Representation of subsurface storm flow and a more responsive water table in a TOPMODEL-based hydrology model

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Received 27 April 2001; revised 11 March 2002; accepted 13 March 2002; published 27 August 2002.

[1] This study presents two new modeling strategies. First, a methodology for representing the physical process of subsurface storm flow within a TOPMODEL framework is developed. In using this approach, discharge at quick flow timescales is simulated, and a fuller depiction of hydrologic activity is brought about. Discharge of water from the vadose zone is permitted in a physically realistic manner without a priori assumption of the level within the soil column at which subsurface storm flow saturation can take place. Determination of the subsurface storm flow contribution to discharge is made using the equation for groundwater flow. No new parameters are needed. Instead, regions in excess of field capacity that develop during storm events, producing vertical recharge, are also allowed to contribute to soil zone discharge. These subsurface storm flow contributions to river runoff, as for groundwater flow contributions, are a function of catchment topography and hydraulic conductivity at the depth at which such regions in excess of field capacity occur. The second approach improves groundwater flow response through a reduction of porosity and field capacity with depth in the soil column. Large storm events are better captured and a more dynamic water table develops with application of this modified soil column profile (MSCP). The MSCP predominantly reflects soil depth differences in upland and lowland regions of a watershed. Combined, these two approaches, subsurface storm flow and the MSCP, provide a more accurate representation of the timescales at which discharge responds and a more complete depiction of hydrologic activity. Storm events large and small are better simulated, and some of the biases previously evident in TOPMODEL simulations are reduced. *INDEX TERMS:* 1836 Hydrology: Hydrologic budget (1655); 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* TOPMODEL, storm flow, vadose zone processes, soil porosity profile

1. Introduction

[2] Successful modeling of the hydrologic cycle requires representation and quantification of the various pathways by which water migrates through a catchment. Over the last thirty years, many factors impacting the spatial and temporal variability of the hydrologic cycle, and the scales at which these processes operate, have been elucidated and applied to model simulations. These developments have permitted modeling of the spatial distribution of soil moisture levels across the land surface, water movement within the soil column, and the relative contributions of evapotranspiration and river runoff to the efflux of water from the catchment system.

[3] Many hydrology models have been developed using TOPMODEL formulations [*Ambroise et al.*, 1996a; *Beven and Kirkby*, 1979; *Koster et al.*, 2000; *Sivapalan et al.*, 1987; *Stieglitz et al.*, 1997]. A framework of analytic equations, TOPMODEL is based on the idea that topography is the primary determinant of the distribution of soil moisture at and within the land surface [*Beven*, 1986a, 1986b; *Beven and Kirkby*, 1979; *Beven et al.*, 1994].

[4] TOPMODEL formulations define areas of hydrological similarity, that is, points within a watershed that respond to meteorological forcing in similar fashion, saturating to the same extent, producing the same levels of discharge, etc. These points of hydrological similarity are identified by an index that is derived from analysis of catchment topography. This topographic index is often of the form $ln(a/tan\beta)$, where $tan\beta$ is the local slope angle at a patch on the land surface, and a is the amount of upslope area draining through that patch. Lowland areas tend toward higher topographic index values, due to a combination of either low slope angle or large upslope area. Upland areas tend conversely toward lower topographic index values. Points within a catchment with the same topographic index value are assumed to respond identically to atmospheric forcing. Thus within a TOPMODEL framework, the topographic index provides the fundamental unit of hydrological response.

[5] This fundamental topographic unit is derived from three basic assumptions (see *Ambroise et al.* [1996a] and *Beven* [1997] for details): (1) the water table is approximately parallel to the topographic surface so that the local hydraulic gradient is close to $tan\beta$; (2) the saturated hydraulic conductivity falls off exponentially with depth;

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0043-1397/02/2001WR000636

and (3) the water table is recharged at a spatially uniform, steady rate that is slow enough, relative to the response timescale of the watershed, to allow the assumption of a water table distribution that is always at equilibrium. These assumptions permit reconstruction of the spatial variability of catchment response to meteorological forcing solely from modeling of the response of the mean state. This quasi-stochastic approach is at once computationally efficient while still permitting dynamic representations of physical processes within the system.

[6] These conceptual underpinnings provide a foundation for physically based modeling of catchment hydrology. Land surface models based on these formulations have been applied to catchments both large [*Ducharne et al.*, 2000] and small [*Beven and Kirkby*, 1979]. However, while the TOPMODEL framework has provided hydrologists with a powerful and efficient tool for modeling hydrologic conditions, the full complement of dynamic processes is not represented in most TOPMODEL applications. As a consequence, model simulations often perform poorly during drier conditions. The response of watersheds to wetting by spring snowmelt and to storms after an extended dry period have proven particularly difficult to represent. Correction of these simulation inaccuracies requires a more detailed depiction of the hydrologic cycle and catchment physical structure.

2. Discharge Response

[7] Four physical processes contribute to river runoff in a watershed: (1) precipitation onto stream channels; (2) overland flow; (3) shallow subsurface storm flow; and (4) groundwater flow [*Hornberger et al.*, 1998]. The first two of these processes respond very rapidly, producing spikes in hydrographs during and immediately after storm events.

[8] The third mechanism, shallow subsurface storm flow, responds at the quick flow timescale. (Note: in this paper the terms subsurface storm flow and groundwater flow refer to physical processes; the terms quick flow and base flow define short and long timescales of response.) Tracer studies have shown that shallow, subsurface regions of the soil column can support significant levels of flow during storm events [*Dewalle and Pionke*, 1994; *Hendershot et al.*, 1992; *Ogunkoya and Jenkins*, 1993]. Such regions can exist as perched water tables, disconnected from the true water table supporting groundwater flow [*Gile*, 1958; *Hammermeister et al.*, 1982; *Noguchi et al.*, 1999; *Wilson et al.*, 1990]. These perched water tables, by virtue of their development in the vadose zone nearer the land surface, can flow more quickly, discharging their waters more rapidly to the catchment river network. However, the timing of the development of these perched water tables and their size and placement within the soil column have proven difficult to model.

[9] Subsurface storm flow has been represented in Variable Infiltration Capacity (VIC) models [*Liang et al.*, 1994; *Lohmann et al.*, 1998a, 1998b]. VIC models provide a viable modeling alternative to the more physically based TOPMODEL approach. These parameterized reservoir models mimic the timescales of catchment hydrologic response to storm events and can be structured to emulate quick flow and base flow timescales. Such timescales are calibrated to inferred rates of quick flow and base flow derived from runoff analyses.

[10] Recently, *Scanlon et al.* [2000] included subsurface storm flow in a TOPMODEL-based hydrology model through introduction of a parameterized quick flow reservoir. This model represents a hybridization of the parameterized reservoir and TOPMODEL approaches. The authors used a saturation deficit model as their basic soil column structure, then added a second saturation deficit reservoir from which subsurface storm flow would be determined. The groundwater flow and subsurface storm flow components were partitioned so as not to overlap and thus supersaturate the soil column. Analyses of hydrograph response to different storm events and antecedent conditions, and piezometer sampling of the study catchment were used to determine the saturation deficit recession coefficients. Two timescales of response, an order of magnitude apart (471 and 36 hours for groundwater flow and subsurface storm flow, respectively), were delineated; these rates were applied to the reservoir discharge formulations. The authors used a linear rate of decrease in the transmissivity of the soil column for the subsurface storm flow reservoir, while maintaining an exponential decay of transmissivity for the groundwater reservoir. Flow from the subsurface storm flow reservoir to the groundwater reservoir was facilitated by a linear recharge function. For the study watershed, the model depicted both the rapid and slow discharge of water from the soil column following storm events.

[11] This hybrid modeling approach [*Scanlon et al.*, 2000] produced three additional parameters: one for subsurface storm flow reservoir maximum capacity; a second for the subsurface storm flow discharge rate; and a third for the linear recharge function. Successful simulation of catchment hydrology required calibration of these parameters to rates inferred from analysis at a highly instrumented experimental watershed. An attractive alternative to this hybrid model approach would be one allowing a more general inclusion of subsurface storm flow, while requiring fewer parameterizations. Indeed, if subsurface storm flow could be incorporated in a manner consistent with the TOPMODEL formulations that govern the flow of water within the soil column, no additional parameters would be necessary.

[12] The fourth process contributing to river runoff in a watershed, groundwater flow, provides most of the base flow during extended periods between storm events. This discharge mechanism is represented in land surface hydrology models constructed in the TOPMODEL framework [*Ambroise et al.*, 1996a, 1996b; *Stieglitz et al.*, 1997; *Wood et al.*, 1990]. Specifically, TOPMODEL formulations permit dynamically consistent calculations of both the partial contributing area, from which precipitation onto stream channels and overland flow can be determined, and the groundwater flow that supports this area. However, model recession hydrographs often run high during wet periods, then low during drier months, as will be shown in this paper. Consequently, calibrations applied during wet conditions corrupt simulation accuracy during dry conditions, and vice versa.

