Controls of land surface and bedrock topography on the spatial distributions of water table and storage: unifying saturation excess runoff models

Lili Yao[1] and Dingbao Wang[1]

[1]University of Central Florida

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Abstract

The control of land surface topography on the configuration of groundwater table has been recognized and well explored. However, the control of bedrock topography on water table is much less studied, potentially due to the limited observations of bedrock. This paper evaluates the controls of both surface and subsurface topography on the spatial distributions of steady-state water table and the corresponding water storage at the catchment scale based on numerical simulations. Numerical models with different topographic features are developed using MODFLOW (USG). When water table is shallow, the control on the spatial distributions of water table is dominated by land surface topography (i.e., water table is approximately parallel to land surface); with the increase of water table depth, the role of land surface topography decreases; when water table is deep and close to bedrock surface, the spatial distributions of water table is dominated by bedrock topography (i.e., water table is approximately parallel to bedrock surface). For land surface-dominated water table, storage capacity in unsaturated area is spatially uniform, which is the underlying assumption of TOPMODEL; however, for bedrock-dominated water table, water storage in unsaturated area is spatially uniform, which is the underlying assumption of VIC-type model. The systematical variations of the controls of surface and subsurface topography on water table configuration provide a framework to unify saturation excess runoff models by treating TOPMODEL and VIC-type model as two endmembers.

Controls of land surface and bedrock topography on the spatial distributions of water table and storage: unifying saturation excess runoff models

Lili Yao and Dingbao Wang*

Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, USA

*Correspondence to: dingbao.wang@ucf.edu

Abstract

The control of land surface topography on the configuration of groundwater table has been recognized and well explored. However, the control of bedrock topography on water table is much less studied, potentially due to the limited observations of bedrock. This paper evaluates the controls of both surface and subsurface topography on the spatial distributions of steady-state water table and the corresponding water storage at the catchment scale based on numerical simulations. Numerical models with different topographic features are developed using MODFLOW (USG). When water table is shallow, the control on the spatial distributions of water table is dominated by land surface topography (i.e., water table is approximately parallel to land surface); with the increase of water table depth, the role of land surface topography decreases; when water table is deep and close to bedrock surface, the spatial distributions of water table is dominated by bedrock topography (i.e., water table is approximately parallel to bedrock surface). For land surface-dominated water table, storage capacity in unsaturated area is spatially uniform, which is the underlying assumption of TOPMODEL; however, for bedrock-dominated water table, water storage in unsaturated area is spatially uniform, which is the underlying assumption of VIC-type model. The systematical variations of the controls of surface and subsurface topography on water table configuration provide a framework to unify saturation excess runoff models by treating TOPMODEL and VIC-type model as two endmembers.

Keywords: Water table; Topography; Bedrock; TOPMODEL; VIC; Saturation excess

Key points:

1. The configuration of groundwater table emulates the subsurface (surface) topography at deep (shallow) water table.

2. For land surface-dominated water table, storage capacity in unsaturated area is spatially uniform (TOPMODEL).

3. For bedrock-dominated water table, water storage in unsaturated area is spatially uniform (VIC-type model).

1. Introduction

Groundwater table is an important hydrologic interface controlling water exchange between surface and subsurface (Condon, et al., 2020; Ferguson & Maxwell, 2010; Hooshyar & Wang, 2016; Liang et al., 2003; Maxwell & Condon, 2016; Spence et al., 2009). The depth of water table at the catchment scale varies spatially (Condon & Maxwell, 2015), and the configuration of water table is directly related to the spatial distribution of water storage which determines the locations of source area for runoff generation and how much rainfall could be retained underground during a saturation excess runoff process (Appels et al., 2017; Berghuijs et al., 2016; Kollet & Maxwell, 2008; Soylu et al., 2011).

The configuration of water table has been widely simplified as the subdued replica of topography (Cardenas, 2007; Jiang et al., 2010; Micallef et al., 2020; Toth, 1963; Zhang et al., 2020). Though studies have confirmed the benefit from this simple conceptualization, it has been found that water table is not always highly correlated to the land surface topography (Condon &

Maxwell, 2015; Desbarats et al., 2002; Grayson & Western, 2001; Shaman et al., 2002). To quantify the extent of water table interactions with land surface topography, a dimensionless number called water table ratio, which is defined as the ratio of potential groundwater mounding to topographic relief, was proposed by Haitjema & Mitchell-Bruker (2005). They categorized water table into two types: topography-controlled or recharge-controlled. Topography-controlled water table is closely connected to land surface topography and is more likely developed in humid, low-permeability terrain; whereas, recharge-controlled water table is more disconnected from the land surface topography and more likely occurs in arid, more permeable terrain (Haitjema & Mitchell-Bruker, 2005). The topography-controlled water table is often associated with shallow water table depth, whilst the recharge-controlled water table commonly has a deep water table depth (Cuthbert et al., 2019; Gleeson & Manning, 2008). It is worth noting that this categorization does not account for the effect of subsurface topography since they assumed a deep horizontal bedrock.

Groundwater in unconfined aquifer is vertically constrained by both the land surface and the hydrological impeding layer. The latter could be a fresh bedrock or a soil layer with hydraulic conductivity several orders of magnitude lower than that of the surficial soil formation (Condon, et al., 2020; Freeze & Cherry, 1979). For the sake of brevity, we will refer to the hydrological impeding layer that restricts percolation as bedrock in this paper. The use of geophysical techniques revealed that the underlain bedrock topography can be substantially different from the land surface topography (McDonnell et al., 1996; St. Clair et al., 2015; Zimmer & McGlynn, 2017). Considering that the bedrock is the lower boundary of groundwater, one may be curious about the role of bedrock topography on the configuration of groundwater table. However, the correlation between bedrock and groundwater table is much less studied because it is not easy to obtain the details of bedrock topography at large spatial scales. Whilst, a number of studies focused on hillslope-scale processes have identified that bedrock topography was one of the most important physical characteristics affecting the response of groundwater to rainfall (Bachmair & Weiler, 2012; Freer et al., 2002). The topography of bedrock surface was found to exert a key control on the hydrological connectivity of subsurface drainage network (Penna et al., 2015; Tromp-van Meerveld & McDonnell, 2006).

Since both land surface and bedrock topography are important controls on the groundwater, the question then is under what circumstances does the land surface topography dominantly control the water table and under what circumstances does bedrock dominantly control the water table. Based on observations at the hillslope scale, van Meerveld et al. (2015) and Hutchinson & Moore (2000) reported that the shapes of water table change with groundwater levels, and water table configuration follows land surface topography when the water table is shallow, whereas, water table configuration follows bedrock topography when the water table is close to the bedrock. However, much uncertain still exists about the control of land surface and bedrock surface topography on the groundwater configuration and the corresponding water storage distribution at the catchment scale due to the limitation of bedrock information as mentioned previously.

