1}] equals the recharge R and can be written as a function of $\bar{z}$ by rearranging Eq. (4) to Eq. (6).

$$q_{GW} = \exp(-f \; \bar{z} - (\bar{I} - \overline{\ln T})) \tag{6}$$

In model applications $\bar{z}$ is updated at every time step Δt using Eq. (7), where q_v [L T^{-1}] is the simulated vertical flow down to the saturated zone and S is the storage coefficient of the soil.

$$\bar{z}^{\,t+\Delta t} = \bar{z}^{\,t} + \frac{q_{GW} - \overline{q_v}}{S} \Delta t \tag{7}$$

In summary, there are two central equations derived by the TOPMODEL theory. The first relates the mean groundwater level within the catchment, $\bar{z}$, to the local groundwater levels at any location i within the catchment (Eq. 5). The second links the catchment runoff from the saturated zone, q_{GW}, to $\bar{z}$ (Eq. 6). The following assumptions have been made to derive the equations: (I) hydraulic gradient equals surface gradient, (II) exponential decrease of transmissivity with depth to water table, (III) lateral groundwater flow, (IV) no lateral unsaturated flow, (V) steady state flow rates, and (VI) spatially uniform recharge (always larger than zero).

Assumptions I-IV often have been found to be reasonable. Assumption I can be relaxed using the concept of reference levels (Quinn *et al.*, 1991) and other than exponential shapes can be used to describe the decrease of transmissivity (II) (Ambroise *et al.*, 1996). Assumptions V and VI are difficult to relax within the framework of TOPMODEL and their impacts may be somewhat puzzling. Therefore, this study concentrates on them. The aim is not to provide any solutions but to motivate the need of further research before TOPMODEL can be used to simulate groundwater dynamics.

THE ASSUMPTION OF SPATIALLY UNIFORM RECHARGE

The assumption of a spatial uniform recharge to the saturated zone is needed to eliminate R in Eq. (4) and to derive the simple relationship between local and mean groundwater level (Eq. 5). However, it is questionable how reasonable this assumption is. Looking at the situation during and shortly after a rainfall event one should expect the recharge to increase with decreasing depth to the groundwater for two reasons: the vertical path through the unsaturated zone is shorter and there is less storage per unit depth possible in the unsaturated zone above the groundwater. As a consequence, groundwater levels should rise first in areas with high groundwater levels (e.g. Freeze & Banner, 1970; Winter, 1983). Looking at longer time intervals evaporation is another factor controlling local recharge to groundwater (e.g. Salvucci & Entekhabi, 1995). Evaporation varies spatially depending, among other things, on varying vegetation, slope, aspect, and groundwater levels. In mountainous basins the precipitation commonly increases with elevation, thus making the assumption of spatial uniform recharge unrealistic if the elevation range of the simulated basin is large. The recharge may be far from spatially uniform if it is generated by snow melt in mountainous basins where the melt rate, and by this the recharge, varies with elevation and aspect (e.g. Cazorzi & Dalla Fontana, 1996) and may be zero in some parts but several millimetres per day in others.

Surprisingly, the spatially uniform-input assumption used in the derivation of the TOPMODEL theory seems to have been "forgotten" in almost all TOPMODEL applications. Having simulated spatially varying groundwater levels it appears, indeed, logical to allow for spatial variations in groundwater recharge. However, the vertical flow to the saturated zone is averaged over the entire catchment after each time step to calculate a new mean groundwater level (Eq. 7). The updated mean groundwater is then used to compute the new local groundwater levels (Eq. 5), i.e., the recharge is spread out over the basin after each time step.