[13] These model discharge biases reflect inappropriate levels of groundwater flow generation. Within the TOPMODEL framework, groundwater discharge is determined

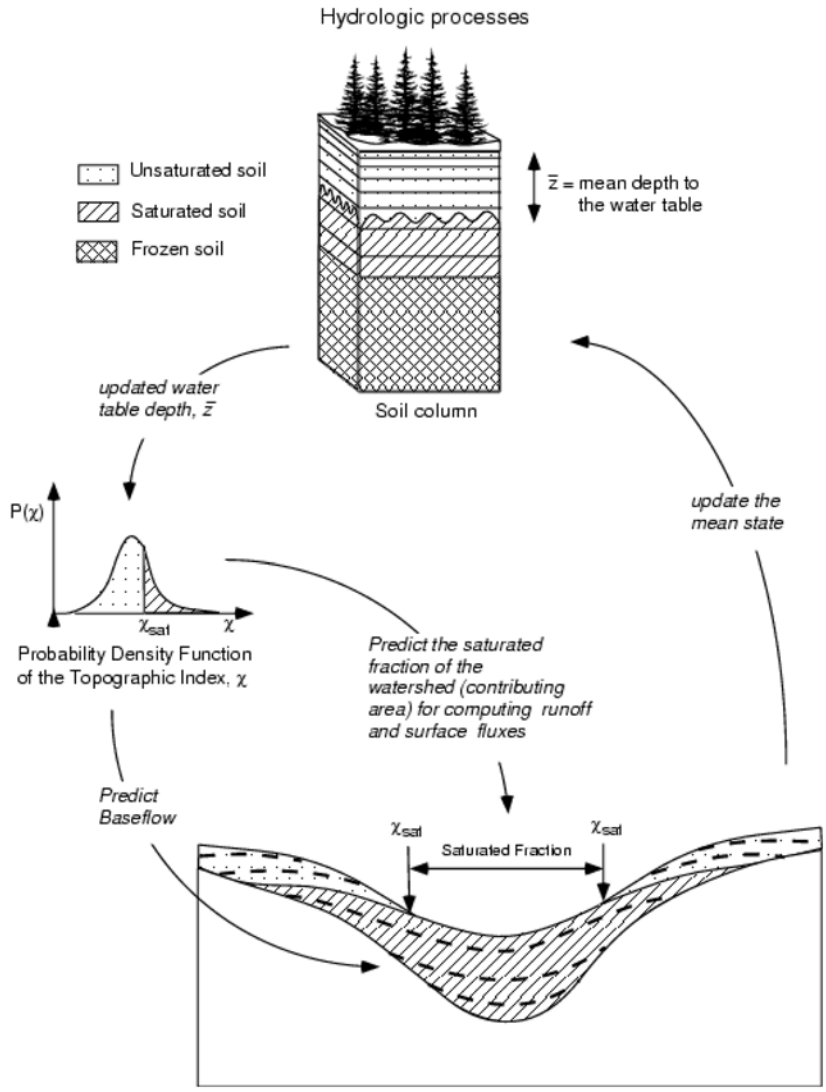


Figure 1. Schematic of the hydrology model. The model couples the analytic form of TOPMODEL equations within a discretized column framework. From an update of the mean water table depth, TOPMODEL equations and DEM data are used to generate groundwater flow and the saturated fraction of the watershed.

by the height of the water table (or analogously by the saturation deficit). Low groundwater flow simulation during dry conditions stems from greater depth of the water table and concomitant lower hydraulic conductivities controlling both discharge and recharge rates. During such dry conditions the model water table height often is not sufficiently responsive to recharge, and thus groundwater flow discharge is muted. A more responsive water table needs to be represented if groundwater discharge rates are to be more accurately modeled.

[14] Altering the rate of exponential decay in saturated hydraulic conductivity with soil depth can produce a more responsive water table and a better hydrograph match during dry conditions; however such alterations corrupt model simulation during wet conditions. A more dynamic water table could also be effected by increasing infiltration-recharge rates; however, these rates are set by Darcy's Law and the TOPMODEL assumption that saturated hydraulic conductivity decays exponentially with depth: the same attributes controlling groundwater discharge. Thus recharge cannot be altered without changing groundwater discharge, or decoupling the mechanisms controlling these two processes. Given that the true geometry and extent of soil types and preferential flow pathways used for recharge and discharge within most hillslopes are unknown, such a decoupling, which assumes different pathways supporting recharge and discharge, is questionable. Instead, a physically representative modification is needed that engenders greater response of the water table to recharge, thereby intensifying groundwater flow response.

[15] Here we present two new strategies intended to address these model shortcomings: (1) a physically based approach to modeling subsurface storm flow and its application in a manner consistent with TOPMODEL assumptions; (2) a modified soil column framework, in which porosity and field capacity are realistically allowed to change with depth, that provides a more responsive water table and better groundwater flow simulation. Together,

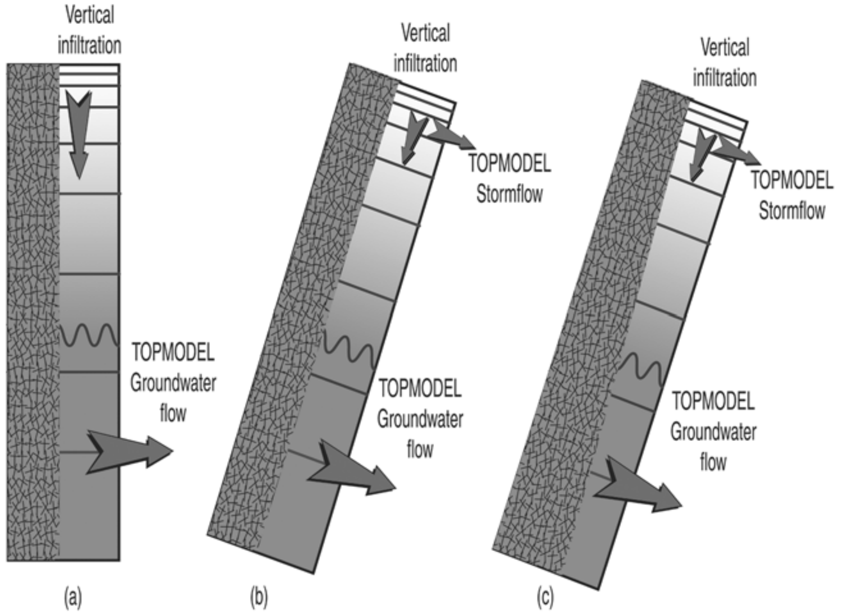


Figure 2. Schematic of the subsurface storm flow and MSCP modifications. (a) Baseline model soil column with a fixed level of porosity and field capacity with depth. Porosity and field capacity are represented jointly by the open areas of the column; solid soil is represented by the hatched brick filling the left of the column; in this version, vertical infiltration recharges the water table raising groundwater flow. (b) Model with subsurface storm flow. Gravity directs a component of the recharge laterally generating subsurface storm flow. (c) Model with subsurface storm flow and the MSCP, as for Figure 2b) but with reduced porosity and field capacity with depth (represented by the expanding hatched brick). See color version of this figure at back of this issue.

these strategies produce a more complete and accurate depiction of hydrologic activity at the catchment scale.

3. Hydrology Model

[16] The hydrology model employed for this study has been previously described [*Stieglitz et al.*, 1997]. Two methods are used for modeling the flow of water within a catchment. The first is a soil column model that simulates the vertical movement of water and heat within the soil and between the soil surface plus vegetation to the atmosphere. The ground scheme consists of ten soil layers. Layer thicknesses are structured in a geometric series determined from the depth of the first ground layer, typically 4 centimeters for this study. Diffusion and a modified tipping bucket model govern heat and water flow, respectively. The prognostic variables, heat and water content, are updated at each time step. In turn, the fraction of ice and temperature of a layer may be determined from these variables. A three-layer snow model is incorporated in the model structure [*Lynch-Stieglitz*, 1994; *Stieglitz et al.*, 2001].Transpiration and other surface energy balance calculations use a standard vegetation model [*Pitman et al.*, 1991] that includes bare soil evaporation and canopy interception loss.

[17] The second method partitions the catchment surface into two distinct hydrologic zones: saturated lowlands; and unsaturated uplands. Using the statistics of the topography, the horizontal movement of groundwater is tracked from the uplands to the lowlands (a TOPMODEL approach). Combining these two approaches (Figure 1) produces a three-dimensional picture of soil moisture distribution within a catchment. The partitioning of runoff and surface water and energy fluxes is effected without the need to explicitly model the landscape. Specifically, an analytic relation, derived from TOPMODEL assumptions, exists between the mean water table depth ($\bar{z}$), determined from the soil column model, and local water table depth at any location x (z_x) [*Sivapalan et al.*, 1987; *Wood et al.*, 1990]

$$z_x = \bar{z} - 1/f\left[ln(a/tan\beta)_x - \lambda\right] \tag{1}$$

where $ln(a/tan\beta)_x$ is the local topographic index at location x; λ is the mean watershed value of $ln(a/tan\beta)$, and f is the rate of decline of the saturated hydraulic conductivity with depth in the soil column. By setting z_x equal to zero, i.e., locating the local water table depth at the surface, saturated regions of the land surface can be identified. This partial contributing area includes all locations for which

$$ln(a/tan\beta)_x \geq \lambda + f\bar{z} \tag{2}$$

[18] From this partitioning, the contributions to river runoff of both precipitation directly onto stream channels and overland flow (saturation-excess runoff) can be quantified. Following *Sivapalan et al.* [1987], groundwater flow (Q_b) is

$$Q_b = \frac{AK_s(z=0)}{f} e^{-\lambda} e^{-f\bar{z}} \tag{3}$$

where A is the area of the watershed, and K_s is the saturated hydraulic conductivity at the surface. This flow through the soil matrix supports river discharge between storm events.