Characterizing the antecedence wetness condition in the catchment is a prerequisite for the saturation excess runoff modeling. As the two most popular saturation excess runoff models, the TOPMODEL and the Probability Distributed Model (PDM) adopt different methods for the conceptualization of antecedence wetness condition. In the TOPMODEL, the hydraulic gradient of groundwater is assumed to be same as the gradient of land surface topography, and the position of water table is treated to rise or fall with spatially uniform amounts (Beven & Kirkby, 1979; Sivapalan et al., 1987). Tough it is known that water table does not always mirror land surface, it is still a reasonable simplification in regions with topography-controlled water table (Rinderer et al., 2014; Troch et al., 1993). The PDM includes the Xinanjiang model (Zhao, 1992), VIC model (Liang et al.,1994), and HyMOD (Moore, 1985), and we will use the VIC-type model to refer to the PDM hereinafter. Different from TOPMODEL, VIC-type model explicitly characterizes water storage instead of the position of water table. To facilitate the development of water balance equations, the spatial variability of maximum water storage capacity in VIC-type model is quantified using a cumulative distribution function, such as the generalized Pareto distribution function (Liang et al., 1994; Zhao, 1992) and the SCS distribution function (Yao et al., 2020). However, to the best of our knowledge, the underlying water table configuration inferred from the storage distribution of the VIC-type model is not discussed in the literature yet.

Both the TOPMODEL and VIC-type model have a hypothesis on the configuration of groundwater table. This leads to the question that if there is any linkage between these two models. As mentioned, the critical assumption about the water table configuration in TOPMODEL is more valid in regions where the water table is close to the land surface topography (i.e., shallow water table). However, it is unknown about the connection between the topography and the water table assumed in VIC-type model, and neither the suitability of VIC-type model at different water table conditions considering its underlying assumption on the water table configuration.

The objective of this paper is to gain a better understanding of the spatial pattern of groundwater table and water storage at the catchment scale with considerations of surface and subsurface topography. It will also shed light on the saturation excess runoff models regarding their assumptions of the groundwater table configuration. To achieve these goals and considering the limitation of the available observation data in the reality, we conduct numerical simulations to model groundwater flow under different conditions. The second section introduces the topographic information of the model domain, and the main features of the numerical model. Section 3 presents the spatial distributions of water table and storage at different bedrock settings, and discusses the implication of the findings to the unification of saturation excess runoff models. The final section summaries the main findings of this paper.

2. Methodology

The purpose of this paper is not to develop a numerical model for the groundwater system in a specific catchment, but to gain understanding about the controls of catchment properties on the spatial distributions of water table and storage at different steady-state groundwater levels. Therefore, a series of hypothetical models are developed in this paper.

2.1 Land surface topography

The numerical model domain is bounded by the land surface topography on the top, and the selected model area is the Crab Orchard Creek catchment located in Illinois (USGS gauge ID: 05597500) with a drainage area of approximately 80 km^2. The land surface elevation in the catchment ranges from 129 to 185 m above mean sea level as presented in Figure 1a. The average land surface slope is 0.017. The stream network on the land surface shown in Figure 1a was extracted from the digital elevation model (DEM) with a resolution of 30 m, and the "slope-drainage area" relation was used to determine the origin of the stream network (Tromp & McDonnell, 2006), which is approximately 0.14 km^2 for the model area. The highest stream order in the study catchment is 5.

2.2 Bedrock topography

Investigating the role of bedrock topography on the water table configuration is one of the main objectives in this paper. The observed bedrock of the model domain is shown in Figure 1b

(Data source is provided in the Acknowledgement section), and the average soil thickness (AST), i.e., the vertical distance between land surface and bedrock surface, is 10 m. Bedrock topography may be similar with land surface topography such as that in the model area, while the similarity of topographies between land surface and bedrock surface may vary among catchments (Freer et al., 1997). To explore the effect of bedrock topography on water table configurations, a series of synthetic bedrocks are generated in this paper. Though bedrock surface at the hillslope scale has been simplified as geometric abstractions using mathematical functions such as second-order polynomial function and curvature function (Fan & Bras, 1998; Troch et al., 2002), there is no uniform method to conceptualize the bedrock surface at the catchment scale. To facilitate practice, we proposed to utilize the observed bedrock data combined with stream network on the land surface to generate synthetic bedrocks.

The elevation (E [m]) of a synthetic bedrock at the point scale is generated by the following equation:

$$E = E_0 + s \times d \quad (1)$$

where E_0 [m] is the observed bedrock elevation of the closest cell in the stream network; s [-] is the slope of the bedrock between the cell and its closest cell, and is set to 0.002 in this study; d [m] is the horizontal component of the minimum downslope distance to a cell on the stream network, following the flow path. Since the slope of land surface is higher than 0.002, the soil depth for the generated bedrocks increases from channel to upland, which has been widely observed in nature and used in conceptual models (Rempe & Dietrich, 2014; St. Clair et al., 2015; Troch et al., 2002; Zimmer & McGlynn, 2017). The stream network used for determining the values of E_0 and d includes different orders of streams when generating different bedrocks. The bedrock, which is generated using the completed stream network, is called as the 1st-order bedrock and shown in Figure 2a. While, the 1st-order streams are excluded from the stream network when generating the 2nd bedrock which is called as the 2nd-order bedrock and shown in Figure 2b. Likewise, the 2nd-order, 3rd-order, and 4th-order streams are excluded from stream network when generating the 3rd, 4th, and 5th-order bedrock, respectively. Therefore, the topography of bedrock surface inherits less and less topographic information of land surface from the 1st to the 5th-order bedrock (Figures 2a~e). Among the 5 synthetic bedrocks, the 2nd-order bedrock (Figure 2b) has the highest similarity with the observed bedrock (Figure 1b), and their average difference of the cell-scale elevation is -0.05 m with a range from -12 m to 14 m. Noted that Figures 2a~e show the elevation relative to the lowest point in each synthetic bedrock.

To explore the control of bedrock surface topography on the water table configuration, numerical models #1-#5 with the 1st-order to 5th-order bedrocks are developed, and they are controlled to have the same AST (10 m, as same as the observation) by raising or falling the bedrock surface with a spatially uniform amount. In addition, to investigate the role of soil thickness on the water table, model #6 with the 2nd-order bedrock but with a different AST (i.e., 13 m) is further developed for comparison with model #2.

2.3 Spatial distribution of water table

The spatial distribution of the steady-state water table is obtained via numerical simulation using MODFLOW (USG) (Panday et al., 2013). The modeled domain is horizontally discretized into finite difference square cells with a resolution of 100 m × 100 m, leading to a total number of 8019 cells. The model is not discretized vertically considering that the soil thickness is much smaller than the horizontal dimensions by two to five orders of magnitude. A “drain” boundary condition is assigned to the top face of each grid (Goderniaux et al., 2013). Drain boundary is a head-dependent flux boundary, through which water leaves groundwater system when the head is higher than the land surface elevation, and it turns inactive when the head of the model cell drops below the land surface (McDonald & Harbaugh, 1998). Discharge of groundwater from an active drain surface is proportional to the drain conductance, which is assumed to be 10^6 m^2/year in this paper and is subject to change as needed. A spatially uniform recharge is applied to the model domain, and different steady-state groundwater levels are obtained by adjusting the value of recharge. The recharge considered here is the net recharge since evaporation is not considered directly in this paper. All other lateral and vertical edges of the model are set as no-flow boundaries. The saturated hydraulic conductivity is assumed to be homogeneous and isotropic. Given land surface and bedrock topography, the ratio of recharge and saturated hydraulic conductivity determines water table configuration, therefore, the absolute value of the saturated hydraulic conductivity (i.e., 315 m/year in this paper) is less important here (Gleeson & Manning, 2008; Haitjema & Mitchell-Bruker, 2005).