In all TOPMODEL applications precipitation falling onto saturated areas (i.e., $z_i \leq 0$) is simulated to be saturation excess overland flow and is directly added to the runoff, i.e., the simulated recharge in these areas becomes zero. For the non-saturated areas varying rates of recharge, q_v, are computed. In many recent versions of TOPMODEL recharge is computed by an equation similar to Eq. (8) where K_0 is the vertical saturated conductivity at the ground surface (e.g. Robson *et al.*, 1992; Beven *et al.*, 1995).

$$q_{v,i} = K_0 \exp(-f z_i) \tag{8}$$

The effect of the inconsistency of Eq. (8) with the spatial uniform recharge assumption can be illustrated by the following example. For a 200 m long, straight hillslope (surface gradient (tan*ß*) = 0.2, f = 2 m^{-1}) the groundwater is assumed to be in a steady state condition, i.e., recharge equals specific discharge from the groundwater. Two situations with different mean groundwater levels of 0.6 m (case A) and 0.3 m (case B) below surface are considered. The local groundwater levels are computed by Eq. (5). In the first case the levels obtained thus give no surface saturation, while in the second case the lower quarter of the hillslope is saturated up to the surface. Local recharge is computed using Eq. (8). The mean groundwater level (Eq. 7) and, consequently, the local levels (Eq. 5) do not change over time, even though the varying recharge differs significantly from a spatially uniform recharge (Figure 1). This means that water from areas with higher recharge is redistributed to upslope areas (case A and B) and to downslope areas (case B) with lower recharge. In other words, TOPMODEL predicts a specific groundwater flow at the middle of the slope (Eqs. 5 and 1), which is higher than the mean recharge in the upper half of the slope according to the spatially variable recharge (case A). However, groundwater levels are not allowed to change. Consequently, the variable recharge is spread out, and about half the predicted downslope flow is redistributed from the lower to the upper parts of the slope. This example illustrates that the use of spatial variable recharge rates, even though these may be physically more correct than the uniform rate, causes a physically unreasonable, upslope redistribution of water. Therefore, a spatially variable recharge should not be used unless the assumption of a spatially uniform recharge has been relaxed.

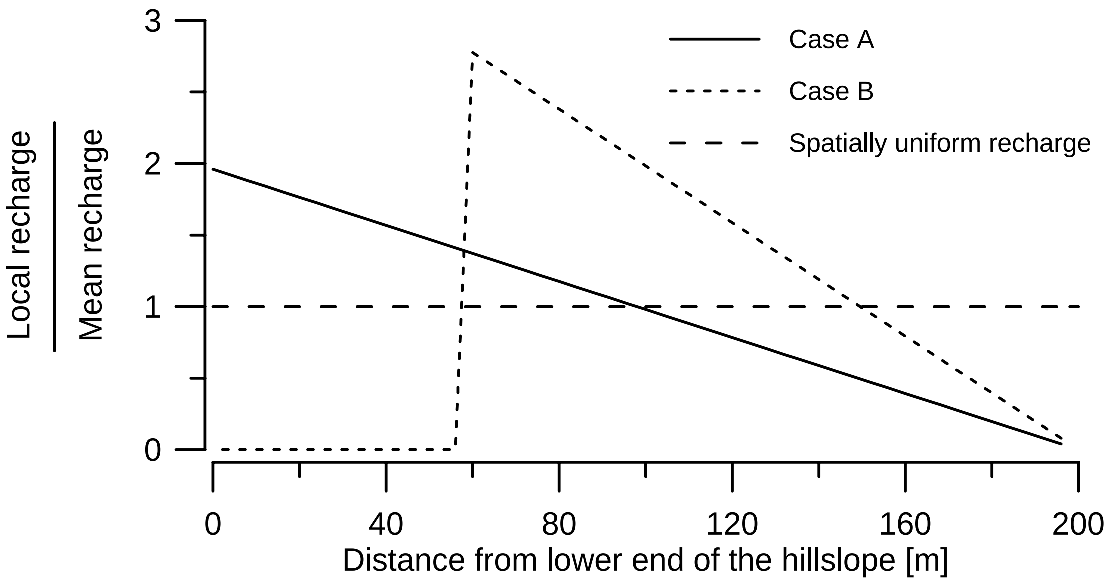

Figure 1. Ratio between local recharge along the hillslope and mean recharge, see text for further explanation