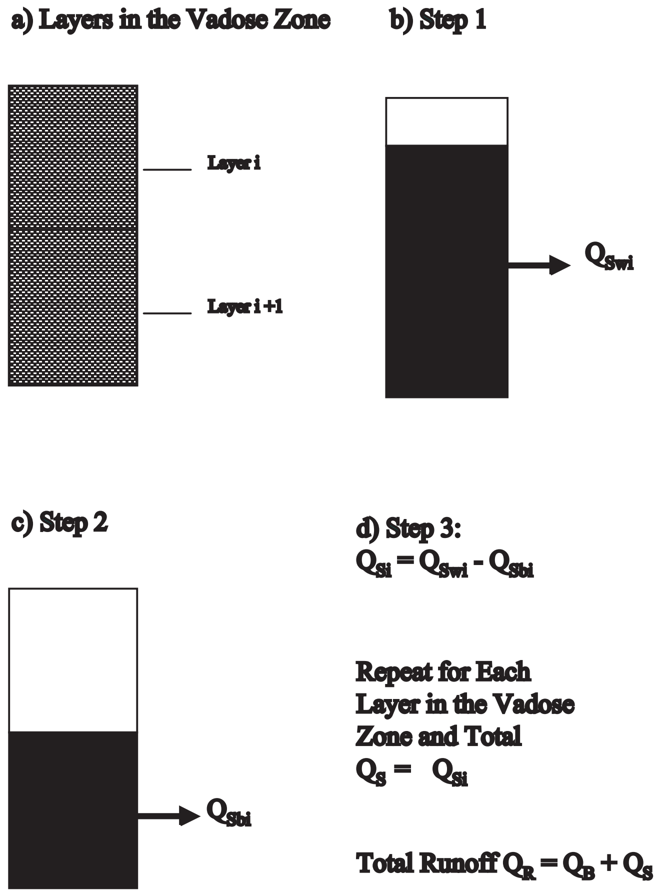


Figure 3. Calculation of subsurface storm flow. (a) Calculation of subsurface storm flow in layer i begins if saturation exceeds field capacity. (b) Water in excess of field capacity is redistributed in a fully saturated band from the base of layer i upward; all layers below are filled and groundwater flow is calculated for a water table of this height (Q_{Swi}). (c) Groundwater flow is calculated a second time for a water table height filled to the base of layer i (Q_{Sbi}). (d) Subsurface storm flow for layer i (Q_{Si}) is the difference between Q_{Swi} and Q_{Sbi}. Total subsurface storm flow (Q_S) is the summation of subsurface storm flow from each layer. Total runoff (Q_R) is the sum of total subsurface storm flow and groundwater flow (Q_B).

[19] This combined approach to modeling the land surface has been validated at several watersheds, ranging in scale from 2.2 km^2 [*Stieglitz et al.*, 1999] to 570,000 km^2 [*Ducharne et al.*, 2000].

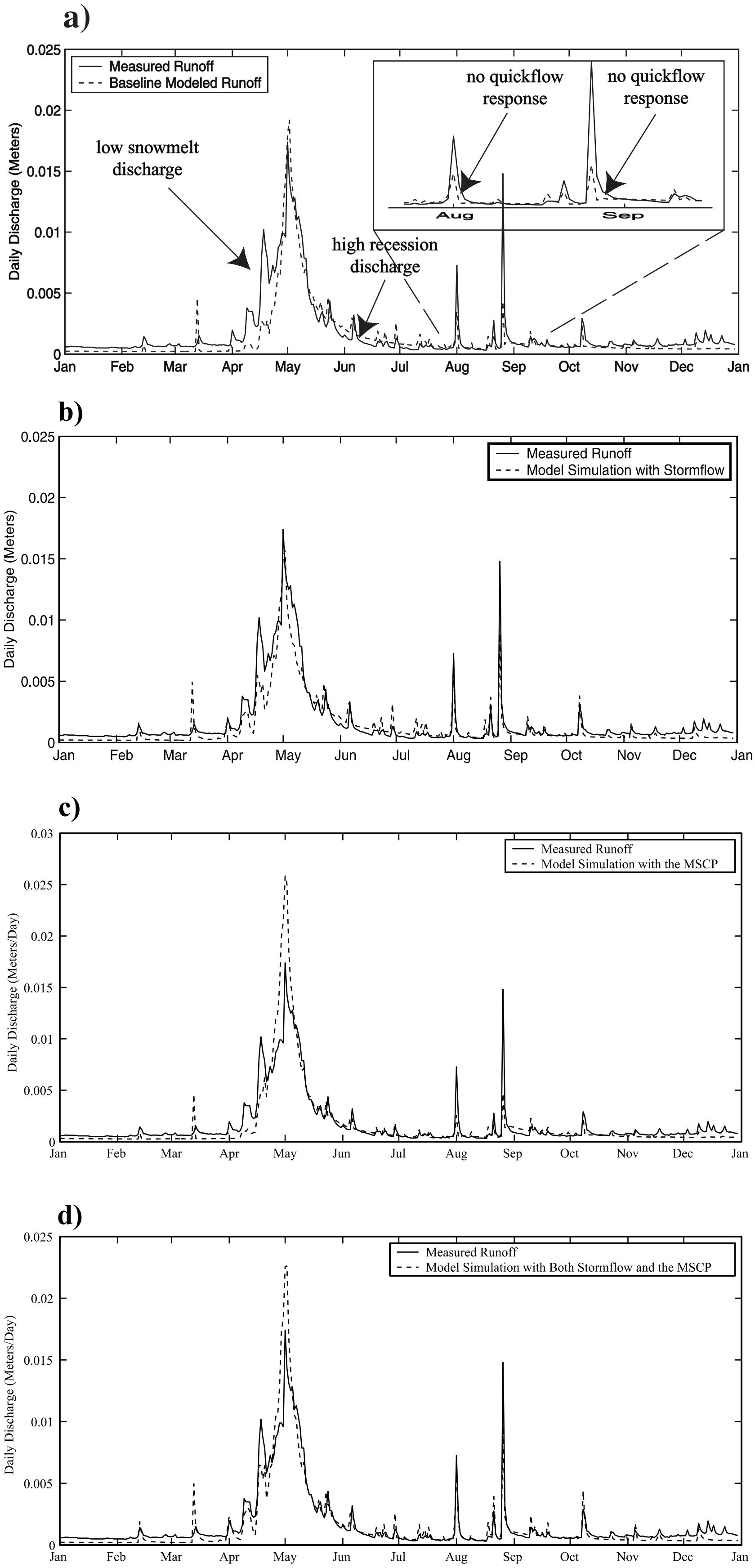
4. Approach

4.1. Conceptualization of Subsurface Storm Flow

[20] Within our hydrology model, field capacity (θ_{fc}) is taken from the empirical analysis of *Hillel* [1977], which found infiltration to initiate at 70% of the volumetric moisture retained within soils at −33kPa [see *Rawls and Brakensiek*, 1985]. Darcian flow accounts for recharge of the water table within our model, and therefore occurs in layers for which volumetric soil moisture is greater than θ_{fc}. Our conceptualization of subsurface storm flow makes use of this condition. We argue that not only will Darcian flow produce vertical recharge of the water table, but it will also bring about subsurface storm flow discharge. Such subsurface storm flow is a natural consequence of the topographic variability of the watershed and the TOPMODEL assumption that water tables form parallel to the land surface. While our hydrology model conceptualizes a vertical soil column and horizontal land surface, in fact most of the land surface is sloped (Figure 2). Thus gravity will not force Darcian flow within the soil column solely in the direction of the water table: a component of the flow will also be directed laterally. Just as the true water table migrates through the soil column, regions in excess of field capacity in the vadose zone will also produce discharge. It is thus possible to develop a representation of shallow subsurface storm flow making use of the existing formulations for groundwater flow (i.e., equation (3)). As with groundwater flow, gravity guides the motions of these subsurface storm flow waters.

[21] Model subsurface storm flow is initiated within a layer of the vadose zone when the volumetric soil moisture level exceeds field capacity (Figure 3). Calculation of the subsurface storm flow component begins with redistribution of the excess water into a fully saturated region from the base of the layer upward:

$$sw_i = zb_i - \left(\frac{\theta_i - 0.7\theta_{fci}}{\phi_i - 0.7\theta_{fci}}\right)\Delta z_i \theta_i > 0.7\theta_{fci}, \tag{4}$$


a)
Measured Runoff
Baseline Modeled Runoff
Daily Discharge (Meters)
low snowmelt discharge
high recession discharge
no quickflow response
no quickflow response
Aug
Sep
0.025
0.02
0.015
0.01
0.005
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
b)
Measured Runoff
Model Simulation with Stormflow
Daily Discharge (Meters)
0.025
0.02
0.015
0.01
0.005
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
c)
Measured Runoff
Model Simulation with the MSCP
Daily Discharge (Meters/Day)
0.03
0.025
0.02
0.015
0.01
0.005
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
d)
Measured Runoff
Model Simulation with Both Stormflow and the MSCP
Daily Discharge (Meters/Day)
0.025
0.02
0.015
0.01
0.005
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

where sw_i is the subsurface storm flow water table in layer i, zb_i is the bottom boundary of model layer i, θ_i is the volumetric soil moisture in layer i, θ_{fci} is the field capacity in layer i, and ϕ_i is the porosity in layer i. As in the work of *Stieglitz et al.* [1997], groundwater flow is calculated given a water table of that height (Q_{swi}). Groundwater flow is then calculated a second time for a water table of height to the top of the layer below (Q_{Sbi}). This second value is subtracted from the first, leaving only the flow within the layer in question.

$$Q_{Si} = Q_{Swi} - Q_{Sbi} \tag{5}$$

Total subsurface storm flow for a given time step is merely the sum of the subsurface storm flows for each layer in the vadose zone.

$$Q_S = \Sigma Q_{Si} \tag{6}$$

[22] This formulation requires no new parameterizations. It incorporates the local hydraulic conductivities within each layer. Zones in excess of field capacity that develop close to the surface flow more quickly than zones formed at depth. This circumstance necessarily generates different rates of subsurface storm flow and groundwater flow. These differences reflect the timescales of quick flow and base flow.

4.2. Modified Soil Column Profile (MSCP)

[23] Catchment upland areas tend to possess shallower soils than lowland areas [*Cox and McFarlane*, 1995; *Webb and Burgham*, 1997; *Yanagisawa and Fujita*, 1999]. Consequently, at the depth of upland bedrock, lowland areas may still be comprised of sedimented sands, clays and organics, supporting a greater porosity and field capacity. Because our hydrology model employs a single soil column framework, we cannot explicitly depict these different soil depths. However, we contend that these differences in soil depth among upland and lowland areas can be represented by an averaging of spatial attributes in application to the single column TOPMODEL framework.