2.4 Soil water storage

Soil water storage in a soil column referred in this paper includes both the groundwater in the saturated zone and the soil moisture in the unsaturated zone. The groundwater storage in the saturated zone is calculated as the groundwater thickness multiplied by the soil porosity. It is assumed that the vertical distribution of soil moisture is at hydraulic equilibrium condition in the unsaturated zone (e.g., Yao et al., 2018), and the Brooks-Corey model is used for estimating the soil moisture distribution (Brooks & Corey, 1964):

$$\theta(z) = \begin{cases} (\theta_s - \theta_r)\left(\frac{L-Z}{|\varphi_a|}\right)^{-\lambda} + \theta_r, & Z \leq L - |\varphi_a| \\ \theta_s & , Z > L - |\varphi_a| \end{cases} \quad (2)$$

where θ [-] is volumetric soil water content; z [m] is the depth measured from soil surface (positive downward); θ_r [-] and θ_s [-] are the residual and saturated water content, respectively;

φ_a [m] is the bubbling pressure; λ [-] is the pore-size distribution index; and L [m] is the distance between land surface and groundwater table. The total water storage (S [m]), including the water below and above the groundwater table in each cell is calculated as follows:

$$S = \begin{cases} \int_0^{L-|\varphi_a|} \theta(z)dz + (D + |\varphi_a|)\theta_s, & L > |\varphi_a| \\ (L + D)\theta_s & , L \le |\varphi_a| \end{cases} \tag{3}$$

where D [m] is the groundwater thickness above the bottom of the grid cell. Substituting Equation (2) into Equation (3), one obtains:

$$S = \begin{cases} \frac{\theta_s - \theta_r}{(\lambda-1)|\varphi_a|^{-\lambda}}\left(|\varphi_a|^{-\lambda+1} - L^{-\lambda+1}\right) + (L - |\varphi_a|)\theta_r + (D + |\varphi_a|)\theta_s, & L > |\varphi_a| \\ (L + D)\theta_s & , L \le |\varphi_a| \end{cases} \tag{4}$$

The cell-scale water storage is calculated for each steady-state simulation.

3. Results and discussions

3.1 Spatial distribution of maximum storage capacity

The maximum storage capacity is defined as the total soil water storage space from land surface to bedrock surface. For homogeneous soil, the spatial variability of maximum storage capacity is dependent on the spatial variability of soil thickness which is determined by land surface and bedrock topography. The impact of bedrock topography on the spatial distribution of maximum storage capacity is obtained by comparing the models with each of the 5 synthetic bedrocks (Figure 2), i.e., model #1-#5. Figure 3a shows the empirical cumulative distribution function (CDF) of the normalized maximum storage capacity, i.e., the cell-scale storage capacity is normalized by its average value over the catchment (the product of 10 m and soil porosity). It can be found that each CDF presents an "S" shape, which is accordance with previous studies (Gao et al., 2020; Sivapalan et al., 1997). It is also found that the distributions of the maximum storage with the 1st and 2nd-order bedrocks are very close to the observation. The distributions with the 3rd, 4th, and 5th-order bedrocks are similar, and have a larger fraction of the catchment area with high storage capacity.

The SCS distribution (Wang, 2018) is used to model the spatial distribution of the maximum storage capacity:

$$F(x) = 1 - \frac{1}{a} + \frac{x+(1-a)}{a\sqrt{(x+1)^2-2ax}} \tag{5}$$

where x [-] is the normalized maximum storage capacity at cell scale; $F(x)$ is the fraction of the catchment area for which the normalized maximum storage capacity is less than or equal to x; a [-] is the shape parameter describing the spatial variability of the maximum storage capacity with a range from 0 to 2, and a smaller value of a indicates a larger catchment area with low storage capacity. The shape parameter of each model is obtained by fitting the normalized value of the maximum storage against Equation (5) using the non-linear least square method.

The small difference of the distribution in Figure 3a suggests that the shape of bedrock does not significantly influence the spatial distribution of the maximum storage capacity, and this is attributed to the large soil thickness considered in this paper. Compared with the shape of bedrock, soil thickness has a larger impact on the spatial variability of the maximum storage capacity. Figure 3b presents the empirical CDFs of the normalized maximum storage capacity for the model domain with the shape of the 2nd-order bedrock but having different average soil thicknesses by moving the bedrock downward with a spatially uniform value. Figure 3b shows that as soil thickness increases, the lower portion of the CDF moves upward while the upper portion moves downward, leading to a larger shape parameter. It suggests that the spatial variability of the maximum storage capacity decreases as the mean thickness increases, and it is because that the increasing thickness offsets the dispersion of maximum storage capacity at the cell scale.

Results show that the shape parameter increases systematically as the AST increases which has significant impacts on the saturation excess runoff production. Gao et al. (2020) found that the runoff generation is sensitive to shape parameter, especially when the shape parameter is close to its upper limit (i.e., 2). Specifically, the saturation excess runoff decreases as the shape parameter increases because a larger shape parameter indicates a larger percentage of catchment area having large maximum storage capacity, therefore more precipitation is retained by the soil for evaporation between precipitation events. Based on the principle of VIC-type model (Liang et al., 1994; Moore, 2007), the amount of soil wetting during a precipitation event (P) is the integration below the CDF curve along y-axis from the initial storage state (C) to the storage state with the amount of precipitation ($C + P$) (see Figure 10a). Correspondingly, runoff is the difference between the precipitation depth and the soil wetting. Therefore, for given mean maximum storage capacity and precipitation depth, if the catchment is under a dry condition which means the antecedent storage occupies only a small portion of the distribution, the catchment with a smaller shape parameter favorites the runoff generation; whereas, if the catchment is wet when the antecedent storage extends to the upper part of the distribution, the catchment with a larger shape parameter create favorable conditions for runoff generation.

3.2 Water table configuration

As mentioned in Section 2.3, mean water table depth in each model is directly determined by the ratio of recharge and saturated hydraulic conductivity (R/K); therefore, a series of water tables with mean depths from 0.5 m to 8 m were obtained by adjusting the values of R/K during simulations for each model, e.g., R/K ranges from 0.002 to 6.3E-08 for the model with the 1st-

order bedrock (AST=10 m). As mentioned in the Introduction section, groundwater is bounded by the land surface on the top and the bedrock surface on the bottom; therefore, groundwater table configuration is supposed to be controlled by the topography of both land surface and bedrock surface. Figure 4 displays the groundwater tables for the 5 synthetic bedrocks (AST=10 m) at 3 recharge conditions: WTD = 1.5 m, WTD = 4 m, and WTD = 8 m. For given land surface and bedrock surface, the similarity between water table and land surface topography decreases as the mean water table depth increases. When WTD = 1.5 m, the spatial variability of water table (Figure 4a1-4e1) in each model is almost identical to the land surface topography (Figure 1a), whereas, the water table (Figure 4a2-4e2) is much smoother when the mean water table drops to 4 m, and the water table (Figure 4a3-4e3) is much different from the land surface when WTD = 8 m. The decreasing similarity between water table and land surface confirms the decreasing control of land surface topography on the shape of water table as the mean water table depth increases (Cuthbert et al., 2019; Gleeson & Manning, 2008).