THE STEADY STATE ASSUMPTION

The steady state assumption in the TOPMODEL approach causes all simulated groundwater levels in a catchment to always rise and fall in parallel. This was checked against examples of measured data from three catchments in Sweden (Gårdsjön (Nyberg, 1995), Svartberget (Bishop, 1991) and Östfora (Eklund, 1996), where groundwater levels were monitored with a high temporal resolution. In all catchments a spatially varying response of groundwater levels to rainfall was found. The time of peak level differed up to several days between the different tubes even though they were located within distances of not more than 50 metres. The groundwater level reached its peak level earliest in the downslope parts at Gårdsjön (Seibert *et al.*, 1997) and Svartberget (Figure 2), whereas the situation was reversed in Östfora (Figure 3). Similar examples can be found in literature. Hinton *et al.* (1993) studied fluctuations of groundwater levels and discharge within a Canadian till catchment (3.7 ha). They found "a basic pattern" of the response of groundwater levels to storms. Groundwater levels increased rapidly in the lowermost part of the catchment, whereas they responded more slowly in the upper parts. In one example, the peak was reached about one day later in the upper than in the lower part. Flerchinger *et al.* (1992) studied the groundwater response to snow melt in a mountainous catchment and found that response to snow melt for tubes and weirs located 135 m downslope from an isolated drift was delayed 3-5 days for an average snow year.

As pointed out by Franchini *et al.* (1996) there is an obvious contradiction between Eq. (7) and the steady state assumption. For the local mass balance at any location there is no change in storage (steady state, Eq. 2), whereas for the mean of all locations, i.e., the catchment water balance (Eq. 7), the storage changes. The local depths of groundwater describe the shape of the groundwater table under steady state conditions where q_v equals q_{GW} (=R). The contradiction results from the fact that this

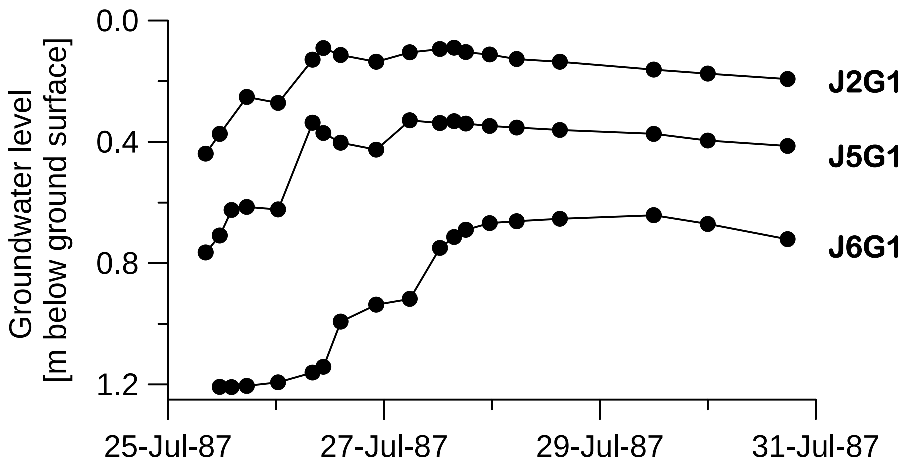

Figure 2. Groundwater levels in the Svartberget catchment, the tubes are located along a hillslope at distances of 8 m (J2G1), 50 m (J5G1) and 100 m (J6G1) from the creek (data from Bishop, 1991).