[24] Like many hydrology models, ours has previously used a single parameter value for porosity, and a second for field capacity, regardless of depth in the soil column [*Stieglitz et al.*, 1997]. We argue that because of shallower upland soils, single parameter values for porosity and field capacity are not appropriate. Deeper in the soil column, where a greater percentage of the catchment is bedrock, the mean porosity and field capacity of the catchment should decrease. We introduce a new parameterization in which porosity and field capacity are allowed to decrease with depth in the soil column profile. Such a modified soil column profile (MSCP) is consistent with TOPMODEL steady-state assumptions. This MSCP could, in a sense, be interpreted as an averaging of soil depth properties over the upland and lowland areas of the catchment—as depth in the soil increases, the fraction of the catchment with bedrock at that depth increases, so that the average porosity decreases.

[25] Further support for use of the MSCP is derived from empirical studies. Soil porosity has been shown to decrease with depth in field site analyses using a variety of methods, including mercury intrusion [*Ajmone-Marsan et al.*, 1994], bulk density [*Asare et al.*, 1999; *Bonell et al.*, 1981; *Cox and McFarlane*, 1995], and fractal approaches [*Bartoli et al.*, 1993; *Oleschko et al.*, 2000]. These profiles reflect near-surface bioturbation and soil compaction. Although the impact of compaction and bioturbation on water table dynamics is probably less important than that of spatial variability in bedrock depth, these observed one-dimensional porosity profiles are at least consistent with the proposed parameterization.

[26] A one-dimensional soil column framework, of course, cannot explicitly represent three-dimensional heterogeneity. However, by allowing porosity and field capacity to decrease with depth, we can represent some of the three-dimensional variability present within a catchment; that is, we can characterize some of the depth-related heterogeneity of soils in our one-dimensional TOPMODEL soil column profile.

[27] With use of the MSCP, a unit of recharge will raise the water table level more quickly when the water table is low (that is, when the catchment is dry). Thus the MSCP should produce a more responsive water table and generate greater groundwater flow. To test this hypothesis, we applied simple and equal geometric reductions to both the porosity (cm^3/cm^3) and the field capacity (cm^3/cm^3), ranging from 1% to 15% per layer, to the soil column of our hydrology model. This MSCP formulation introduced a single additional parameter to the model structure. By the above arguments, steeper catchments with shallower upslope soils should require a greater rate of decrease of porosity and field capacity with depth.

4.3. Model Simulations

[28] Experimental watersheds at Sleepers River and at Black Rock Forest were used in this study. These sites are topographically representative of the rolling hillslope and steeper ravine catchments that dominate the hydrology of the northeastern United States. Meteorological conditions at both watersheds typify the daily, seasonal and interannual variability of this mid-latitude region. Periods of drought, particularly during summer, are not uncommon for either watershed.

[29] At each study site, four model simulations were performed: (1) a baseline run without any of the new modifications; (2) simulation with subsurface storm flow; (3) simulations with the MSCP; (4) simulations with both subsurface storm flow and the MSCP. As is standard practice, for the baseline run, the parameters for saturated

Figure 4. (oppposite) 1971 Sleepers River discharge simulations. (a) Comparison of the baseline modeled runoff and the measured hydrograph. Labels and the inset indicate simulation shortcomings. (b) Comparison of model simulation with subsurface storm flow and the measured hydrograph. (c) Comparison of model simulation with a 5% MSCP and the measured hydrograph. (d) Comparison of model simulation with subsurface storm flow and a 5% MSCP with the measured hydrograph.

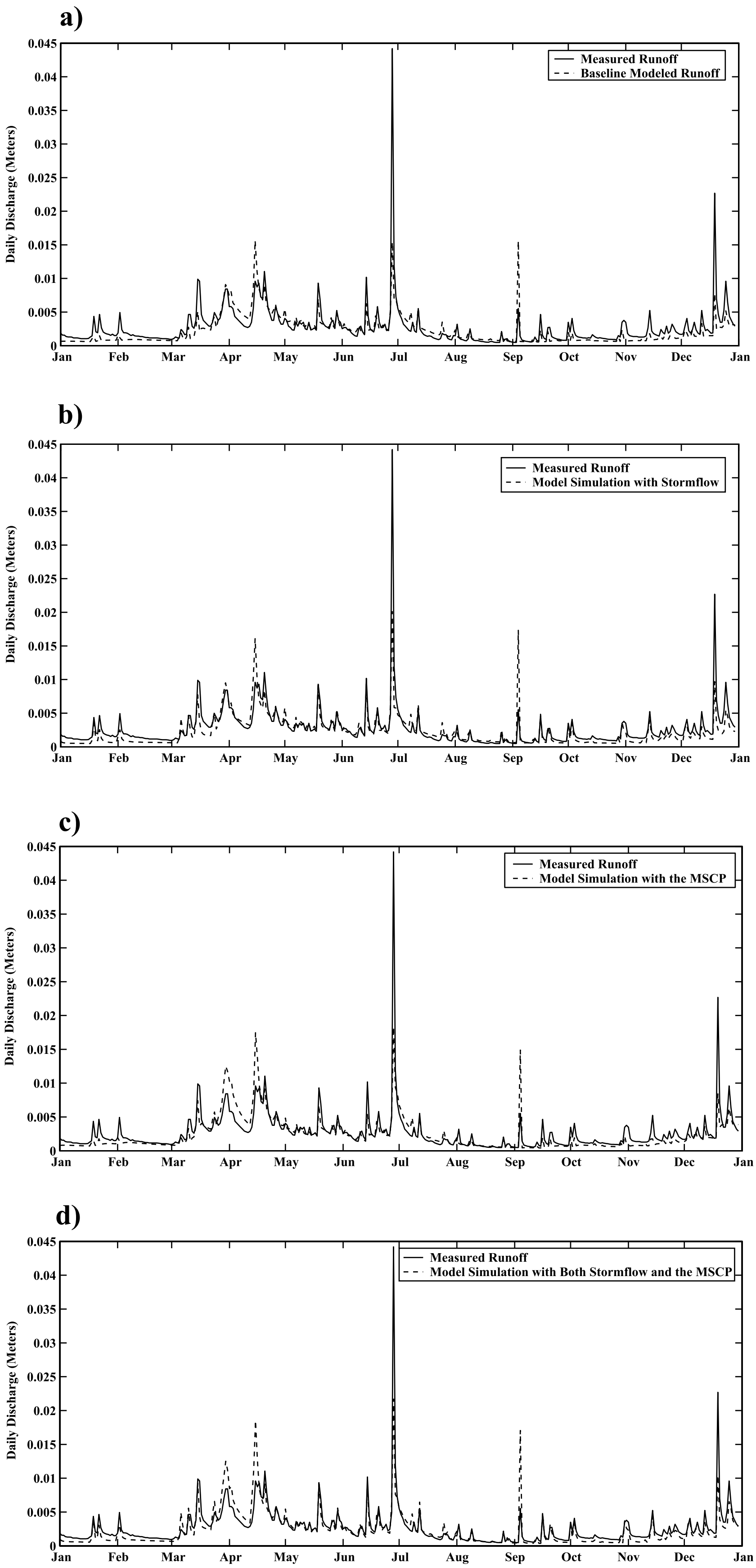


Figure 5. 1973 Sleepers River discharge simulations. As for Figure 4.

Table 1. Sleepers River RMS Error and Correlation Analyses, Comparing Model Simulations to the Measured Hydrograph[a]

	Baseline	Subsurface Storm Flow Only	MSCP Only	Subsurface Storm Flow and the MSCP
RMS Error	0.00144	0.00125	0.00149	0.00125
Correlation Coefficient (r)	0.8596	0.8975	0.8711	0.9039

[a] Analyses are based on all 5 years (1970–1974). RMS error is in units of m/d.

hydraulic conductivity (*Ks*) and the rate of decline of saturated conductivity with depth in the soil column (*f*) were calibrated for best fit of hydrograph. These parameters were left unaltered in the simulations with storm flow and the MSCP, i.e., only the new modifications were incorporated.

5. Results

5.1. Application to the Sleepers River Watershed

[30] The Sleepers River watershed (111 km^2) located in the glaciated highlands of Vermont is hydrologically representative of most upland regions in the northeast United States. As such, this site was chosen in 1957 as an experimental watershed by the Agricultural Research Service (ARS) to provide a better understanding of natural watershed behavior and aid in the development of testing physically based hydrologic models [*Anderson*, 1977]. Nested entirely within the Sleepers River Watershed is the W-3 sub watershed (8.4 km^2). The topography is characterized by rolling hills, and the soils are predominantly silty loams. Vegetation cover is approximately equally distributed among grasses, coniferous forest and deciduous forest. Hourly measurements of air temperature, dew point temperature, incoming shortwave and thermal radiation and wind speed are recorded within the watershed. Average annual air temperature is 4.1°C with a standard deviation of 11.4°C. Mean hourly precipitation is determined from 7 gauges placed within the W3-sub-catchment; annual precipitation totals approximately 109cm. Another data set contains the snow water equivalent (SWE), snow depth, snow temperature and soil temperature. Total snow depth averages about 254 cm and snow cover usually persists from December to March with snowmelt in late March and April. Hourly runoff data are available from a gauge at which the Pope Brook leaves the W3-sub-catchment of the Sleepers River [*Stieglitz et al.*, 1997]. Five years of meteorological and hydrologic data collected between 1969–1974 were used to drive the model.

[31] Hydrographs of the Sleepers River model runs are shown for years 1971 and 1973 (Figures 4 and 5). The baseline model run depicts the gross characteristics of runoff generation; however, many simulation inaccuracies are apparent (Figures 4a and 5a). Specifically, we identify three model shortcomings (see Figure 4a): (1) Model response to storm events during dry conditions, i.e., October through April, is often reduced and spiky, lacking a short-term discharge recession curve in the days immediately following a storm. (2) Groundwater flow response is high during transitions from wet to dry conditions, such as the long May through July 1971 recession at Sleepers River. (3) Model response to initial wetting from spring snowmelt is muted and delayed. A fourth shortcoming, low bias between storm events during dry periods, is also apparent. However, most likely this bias reflects the absence of any depiction of deep aquifer water discharge. Such deep flows operate at very long timescales, which are not represented in TOPMODEL dynamics. It is not our intention in this study to address this shortcoming.