Conversely, the role of bedrock topography is more and more significant in determining water table configuration as the water table declines. By comparing the different configurations of water table for given land surface and bedrock (e.g., the 2nd-order bedrock shown in Figure 2b), it is found that the similarity between water table configuration and bedrock topography increases as the WTD increases (Figures 4b1, 4b2, and 4b3). When water table depth is large (e.g., WTD = 8 m), the distribution of water table elevation is highly similar with that of bedrock regardless the topography of bedrock (Figures 4a3-e3), and the water table configuration displays less variations within the model domain from the model with the 1st-order to that with the 5th-order bedrock which is accordance with the bedrock topography.

The similarity between water table and bedrock is directly determined by the vertical distance between water table and bedrock (DWB) instead of the water table depth. The 5 models in Figure 4 have the same AST (=10 m), therefore, the same water table depth means the same distance between water table and bedrock. To demonstrate the impact of DWB on water table configuration, Figure 5 shows the spatial distributions of water table for the 2nd-order bedrock with AST=13 m. When WTD = 8 m, the average DWB is 2 m when AST=10 m (Figure 4b3) and 5 m when AST=13 m (Figure 5a). It is obvious that the water table with a smaller DWB is more like the topography of bedrock (Figure 2b). While, when the DWB decreases to 2 m in the case of AST=13 m, Figure 5b shows that the shape of water table is also similar to that of bedrock.

To quantitatively compare the groundwater table configuration with land surface or bedrock topography, we compute the vertical separation between water table and land surface or bedrock at the cell scale following Hutchinson & Moore (2000):

$$d_{lw,i} = z_{l,i} - z_{w,i} \tag{6}$$

$$d_{wb,i} = z_{w,i} - z_{b,i} \tag{7}$$

where, $z_{l,i}$ [m], $z_{b,i}$ [m], and $z_{w,i}$ [m] are the elevations of land surface, bedrock surface, and water table at grid cell i, respectively; $d_{lw,i}$ [m] and $d_{wb,i}$ [m] are the vertical distances between water table and land surface, and between water table and bedrock surface at grid cell i, respectively. The standard deviation of $d_{lw,i}$ and $d_{wb,i}$ represents the difference between the shapes of water table and surface and subsurface topography, and a larger standard deviation means a larger difference.

Figure 6 shows the standard deviations versus the mean water table depth for the 1st-order to the 5th-order bedrock with AST=10 m. It can be found that at smaller water table depth, the standard deviation with respect to bedrock is larger than that to land surface, while at larger water table depth, the standard deviation with respect to land surface is larger than that to bedrock. Figure 6 confirms the results from Figures 4 and 5 that water table configuration is more controlled by land surface when the water table is shallow but is more controlled by bedrock when the water table is close to the bedrock. It is noted that in the middle range of water table depths, both standard deviations are quite large, which means neither land surface nor bedrock is a reasonable proxy for the water table configuration. These results are in agreement with the field observations at the hillslope scale (van Meerveld et al., 2015; Hutchinson & Moore, 2000). In addition, Figure 6 shows that standard deviation with respect to bedrock is quite different among models with different bedrocks. At large water table depth (e.g., mean water table depth = 8 m), the standard deviation (the most right triangular) decreases from the 1st-order to the 5th-order bedrock. That is because the microtopographic features on the bedrock surface are smoothed from the 1st-order to the 5th-order bedrock, correspondingly, the groundwater thickness is increasingly uniform.

3.3 Spatial distribution of water storage

It is intuitive that the amount of water storage decreases as the groundwater table depth increases. However, how does the spatial distribution of water storage change with mean water table depth has not been investigated yet. Figure 7 presents the empirical CDFs of the water storage at different mean water table depths (WTDs) for simulations with the 1st-order to the 5th-order bedrock and with 10 m of average soil thickness, in which the cell-scale storage includes groundwater storage and unsaturated zone storage calculated by Equation (4) with the hydraulic parameters of the Brook-Corey model for sand as shown in Table 1 (Rawls et al., 1982). The black curves in Figure 7 presents the empirical CDF of the maximum storage capacity. It is clear that the spatial distribution of storage evolves systematically with water table depth. The dynamics of the storage distribution is a result of groundwater flows, including the local, inter-mediate, and regional flows, which redistribute the recharged water after it reaches the water table although the applied recharge is uniform over the land surface, and groundwater flow system changes with mean water table depth (Detty & McGuire, 2010; Toth, 1963).

Given a shallow water table depth, the spatial distributions of water storage are close to the distribution of their maximum storage capacity which are similar among models with different bedrocks as shown in Figure 3a. The similar distributions of storage at shallow water table confirm that the spatial distribution is dominated by the land surface topography when the water table is shallow. The spatial distributions of water storage become increasingly different among the models as the water table depth increases, indicating the role of bedrock topography in affecting the spatial distribution of water storage at deep water table depth conditions which is consistent with the results for water table configuration in Figures 4 and 6.

Given land surface and bedrock topography, the empirical CDF of water storage gradually deviates from an "S" shape as the mean water table depth increases, and the slope of the middle part of the CDF curve decreases as the mean water table depth increases especially for the 4^{th} and 5^{th}-order bedrocks. The flatter CDF curve suggests a larger percentage of the catchment area having similar water storage. For simulations with the 1^{st}, 2^{nd}, and 3^{rd}-order bedrocks, a large number of cells have small amount of water storage in the north, the southeast, and the west when WTD = 8 m because of the relatively steep bedrocks in these regions, and the storage is mainly distributed in the downstream, leading to the abrupt change of the slope of the CDF curve. Whereas, less microtopographic features are developed in the 4^{th}-order and 5^{th}-order bedrock leading to the more spatially uniform water storage when WTD = 8 m.

3.4 Effect of hydraulic properties of soil on the distribution of water storage

Though the hydraulic properties of soil (e.g., residual and saturated moisture content, pore-size distribution index, and bubbling pressure) do not determine the position of water table directly, they play an important role in affecting the soil moisture profile in the unsaturated zone above water table. Therefore, the type of soil affects the amount of water storage and its spatial variability. Figure 8 presents the spatial distribution of water storage for clay (the hydraulic properties are shown in Table 1) with the same groundwater table depths as those in Figure 7. The empirical CDF curve gradually deviates from the distribution of maximum storage capacity gradually as the mean water table depth increases, and this result is consistent with the conclusion for sand in Figure 7. However, it can be found that given land surface and bedrock topography, the difference in the spatial distributions of water storage between different water table depths is smaller for clay than for sand. For example, the difference between the CDF for WTD = 8 m and that for WTD = 0.5 m is much smaller in Figure 8a compared with Figure 7a. That is because the larger capillary effect in clay increases the water holding capability in the unsaturated zone, leading to the smaller difference of water storage between conditions with different water table depths.