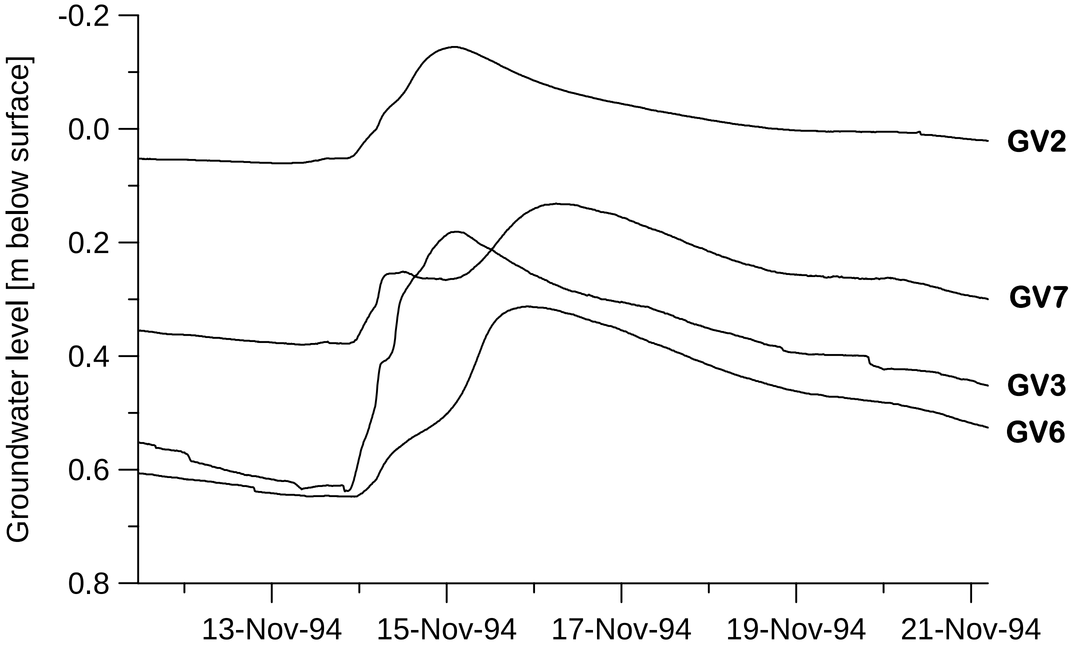

Figure 3. Groundwater levels in the Östfora catchment, the tubes are located along a hillslope at distances of 10 m (GV7), 18 m (GV6), 35 m (GV3) and 60 m (GV2) from the creek (data from Eklund, 1996).

steady-state shape of the groundwater table is assumed to be valid at any time. In combination with Eq. (7) the steady state assumption becomes the assumption that groundwater level variations can be described as a succession of steady state situations, which are reached immediately when the mean groundwater level and runoff change.

Due to the steady state assumption the response of groundwater levels and runoff from the saturated zone to recharge is neither delayed nor dampened. The upslope sub-catchment at a specific location is represented only by the value of *a*, i.e., topography within this sub-basin is of no importance for the groundwater level at this location. If the slope and the upslope area are equal for two locations, the simulated groundwater levels will always be exactly the same, independent of any difference in their upslope topography. As a result, topography has only little effect on the simulated groundwater dynamics and runoff.

In reality, it takes some time for flow from areas with low groundwater levels to contribute to the build-up of saturated areas. On the other hand, due to the steady state assumption the entire upslope area contributes immediately and, therefore, saturated areas expand too fast in TOPMODEL. This is of importance for the generation of saturation excess overland flow because a larger portion of the rain from the event in question will fall on the expanded saturated areas.

The different types of groundwater responses are of importance for the origin of groundwater contributing to discharge. It can be expected that the upslope areas will contribute less to peak discharge if groundwater levels rise later at upslope than at downslope sites.

Combined with the spatially uniform recharge assumption the steady state assumption implies that the simulated contribution of groundwater to discharge per unit area is spatially uniform over the basin at any time. Results from field experiments, however, indicate that the situation in reality can be very different. Sidle *et al.* (1995) measured storm runoff from nested sub-basins at different scales in a humid basin in Japan and found that the specific contribution to discharge from small sub-basins varied from 0 to 300% of the discharge from the entire 2.5 ha basin depending on wetness conditions. Hinton *et al.* (1993) found that the contribution from the upper part of a 3.4 ha catchment varied between 30 and 70% of the total runoff. In both examples, runoff was dominated by contributions from subsurface.