[32] With subsurface storm flow activated there is improvement in the match of modeled and measured hydrographs (Figures 4b and 5b). This model simulation generates river discharge at shorter timescales, better representing storm event response, especially in dry conditions. Smaller storm events are now resolved, and recession curves after summer storm events are evident. There is also considerable improvement in the model hydrograph response to spring snowmelt.

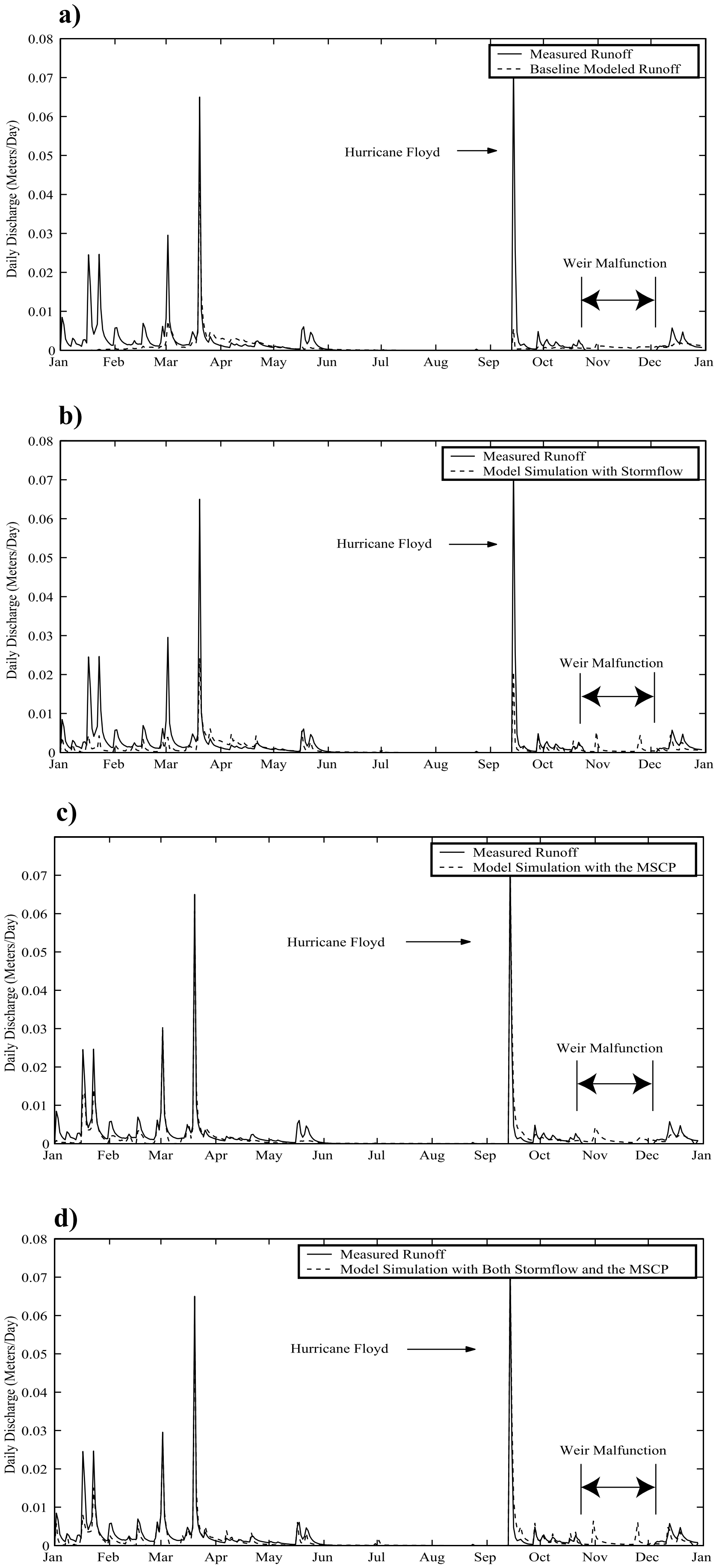
[33] Model simulations with different MSCPs produce modest improvement in the match of modeled and measured hydrographs. A reduction in porosity and field capacity of 5% was found to best improve model discharge (Figures 4c and 5c); however, this simulation still fails to capture many smaller storm events and for those it does, produces little short-term recession in the days immediately following the storm. At the base flow timescale, however, groundwater flow is more responsive, producing greater total discharge than the baseline run. Consequently, the May 1971 response is exaggerated, but the long July recession following this event is better matched (Figure 4c).

[34] Sensitivity analyses were performed to determine which MSCP worked best in conjunction with subsurface storm flow. With both subsurface storm flow and a 5% reduction of porosity and field capacity, modeled and measured hydrographs match best (Figures 4d and 5d). Once again, the subsurface storm flow component generates discharge at quick flow timescales. The model is responsive in both wet and dry conditions, simulating discharge recession for storms large and small, and best captures catchment response to spring snowmelt. Dry season storm events are well depicted; however, groundwater discharge bias between these storms persists.

[35] Improvements to the model hydrograph were assessed using root mean square (RMS) error and correlation analyses (Table 1). Based on RMS error, representation of the measured hydrograph at Sleepers River is best for simulation with subsurface storm flow and simulation with both subsurface storm flow and the MSCP. However, based on the correlation analysis, which measures covariability instead of absolute error distance, the model simulation with both subsurface storm flow and the MSCP is best.

5.2. Application to the Black Rock Watershed

[36] The Black Rock forest is a 1500 hectare preserve located in the Hudson Highlands region of New York. Elevations in the forest range from 110 to 450 m above mean sea level, with seasonal temperatures ranging from −2.7°C to 23.4°C. The medium texture soils are typically very thin, with parent material located from 0.25 to greater than 1m below the surface in the depressional areas. Soils in the lowland areas are more organic than upslope, but bulk


a)
Measured Runoff
Baseline Modeled Runoff
Hurricane Floyd
Weir Malfunction
Daily Discharge (Meters/Day)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
b)
Measured Runoff
Model Simulation with Stormflow
Hurricane Floyd
Weir Malfunction
Daily Discharge (Meters/Day)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
c)
Measured Runoff
Model Simulation with the MSCP
Hurricane Floyd
Weir Malfunction
Daily Discharge (Meters/Day)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
d)
Measured Runoff
Model Simulation with Both Stormflow and the MSCP
Hurricane Floyd
Weir Malfunction
Daily Discharge (Meters/Day)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

densities are not significantly different. Exposed bedrock is common throughout the preserve and consequently the area was not extensively farmed during the period of European settlement. Lumber extraction ceased in 1927 and the forest has been managed as a preserve without significant disturbance since that time. The system is typical of the *Quercus* dominated, secondary growth forests that have characterized the NE United States over the past century. The catchment (1.35 km^2) is drained by a single stream, Cascade Brook. Average hourly discharge from Cascade Brook is monitored continuously using a V-notch weir installed in 1998. Hourly measurements of precipitation, air temperature, dew point temperature, incoming shortwave radiation and wind speed are also taken. Hourly thermal radiation for the site is calculated following the methodology of *Anderson and Baker* [1967]. Three years of meteorological and hydrologic data, collected between 1998–2000, were used to drive the model. (Note that the Black Rock weir malfunctioned during November 1999.)

[37] Hydrographs of the Black Rock model runs are shown for years 1999 and 2000 (Figures 6 and 7). The baseline simulation at Black Rock (Figures 6a and 7a) is considerably less accurate than its Sleepers River counterparts. This circumstance is due in part to differences in catchment structure. The Black Rock watershed is steeper, rockier and possesses shallower soils than Sleepers River. Two of the three shortcomings apparent in the Sleepers River baseline run are evident from the Black Rock baseline simulation: (1) Dry condition storm events are not depicted. (2) Groundwater discharge is high during transitions from wet to dry conditions. Warm winter conditions precluded significant snowpack development at Black Rock from 1998–2000. Consequently, the third shortcoming, poor response to initial wetting from spring snowmelt, is absent. Of particular note is the long summer drought of 1999 that was broken in September by Hurricane Floyd (Figure 6a). The baseline model run fails to simulate this flood event, and the smaller storms subsequent.

[38] The addition of subsurface storm flow generates a better discharge simulation (Figures 6b and 7b). Smaller storm events, particularly during drier periods, are better captured, and there is a visible short-term recession curve following the initial flood event. However, not all of the characteristics of the measured hydrographs are well matched. In particular, large storm events are still not well simulated, and local river runoff maxima, such as the overtopping of the weir during Hurricane Floyd in 1999 are still often underrepresented.

[39] Model runs with the MSCPs produce considerable improvement of discharge simulation. A reduction in porosity and field capacity of 12% was found to best improve model discharge (Figures 6c and 7c). The shallow, rocky soils of hillslope and upland regions of Black Rock justify this larger rate of decrease in porosity and field capacity. The soil profile modification intensifies groundwater flow response to events poorly captured in the baseline simulation, producing greater total discharge. The initial flood due to Hurricane Floyd is now well depicted, as is the large storm in March 1999 (Figure 6c). Many smaller storm events, however, remain unresolved, and the MSCP model run simulates little of the short-term recession present in the measured hydrographs.

[40] Analyses were again performed to determine which MSCP worked best in conjunction with subsurface storm flow. With both subsurface storm flow and a 12% reduction of porosity and field capacity, modeled and measured hydrographs match best at Black Rock (Figures 6d and 7d). Smaller storm events are resolved, and once again the subsurface storm flow component generates discharge at quick flow timescales. The model is responsive in both wet and dry conditions and best captures the intensity of catchment response to large storm events. Hurricane Floyd is well captured, as is the large storm in March 1999, and the recessions following these flood events are represented (Figure 6d). Some problems remain: groundwater flow response remains low between storm events during dry periods; and runoff generation is too heightened in late 2000.