3.5 Percentage of saturated land surface

The percentage of saturated area on the land surface is an important factor for determining runoff generation since precipitation falls on the saturated area transfers to surface runoff directly. Saturated area occurs where the groundwater table intercepts with land surface; therefore, the percentage of saturated area changes with water table depth. Figure 9 presents the percentage of saturated area (defined as the ratio between the flooded area and the total area in the model) as a function of mean water table depth for simulations with the 1^{st}-order to the 5^{th}-order bedrocks (AST=10 m). When the WTD is less than 1 m, data points from different bedrock settings almost fall on a single curve because water table is dominated by the land surface topography, and the approximately linear curve on semi-log plot (Figure 9) suggests that the saturated area follows an exponential relationship with respect to mean water table depth, which is in agreement with Niu et al. (2005) who obtained an exponential relationship between the fraction of saturated area and water table depth by representing the CDF of topographic wetness index using an exponential function. However, when the WTD is larger than 1 m, the data points from different bedrocks deviate from each other because the effect of bedrock on saturated area kicks in.

3.6 Unifying saturation excess runoff models

The TOPMODEL and VIC-type model are popular hydrological models for modeling saturation excess runoff. They are usually considered to have distinct conceptualizations on the physical processes. The fundamental assumption in TOPMODEL is that the gradient of water table equals the gradient of land surface; in other words, the shape of water table is dominated by land surface topography (Beven & Kirkby, 1979). While, the VIC-type model considers the catchment as a collection of storage elements with different storage capacities represented by a probability distribution (Liang et al., 1994; Moore, 2007). What is the assumption of water table configuration in VIC-type model corresponding to the distribution of water storage? To answer this question, we propose to evaluate the VIC-type model from the perspective of water table configuration which controls to the spatial distribution of water storage.

As shown in Figure 10a, the VIC-type model assumes that water storage in the unsaturated area is spatially uniform. Water storage mainly consists of the groundwater below the water table especially for soils with small capillary effects. Thus, the VIC-type model approximately assumes that groundwater storage is spatially uniform in the unsaturated area, which means that water table is parallel to bedrock surface. Therefore, the VIC-type model assumes that the shape of water table is dominated by bedrock topography.

Both the TOPMODEL and VIC-type model assume that the water table rises or falls by spatially uniform amounts, meaning that the shape of water table does not change with water table depths. However, results from Section 3.2 have demonstrated that the shape of water table changes significantly over a wide range of water table depths, i.e., from land surface dominated to bedrock dominated. Figure 10b shows the locations of these two kinds of water tables along a representative hillslope profile in nature. The colors of the double-headed arrow in Figure 10b indicate the transition of water table types with water table depth. Considering their assumptions on the water table configuration, TOPMODEL is more reasonable in the red zone where the water table is more land surface dominated, whereas, the VIC-type model is more reasonable in the blue zone where the water table is more bedrock dominated . It has been discussed in Sections 3.2 that neither land surface nor bedrock surface provides a reasonable estimate of the water table configuration when water table is at the middle range of locations between land surface and bedrock surface indicated by the white color in the double-headed arrow; therefore, neither model is suitable under this condition. While, if the topographies of bedrock and land surface are identical, it can be speculated both the TOPMODEL and VIC-type model are reasonable for land surface-dominated water table or bedrock-dominated water table.

The dynamic of water table configuration with water table depth provides a framework for unifying saturation excess runoff models. When water table is dominated by land surface as assumed in the TOPMODEL, the available space for water storage is same over the unsaturated area, thereby water storage capacity is spatially uniform. Whilst, when water table is dominated by bedrock surface, the existing water storage in the unsaturated area is spatially uniform as assumed by VIC-type model. In the future investigations, it might be possible to have a new method to smoothly characterize the spatial distribution of water storage (or water storage capacity) from land surface-dominated water table to bedrock-dominated water table, and this new method enables a unified saturation excess runoff model suitable for different water table conditions with the TOPMODEL and VIC-type model as the two endmembers.

4. Conclusion

The spatial pattern of groundwater table and the corresponding distribution of water storage are recognized as crucial determinants of saturation excess runoff generation at the catchment scale. This paper evaluated the control of topography of land surface and that of bedrock surface on the configuration of groundwater table at different water table depths. To study the role of bedrock topography, a series of synthetic bedrocks owning different correlations with land surface topography were generated. The steady-state water tables were obtained from numerical simulations using MODFLOW (USG). Water table configuration at the catchment scale was found to be determined by the vertical distance from water table to land surface and bedrock surface. When water table is close to the land surface, land surface is a good proxy of water table; and when the water table is close to the bedrock, bedrock is a good proxy of water table. Results showed that the spatial distribution of water storage, quantified through the empirical cumulative distribution function, changes with water table depth systematically, and the water storage was more uniform when the water table is dominated by bedrock especially when the bedrock has less microtopographic features. The capillary effects of soil were found to decrease the difference of the spatial distribution of water storage between different water table depth conditions. Moreover, it was found that the percentage of saturated area on the land surface follows an exponential relationship with mean water table depth, and the relationship can be divided into two regimes based on the impacts of bedrock topography.

This paper provided a framework to unify the TOPMODEL and VIC-type model based on their assumptions on water table configuration. The assumed water table in TOPMODEL is dominated by land surface, suggesting a uniform water storage capacity in the unsaturated area; whilst the assumed water table in VIC-type model is bedrock dominated, and denotes a uniform water storage in the unsaturated area. Different saturation excess runoff models are possible to be unified by a single model which is capable to characterize the full spectrum of water table configurations: land surface-dominated type, bedrock-dominated type, and the transition between them.

The findings of this study contribute to a better understanding of the spatial distribution of groundwater table and water storage at the catchment scale, representing a further step towards developing process-based hydrological models for modeling the saturation excess runoff generation. However, these findings may be somewhat limited by the modeling sets applied in this study. First, it assumes homogenous geological properties and recharge in the model area; secondly, it assumes a hydrostatic soil moisture profile above groundwater table rather than fully coupling the saturated zone and unsaturated zone. Further studies, which consider more comprehensive spatial heterogeneity of catchment properties, could be undertaken.

Acknowledgement

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models (DEMs) at around 30 m resolution is available from National Map website (https://viewer.nationalmap.gov/basic/). The bedrock topography map of the Ozark, Illinois, Indiana, and Kentucky (OIINK) Region is available from https://clearinghouse.isgs.illinois.edu/data/geology/geologic-and-geophysical-maps-ozark-illinois-indiana-and-kentucky-oiink-region.

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Figure captions:

Figure 1: The Crab Orchard Creek catchment in Illinois (USGS gauge ID: 05597500): (a) the land surface topography and channel network with 30 m resolution; and (b) the observed bedrock topography with 100 m resolution.

Figure 2: The topography of the generated bedrock based on different orders of stream network. The values in the figure represent the relative elevation (m) above the lowest point of the generated bedrock.

Figure 3: The empirical cumulative distribution function (CDF) of the normalized maximum storage capacity (a) in models with different shapes of bedrock but with the same average soil thickness (= 10 m); and (b) in models with the 2nd-order bedrock but with different average soil thickness (AST).

Figure 4: The simulated water table elevations for the 5 synthetic bedrocks with 10 m of average soil thickness when the mean water table depth (WTD) equals 1.5 m (a1-e1), 4 m (a2-e2), and 8 m (a3-e3).

Figure 5: The water tables for the 2nd-order bedrock with 13 m of average soil thickness when (a) the mean water table depth is 8 m (i.e., the mean vertical distance between water table and bedrock surface is 5 m); (b) the mean water table depth is 11 m (i.e., the mean vertical distance between

water table and bedrock surface is 2 m).