DISCUSSION AND CONCLUSIONS

The assumptions of spatial uniform recharge and steady state flow rates are both crude approximations. Measurements in different catchments showed that the response of groundwater levels to storms could show large spatial variations. The steady state assumption has implications for the generation and origin of runoff and, consequently, for geochemical simulations based on the TOPMODEL approach. SVAT models can be aggregated to larger scales by coupling them to TOPMODEL, i.e., the groundwater levels predicted by TOPMODEL are used as lower boundary conditions (e.g. Famiglietti & Wood, 1994). Obviously incorrect groundwater depths will influence the simulations. Moreover, much of the point in such modelling studies is missed, because the interdependence of hydrological fluxes in vertical and horizontal directions is not captured. As a result of the spatially uniform recharge assumption, simulated spatial patterns of evaporation are dependent on spatial patterns of groundwater levels but not vice versa.

Many studies using the TOPMODEL approach during the last years have contributed to highlight the importance of topography to hydrological processes. However, the conclusion of this paper is, that the TOPMODEL approach with its static topographic index is generally not capable of producing the correct dynamics of groundwater levels. The magnitude of the errors depends on the particular conditions. For the hillslopes used as examples in this study with their shallow groundwater table (about one metre below ground surface), the time of peak groundwater level may be missed by 2-3 days and, consequently, the simulated levels may be wrong by a couple of decimetres (Figures 2 and 3). In most applications errors will not only be generated due to the limitations discussed in this paper, but as well due to the problem of finding correct parameter values as, for instance, spatially varying transmissivity values (Seibert *et al.*, 1997). Furthermore, much of the information given by DEMs cannot be utilised by the TOPMODEL approach. Due to the steady state assumption the influence of topography on temporal variations in the response of groundwater levels is neglected, and as a result of the spatially uniform recharge assumption it is not possible to use an atmospheric forcing which depends on topography. Therefore, TOPMODEL in its present form may not be the simple, but realistic model of catchment hydrology awaited by hydrologists, geochemists, SVAT-modellers or ecologists.

Different attempts have been made to overcome the limitations of the TOPMODEL approach. Moore *et al.* (1993) relaxed the assumption of a uniform recharge rate by using an iterative algorithm to calculate a modified topographic index. Their method, however, is only thought to provide equilibrium values over longer time scales (monthly to annual). Band *et al.* (1993) divided the catchment into different hillslopes units to allow for different meteorological forcing. However, the central idea of TOPMODEL to represent natural heterogeneity by distribution functions rather than by subdividing into homogeneous units is partly lost and, more important, the problems caused by the assumptions within a hillslope unit are not resolved.

Barling *et al.* (1994) introduced a "quasi-dynamic" topographic index to relax the steady state assumption. The idea is to compute the time required for water to flow from one point to another by integrating along the flowpath. In this way, for any point the part of its upslope area contributing to subsurface flow at can be estimated using a drainage time-area relationship. As a result, index values can be computed as a function of drainage time. There are, however, serious drawbacks in their derivation of this "quasi-dynamic" index. The recharge is still assumed to be spatially uniform and, moreover, it is assumed to be constant during the entire drainage time. Furthermore, the integration along the flowpath implicitly presupposes a steady state situation.

Wigmosta *et al.* (1994) used an equation similar Equation (1) for downslope subsurface flow, but in their model this equation is explicitly evaluated cell by cell for each time step. A drawback is the large increase of computational burden.

Future research is needed to evolve TOPMODEL towards a more realistic description of groundwater dynamics. The simple analytical solution will have to be changed towards spatially explicit solutions (Kirkby, 1997). Therefore, such work will have to compromise on the simplicity of TOPMODEL. However, it may be possible to achieve more realistic variants of TOPMODEL but to retain part of its simplicity in comparison with other, distributed models (Beven, 1997; Kirkby, 1997).

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