[41] Improvements to the model hydrograph at Black Rock were also assessed using RMS error and correlation analyses (Table 2). Based on RMS error, hydrograph improvement is nominal for simulation with subsurface storm flow alone, but sizeable for simulation with the MSCP alone and for simulation with both subsurface storm flow and the MSCP. In fact, based on RMS error, model representation of the measured hydrograph is best with the MSCP alone; however, based on correlation analysis, the variability of the measured hydrograph is best captured by model simulation with both subsurface storm flow and the MSCP.

5.3. Analysis of Water Table Depth

[42] Further illustration of the impacts of subsurface storm flow and the MSCP can be seen from examination of modeled, mean water table depth, $\bar{z}$. Figure 8 presents comparisons of the three new model simulations with the baseline run for the Sleepers River catchment.

[43] With subsurface storm flow activated (Figure 8a) less water recharges the water table than for the baseline run. As a consequence, the water table is lower, and groundwater flow is necessarily diminished; however, rather than a reduction in hydrograph response, the missing water mass is instead shunted to subsurface storm flow discharge, raising river runoff levels following storm events (Figures 4b and 5b). Not only is the timing of discharge thus redistributed, but overall, the catchment is more responsive with subsurface storm flow activated, generating greater total discharge for the five-year duration of the simulation (data not shown).

[44] Model simulation with the MSCP set to a 5% reduction in porosity and field capacity produces a more dynamic water table (Figure 8b). The modified soil column holds less water at depth and therefore is more responsive to an equal volume of recharge. This greater responsiveness

Figure 6. (opposite) 1999 Black Rock discharge simulations. (a) Comparison of the baseline modeled runoff and the measured hydrograph. (b) Comparison of model simulation with subsurface storm flow and the measured hydrograph. (c) Comparison of model simulation with a 12% MSCP and the measured hydrograph. (d) Comparison of model simulation with subsurface storm flow and a 12% MSCP with the measured hydrograph.

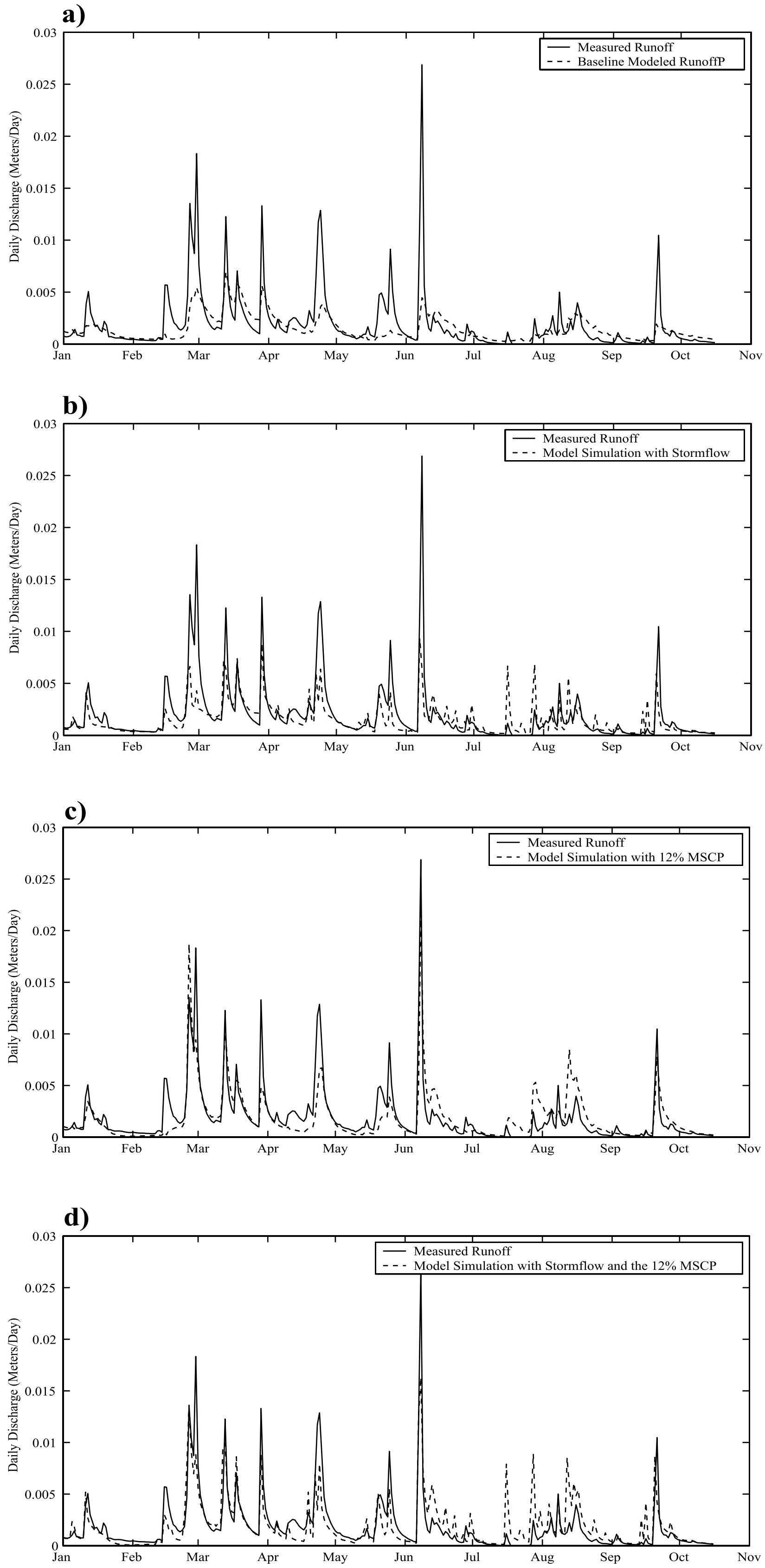


Figure 7. 2000 Black Rock discharge simulations. As for Figure 6.

Table 2. Black Rock RMS Error and Correlation Analyses, Comparing Model Simulations to the Measured Hydrograph[a]

	Baseline	Subsurface Storm Flow Only	MSCP Only	Subsurface Storm Flow and the MSCP
RMS Error	0.00396	0.00370	0.00151	0.00164
Correlation Coefficient (r)	0.5961	0.7188	0.7226	0.7970

[a] Analyses are based on all years of simulation (1998–2000). RMS error is in units of m/d.

necessarily intensifies groundwater flow generation and shortens the timescales at which this discharge occurs. Additionally, the water table drops more abruptly in response to an equal volume of discharge. Thus the water table rises higher in the soil column with wet conditions but lower during dry periods. These changes in water table response and groundwater flow production are not offsetting; rather, the raising of the water table during wet conditions has a disproportionately larger impact on discharge quantities than the lowering during dry periods. Overall, more total discharge is generated. This more dynamic water table explains the May 1971 response at Sleeper River, in which peak runoff is overly simulated, but July recession is well matched (Figure 4c).

[45] The effects of subsurface storm flow and the MSCP on water table depth offset one another during wet conditions (Figure 8c). This balance reduces the exaggerated discharge simulation found in the model run with the modified soil column profile alone; however, the improvement of the July 1971 recession at Sleepers River remains (Figure 4d). During dry conditions, the impacts of the two modifications are additive, as both bring about a lowering of the water table. As a consequence, underrepresentation of discharge persists between dry period storm events. In spite of this bias, water is still available for subsurface storm flow generation, and the recharge that does reach the water table can raise it more quickly, producing faster wetting of the catchment during spring snowmelt.

5.4. Impact of Soil Layer Structure

[46] Additional analyses were performed to determine the sensitivity of the combined subsurface storm flow/MSCP simulations to the layer resolution of the model soil column. Layer thicknesses were altered by changing the depth of the first ground layer, from which all other layer depths are calculated (see Methodology). Runs with both subsurface storm flow and the MSCP were made at both Sleepers River and Black Rock with first ground layer depths of 2, 3, 4, 5, 7 and 12 centimeters. Discharge simulations were found to be insensitive to these alterations and therefore appear robust.

6. Discussion

6.1. Evaluation of Subsurface Storm Flow

[47] The implementation of subsurface storm flow alone produces noticeable improvement in model representation of catchment discharge. These improvements occur primarily during and after storm events, and represent only a short percentage of the total hydrograph time series. Consequently, the statistical improvement to the overall hydrograph due to subsurface storm flow alone, particularly at Sleepers River, is small.

[48] Shallow subsurface storm flow responds to storm events on a shorter timescale than base flow, and thus allows for a more rapid flushing of waters from the catchment. This subsurface storm flow process is critical during dry months. Recharge waters that drain vertically to the deep water table are subject to a very low hydraulic conductivity and thus very low rates of groundwater flow. Consequently, in the absence of subsurface storm flow simulation, storm waters are captured by the deep water table and in essence sequestered until wetter conditions prevail, the water table rises, and groundwater flow rates increase. This mechanism explains why models without subsurface storm flow work best in wetter conditions when groundwater flow is more responsive. With subsurface storm flow activation, however, the catchment is responsive to storm events in both wet and dry conditions. This greater responsiveness results from a partial redirection of vertical recharge waters: instead of first recharging the water table then slowly discharging to river runoff, a portion of the shallow subsurface water moves quickly and directly to streambeds. This effect produces both a redistribution of the timing of discharge and an increase in total runoff generation.

[49] While our conception of subsurface storm flow is physically based, the perched water tables, or fully saturated regions, which can develop above the water table and generate subsurface storm flow, are not explicitly represented by our modeling approach. Within the land surface, these perched water tables can form in several ways. Heterogeneities in the soil column, different soil types, even sheets of bedrock, produce surfaces of lower permeability upon which water may pool within the soil column. These waters then flow downhill over these lower permeable surfaces. This lateral flow continues only as far as the edge of the substrate; once this edge is reached vertical recharge of the true water table can resume [*Noguchi et al.*, 1999]. Because our hydrology model uses a one-dimensional soil column to represent the mean state, it cannot represent such three-dimensional heterogeneities in flow. Similar difficulties are common to all TOPMODEL-based models, which work in reduced space.