Figure 6: The standard deviation of the vertical distance between water table and land surface or bedrock surface versus the mean water table depth when the average soil thickness is 10 m.

Figure 7: The spatial distributions of water storage for sand under different mean water table depths (WTD) when the average soil thickness is 10 m, and the black curve represents the maximum storage capacity.

Figure 8: The spatial distributions of water storage for clay under different mean water table depths (WTD) when the average soil thickness is 10 m, and the black curve represents the maximum storage capacity.

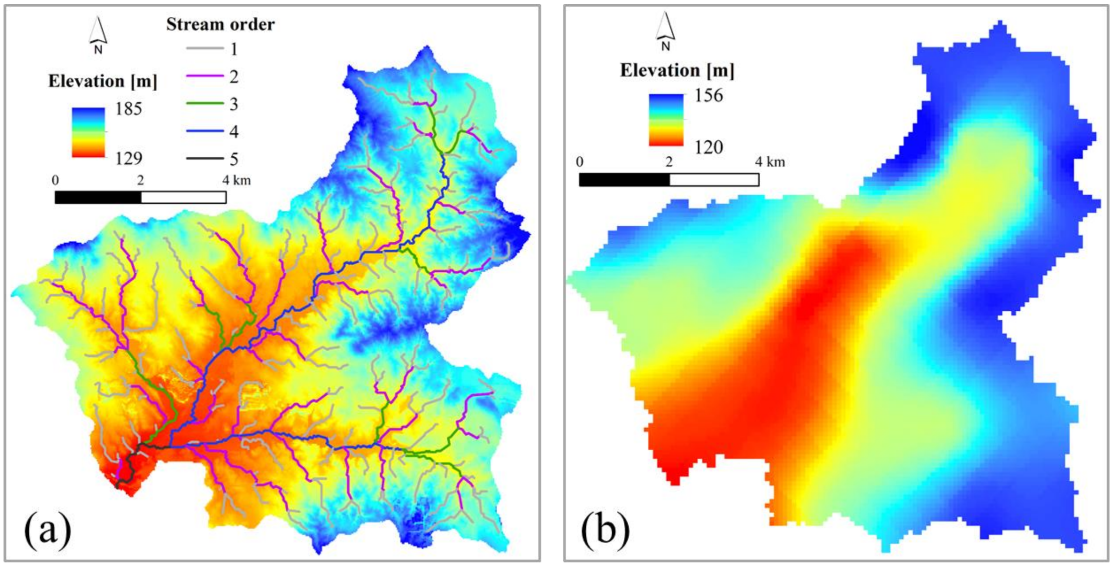
Figure 9: The relationship between saturated area percentage and mean water table depth (WTD) when the average soil thickness is 10 m. When WTD < 1 m (denoted by the black dashed line), saturated area percentage is dominated by land surface.

Figure 10: (a) The conceptualization of water storage in the VIC-type model: $F(C)$ is the fraction of the catchment area for which the storage capacity is less than or equal to C; S_0 is the initial soil water storage; P is the precipitation which is partitioned into the soil wetting (W) and runoff (R). (b) The configuration of groundwater table at different water table depths along a representative

hillslope profile in nature. The colors in the double-headed arrow indicate the transition of water table control.

Table 1 Hydraulic parameters of the Brooks-Corey model for sand and clay (Rawls et al., 1982)

Soil type	$\boldsymbol{\theta_s}$**[-]**	$\boldsymbol{\theta_r}$**[-]**	$\boldsymbol{\lvert\varphi_a\rvert}$ **[m]**	$\boldsymbol{\lambda}$**[-]**
Sand	0.417	0.020	0.072	0.592
Clay	0.385	0.090	0.373	0.131



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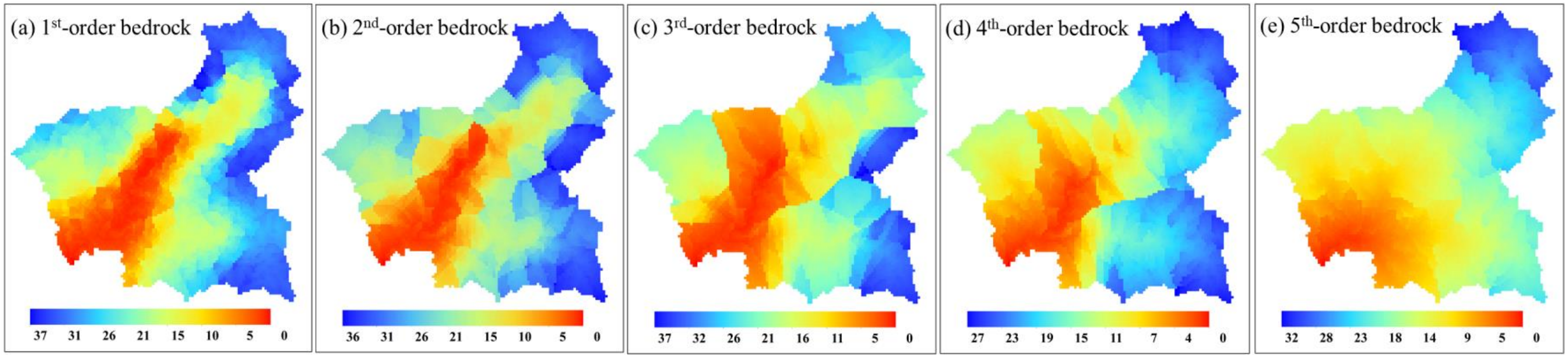


Figure 2: The topography of the generated bedrock based on different orders of stream network. The values in the figure represent the relative elevation (m) above the lowest point of the generated bedrock.