[50] However, another contribution of subsurface storm flow to catchment discharge is derived from perched water tables that develop in the soil column by virtue of the decay of hydraulic conductivity with depth. This decay produces a convergence of water with downward flow in the soil column. As waters converge, zones of saturation form. Such zones can develop over entire regions of the watershed, allowing for continuous lateral flow to discharge areas. Our methodology for generating subsurface storm flow works in similar fashion, using regions in excess of field capacity in the vadose zone to identify wetting fronts and zones of convergent flow. This approach to modeling subsurface storm flow is also consistent with experimental evidence showing that macropores, mesopores, soil pipes, and perched rock within the soil column can direct flow both vertically and laterally [*Noguchi et al.*, 1999; *Sidle et al.*, 2000]. While the TOPMODEL approach does not detail such flow pathways, our subsurface storm flow conceptu-

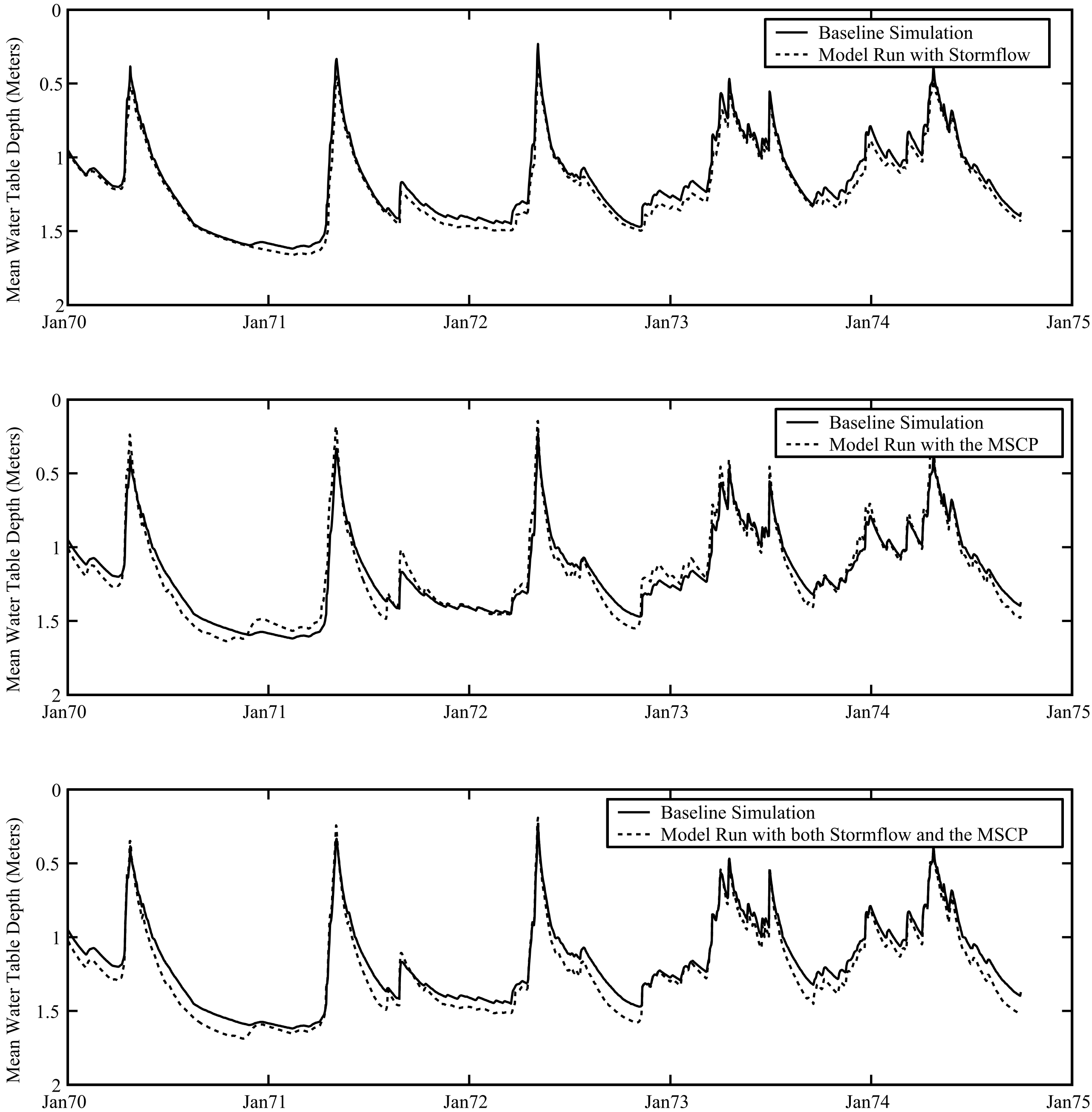


Figure 8. Sleepers River model simulations: 1970–1974 modeled mean water table depth. (a) Comparison of model simulation with subsurface storm flow and the baseline model simulation. (b) Comparison of model simulation with a 5% MSCP and the baseline model simulation. (c) Comparison of model simulation with subsurface storm flow and a 5% MSCP with the baseline model simulation.

alization provides an implicit representation of such lateral flow in the vadose zone. However, while we have developed our representation of subsurface storm flow in a manner consistent with this understanding of bulk hillslope processes and TOPMODEL formulations, whether the improvements to hydrograph simulation were achieved for the right reasons remains to be determined. We have only used streamflow data for validation of model simulation of the subsurface storm flow process. A more rigorous, field-based confirmation of the subsurface storm flow improvement is needed. For instance, model simulation in a watershed extensively monitored with soil moisture probes or wells would provide simultaneous field confirmation of storm flow processes. Alternatively, application of the model to catchments with well-documented stream chemistry might also be used to delineate timescales of flushing and infer the exploitation of storm flow pathways within the hillslope.

6.2. Evaluation of the Modified Soil Column Profile (MSCP)

[51] Application of the decrease in both porosity and field capacity with depth in the soil column produces a more

responsive water table and thus intensifies groundwater flow discharge. Based on RMS error and correlation analyses, the MSCP produces a sizeable improvement at Black Rock, where a larger geometric reduction was applied, but little change at Sleeper River. The MSCP modifications impact different aspects of the model simulation than subsurface storm flow. Response at the quick flow timescale is not engendered; rather, base flow becomes more reactive. Instead of a redistribution of the timing of discharge, the magnitude of response increases. Large storm events can be better simulated due to a more responsive water table, and transition recessions, from wet to dry conditions, are improved by this model modification. However, unlike simulation with subsurface storm flow, few additional storm events are captured with the MSCP, and early spring wetting from snowmelt is not depicted. In addition, during drier conditions, the model still underrepresents discharge between storm events.

[52] Our sensitivity analyses show that differences in catchment response to the MSCP exist. The steeper catchment of Black Rock with its shallower upslope soils requires a greater rate of decrease in porosity and field capacity to best simulate discharge. This difference in mean profile is warranted in the single column TOPMODEL framework. Because the MSCP is a one-dimensional parameterization of structural variability in upland and lowland regions, physical differences among catchments will require different parameterizations. The MSCP parameterization does not violate TOPMODEL assumptions and thus may be appropriately calibrated.

[53] Better hydrologic simulation might be achieved with a more precise determination of the soil column profiles for porosity and field capacity. The geometric decay functions adopted in this study are admittedly somewhat arbitrary. The form of these functions was chosen to depict a combination of effects—differences in depth to bedrock among upland and lowland areas, as well as bioturbation, and soil compaction—in the absence of detailed experimental evidence. In the future, this profile could be more precisely matched on a catchment-by-catchment basis to analyses of soil samples. These matched functions would need not be monotonic.

6.3. Evaluation of the Joint Subsurface Storm Flow/MSCP Application

[54] Combined implementation of both subsurface storm flow and the MSCP produces the greatest improvement in model simulation of catchment discharge. In these simulations, model response to storm events during dry conditions better matches measured discharge intensities and durations. Water that would have otherwise been lost to the deep water table is discharged via subsurface storm flow, and the MSCP intensifies this response for larger events. The magnitude and timing of spring snowmelt response is also much improved. Subsurface storm flow responds quickly to these wetting events, and MSCP permits faster groundwater flow reaction to persistent wetting such as during snowmelt. These two effects amplify one another. Finally, recession curves during the transition from wet to dry conditions are also better represented. The more dynamic water table, produced by the MSCP, effects a more realistic groundwater response during these periods.

[55] Sensitivity analyses also show that different optimum MSCPs exist for the two catchments. As for the model runs with the MSCP alone, this variability reflects differences in catchment structure and relative soil depths among upland and lowland areas.

[56] Simulations with altered soil column layer resolutions demonstrate that the impacts of subsurface storm flow and the MSCP are robust within the constraints of the model layering scheme. We do not suggest that the subsurface storm flow and MSCP methodologies are entirely resolution independent; however, provided there is sufficient discretization of the soil column, subsurface storm flow and groundwater flow discharge simulation appear to be relatively insensitive to changes in layer thicknesses.

7. Summary

[57] This study has presented two new modeling strategies: a methodology for representing subsurface storm flow; and a modified soil column profile (MSCP) that produces a more responsive water table. Both subsurface storm flow and the MSCP are adopted in a manner consistent with TOPMODEL assumptions. The subsurface storm flow methodology allows for discharge from regions in excess of field capacity that develop in the vadose zone during storm events. Determination of the subsurface storm flow contribution to discharge is made using the equation for groundwater flow, and is a function of catchment topography and hydraulic conductivity at the depth of such regions in excess of field capacity. Subsurface storm flow simulation produces discharge at quick flow timescales.

[58] The MSCP represents the different soil column profiles of porosity and field capacity in upland and lowland regions of a watershed in the single column TOPMODEL framework. This parameterization of physical structure creates a more dynamic water table and more responsive groundwater flow. In applying the MSCP, large storm events are better captured and transition recessions from wet to dry conditions are better simulated. Steeper catchments with shallower upland soils appear to require a greater reduction of porosity and field capacity to better simulate large storm event discharge.