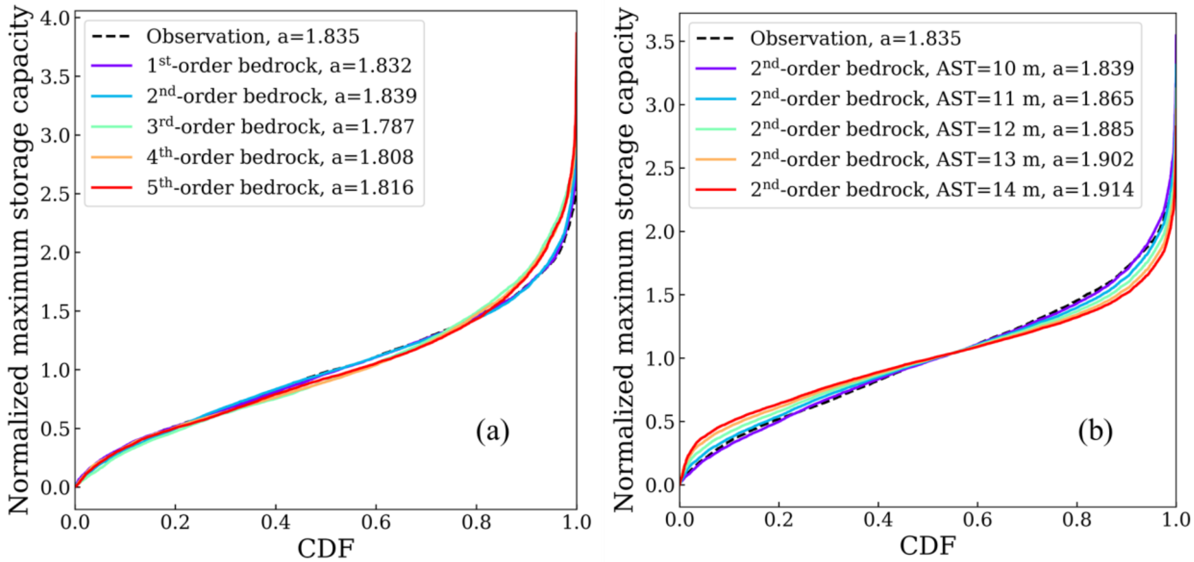
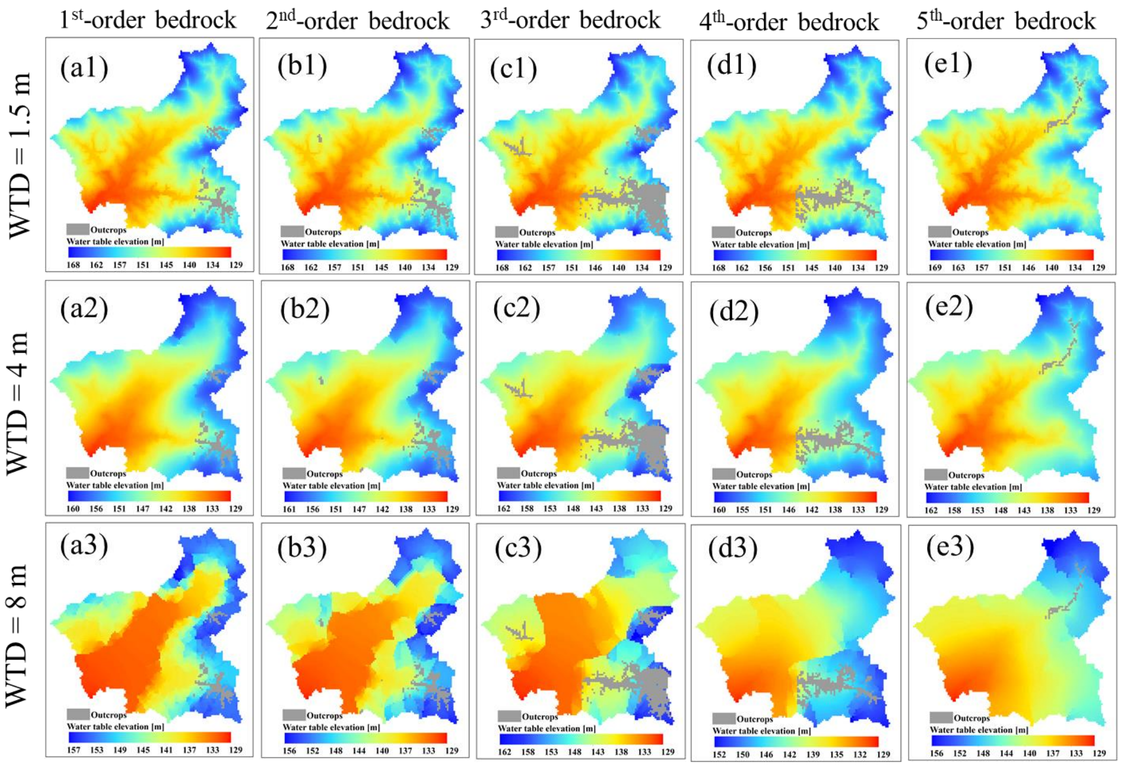


Figure 3: The empirical cumulative distribution function (CDF) of the normalized maximum storage capacity (a) in models with different shapes of bedrock but with the same average soil thickness (= 10 m); and (b) in models with the 2^{nd}-order bedrock but with different average soil thickness (AST).



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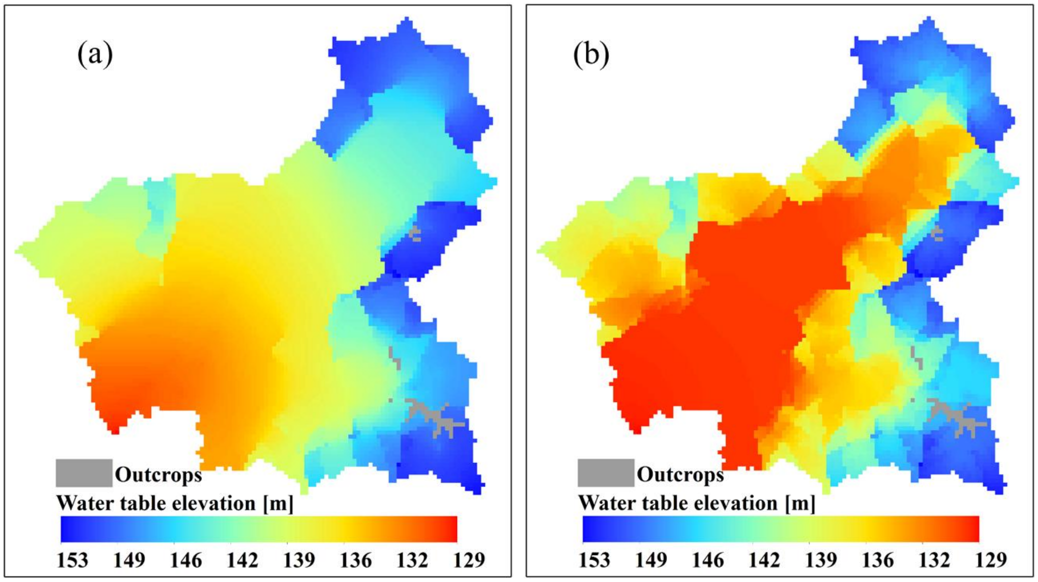

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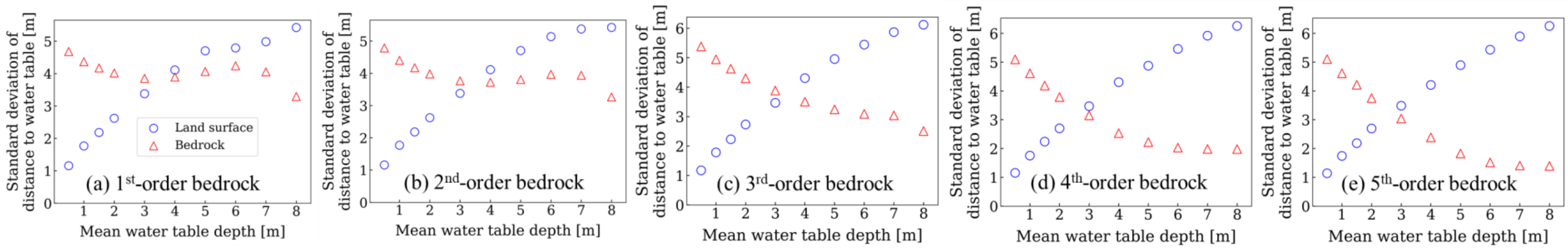

Figure 6: The standard deviation of the vertical distance between water table and land surface or bedrock surface versus the mean water table depth when the average soil thickness is 10 m.

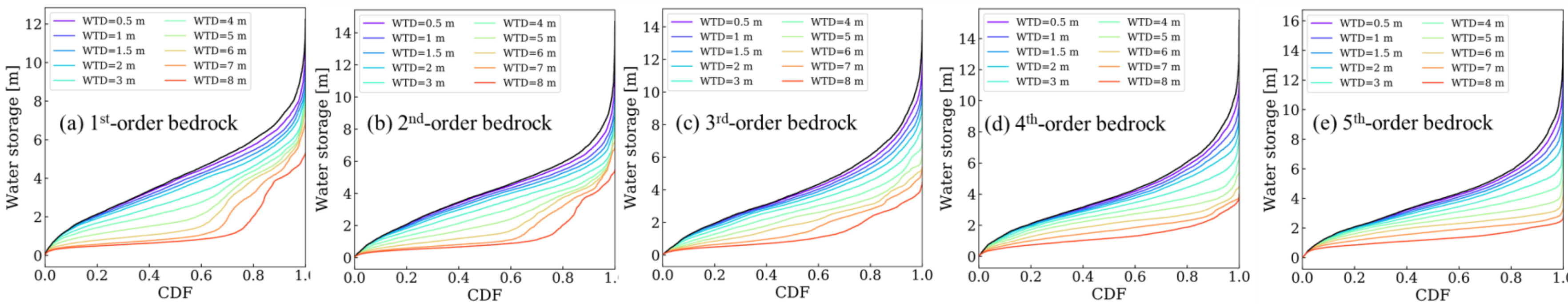

Figure 7: The spatial distributions of water storage for sand under different mean water table depths (WTD) when the average soil thickness is 10 m, and the black curve represents the maximum storage capacity.

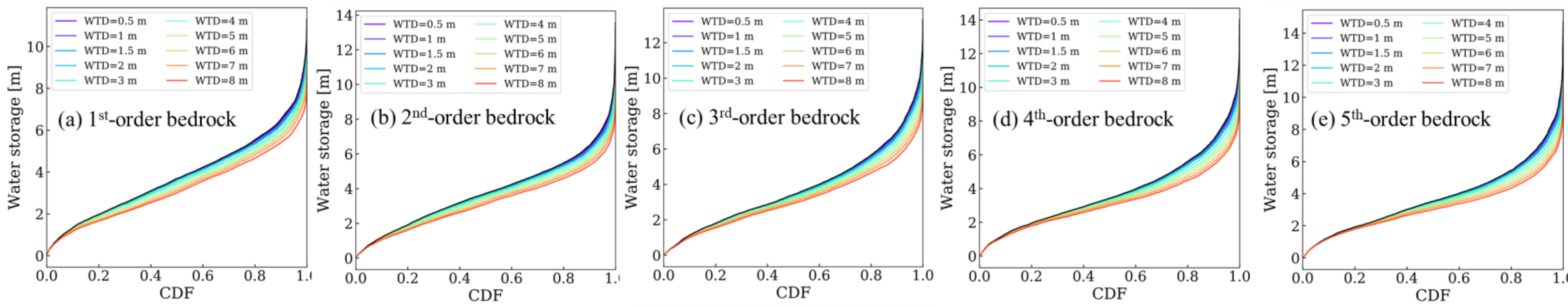

Figure 8: The spatial distributions of water storage for clay under different mean water table depths (WTD) when the average soil thickness is 10 m, and the black curve represents the maximum storage capacity.

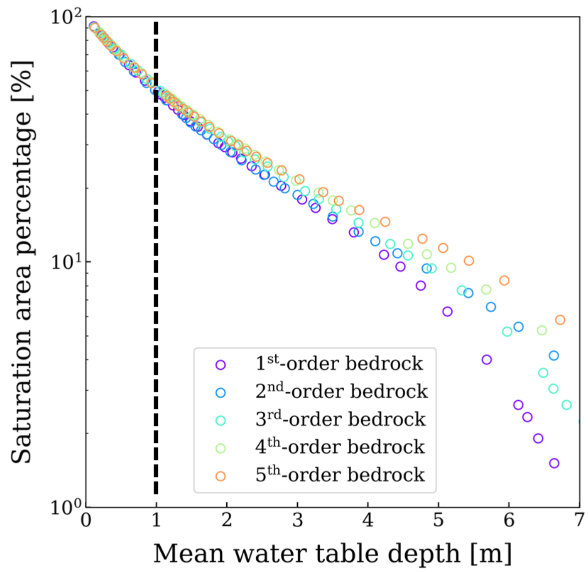

Figure 9: The relationship between saturated area percentage and mean water table depth (WTD) when the average soil thickness is 10 m. When WTD < 1 m (denoted by the black dashed line), saturated area percentage is dominated by land surface.

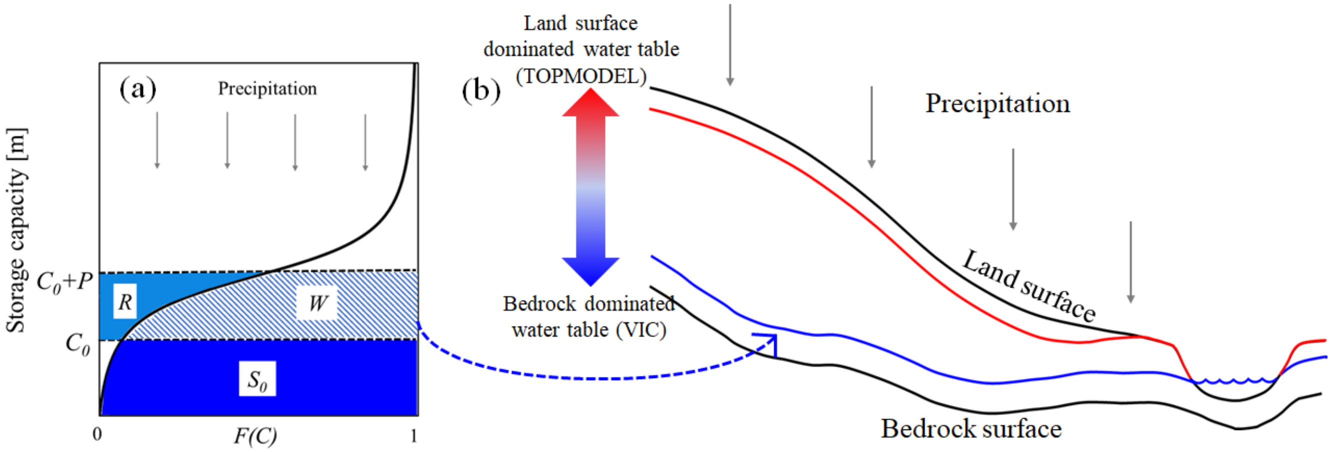

Figure 10: (a) The conceptualization of water storage in the VIC-type model: $F(C)$ is the fraction of the catchment area for which the storage capacity is less than or equal to C; S_0 is the initial soil water storage; P is the precipitation which is partitioned into the soil wetting (W) and runoff (R). (b) The configuration of groundwater table at different water table depths along a representative hillslope profile in nature. The colors in the double-headed arrow indicate the transition of water table control.