[59] The new modeling strategies have been applied to two experimental watershed in the northeastern United States. Used jointly, subsurface storm flow and the MSCP provide a more accurate representation of the timescales of catchment response to storm events and a more complete depiction of hydrologic activity. Storm events large and small are better simulated, and some of the biases previously evident in TOPMODEL simulations are reduced.

[60] **Acknowledgments.** J. Shaman is supported by a NASA Earth System Science Fellowship. This research was supported by the NASA Seasonal-to-Interannual Prediction Project at Goddard Space Flight Center, and NASA's Global Modeling and Analysis Program under RTOP 622-24-47. This work was also supported by NSF grants from the division of Environmental Biology (Arctic LTER Project) and from the office of Polar Programs (Arctic Natural Sciences, Arctic Systems Science). We thank T. Pangburm at the Cold Regions Research and Engineering Laboratory, and J. Thurman at the USDA-ARS Hydrology Laboratory for supplying the data sets and soil maps used for the Sleepers River runs. We thank W. Schuster and the Black Rock Forest Consortium for supplying the data sets used for the Black Rock runs. Finally, we thank M. Cane and A. Karspeck for helpful discussions.

References

Ajmone-Marsan, F., M. Pagliai, and R. Pini, Identification and properties of fragipan soils in the Piemonte Region of Italy, *Soil Sci. Soc. Am. J.*, *58*(3), 891–900, 1994.

Ambroise, B., K. Beven, and J. Freer, Toward a generalization of the TOPMODEL concepts: Topographic indices of hydrological similarity, *Water Resour. Res.*, *32*(7), 2135–2145, 1996a.

Ambroise, B., J. Freer, and K. Beven, Application of a generalized TOPMODEL to the small Ringelbach catchment, Vosges, France, *Water Resour. Res.*, *32*(7), 2147–2159, 1996b.

Anderson, E. A., NOAA-ARS cooperative snow research project—Watershed hydroclimatology and data for water years 1960–1974, *NOAA-S/T 77-2854*, Natl. Oceanic and Atmos. Admin., Silver Spring, Md., 1977.

Anderson, E., and D. Baker, Estimating incident terrestrial radiation under all atmospheric conditions, *Water Resour. Res.*, *3*(4), 975–988, 1967.

Asare, S. N., R. P. Rudra, W. T. Dickinson, and A. Fenster, Quantification of soil macroporosity and its relationship with soil properties, *Can. Agric. Eng.*, *41*(1), 23–34, 1999.

Bartoli, F., G. Burtin, R. Philippy, and F. Gras, Influence of fir root zone on soil structure in a 23-M forest transect—The fractal approach, *Geoderma*, *56*(1–4), 67–85, 1993.

Beven, K. J., Hillslope runoff processes and flood frequency characteristics, in *Hillslope Processes*, edited by A. D. Abrahams, pp. 187–202, Allen and Unwin, Concord, Mass., 1986a.

Beven, K. J., Runoff production and flood frequency in catchments of order *n*: An alternate approach, in *Scale Problems in Hydrology*, edited by V. K. Gupta, I. Rodriguez-Iturbe, and E. F. Wood, pp. 107–131, D. Reidel, Norwell, Mass., 1986b.

Beven, K., TOPMODEL: A critique, *Hydrol. Processes*, *11*(9), 1069–1085, 1997.

Beven, K. J., and M. J. Kirkby, A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci.*, *24*, 43–69, 1979.

Beven, K. J., et al., TOPMODEL and GRIDATB, a users guide to the distribution versions (94.01). *Tech Rep. TR110/94*, Cent. for Res. on Environ. Syst. And Stat., Lancaster Univ., Lancaster, England, 1994.

Bonell, M., D. A. Gilmour, and D. F. Sinclair, Soil hydraulic-properties and their effect on surface and subsurface water transfer in a tropical rainforest catchment, *Hydrol. Sci. Bull.*, *26*(1), 1–18, 1981.

Cox, J. W., and D. J. McFarlane, The causes of waterlogging in shallow soils and their drainage in southwestern Australia, *J. Hydrol.*, *167*(1–4), 175–194, 1995.

Dewalle, D. R., and H. B. Pionke, Streamflow generation on a small agricultural catchment during autumn recharge,.2, Stormflow periods, *J. Hydrol.*, *163*(1–2), 23–42, 1994.

Ducharne, A., R. D. Koster, M. J. Suarez, M. Stieglitz, and P. Kumar, A catchment-based approach to modeling land surface processes in a GCM, 2, Parameter estimation and model demonstration, *J. Geophys. Res.*, *105*, 24,823–24,838, 2000.

Gile, L. H., Fragipan and water table relationships of some brown podzolic and low humic-gley soils, *Soil Sci. Soc. Proc.*, *22*, 560–565, 1958.

Hammermeister, D. P., G. F. Kling, and J. A. Vomocil, Perched water tables on hillsides in western Oregon, 1, Some factors affecting their development and longevity, *Soil Sci. Soc. Am. J.*, *46*(4), 811–818, 1982.

Hendershot, W. H., L. Mendes, H. Lalande, F. Courchesne, and S. Savoie, Soil and stream water chemistry during spring snowmelt, *Nord. Hydrol.*, *23*(1), 13–26, 1992.

Hillel, D., Computer simulation of soil water dynamics: A compendium of recent work., 214 pp., Int. Dev. Res. Cent., Ottawa, Ontario, Canada, 1977.

Hornberger, G. M., J. P. Raffensperger, P. Wiberg and K. N. Eshleman, *Elements of Physical Hydrology*, 302 pp., Johns Hopkins Univ. Press, Baltimore, Md., 1998.

Koster, R. D., M. J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar, A catchment-based approach to modeling land surface processes in a GCM, 1, Model structure, *J. Geophys. Res.*, *105*, 24,809–24,822, 2000.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models, *J. Geophys. Res.*, *99*, 14,415–14,428, 1994.

Lohmann, D., E. Raschke, B. Nijssen, and D. P. Lettenmaier, Regional scale hydrology, I, Formulation of the VIC-2L model coupled to a routing model, *Hydrol. Sci. J.*, *43*(1), 131–141, 1998a.

Lohmann, D., E. Raschke, B. Nijssen, and D. P. Lettenmaier, Regional scale hydrology, II, Application of the VIC-2L model to the Weser River, Germany, *Hydrol. Sci. J.*, *43*(1), 143–158, 1998b.

Lynch-Stieglitz, M., The development and validation of a simple snow model for the GISS GCM, *J. Clim.*, *7*, 1842–1855, 1994.

Noguchi, S., Y. Tsuboyama, R. C. Sidle, and I. Hosoda, Morphological characteristics of macropores and the distribution of preferential flow pathways in a forested slope segment, *Soil Sci. Soc. Am. J.*, *63*(5), 1413–1423, 1999.

Ogunkoya, O. O., and A. Jenkins, Analysis of storm hydrograph and flow pathways using a 3-component hydrograph separation model, *J. Hydrol.*, *142*(1–4), 71–88, 1993.

Oleschko, K., S. B. Figueroa, M. E. Miranda, M. A. Vuelvas, and R. E. Solleiro, Mass fractal dimensions and some selected physical properties of contrasting soils and sediments of Mexico, *Soil Tillage Res.*, *55*(1–2), 43–61, 2000.

Pitman, A. J., Z.-L. Yang, J. G. Cogley and A. Henderson-Sellers, Description of bare essentials of surface transfer for the Bureau of Meteorological Research Centre AGCM, *BMRC Res. Rep. 32*, Bur. of Meteorol. Res. Cent., Melbourne, Australia, 1991.

Rawls, W. J., and D. L. Brakensiek, Prediction of soil water properties for hydrologic modeling, in *Watershed Management in the Eighties*, edited by E. B. Jones, pp. 293–299, Am. Soc. of Civ. Eng., New York, 1985.

Scanlon, T. M., J. P. Raffensperger, G. M. Hornberger, and R. B. Clapp, Shallow subsurface storm flow in a forested headwater catchment: Observations and modeling using a modified TOPMODEL, *Water Resour. Res.*, *36*(9), 2575–2586, 2000.

Sidle, R. C., et al., Stormflow generation in steep forested headwaters: A linked hydrogeomorphic paradigm, *Hydrol.l Processes*, *14*(3), 369–385, 2000.

Sivapalan, M., K. Beven, and E. F. Wood, On hydrologic similarity, 2, A scaled model of storm runoff production, *Water Resources Research*, *23*(12), 2266–2278, 1987.

Stieglitz, M., D. Rind, J. Famiglietti, and C. Rosenzweig, An efficient approach to modeling the topographic control of surface hydrology for regional and global climate modeling, *J. Clim.*, *10*(1), 118–137, 1997.

Stieglitz, M., J. Hobbie, A. Giblin, and G. Kling, Hydrologic modeling of an arctic tundra watershed: Toward pan-Arctic predictions, *J. Geophys. Res.*, *104*, 27,507–27,518, 1999.

Stieglitz, M., A. Ducharne, R. D. Koster, and M. J. Suarez, Simulation of North American snow cover with a new catchment based LSM, *J. Hydrometeorol.*, *2*(3), 228–242, 2001.

Webb, T. H., and S. J. Burgham, Soil-landscape relationships of downlands soils formed from loess, eastern South Island, New Zealand, *Aust. J. Soil Res.*, *35*(4), 827–842, 1997.

Wilson, G. V., P. M. Jardine, R. J. Luxmoore, and J. R. Jones, Hydrology of a forested hillslope during storm events, *Geoderma*, *46*(1–3), 119–138, 1990.

Wood, E. F., M. Sivapalan, and K. Beven, Similarity and scale in catchment storm response, *Rev. Geophys.*, *28*(1), 1–18, 1990.

Yanagisawa, N., and N. Fujita, Different distribution patterns of woody species on a slope in relation to vertical root distribution and dynamics of soil moisture profiles, *Ecol. Res.*, *14*(2), 165–177, 1999.

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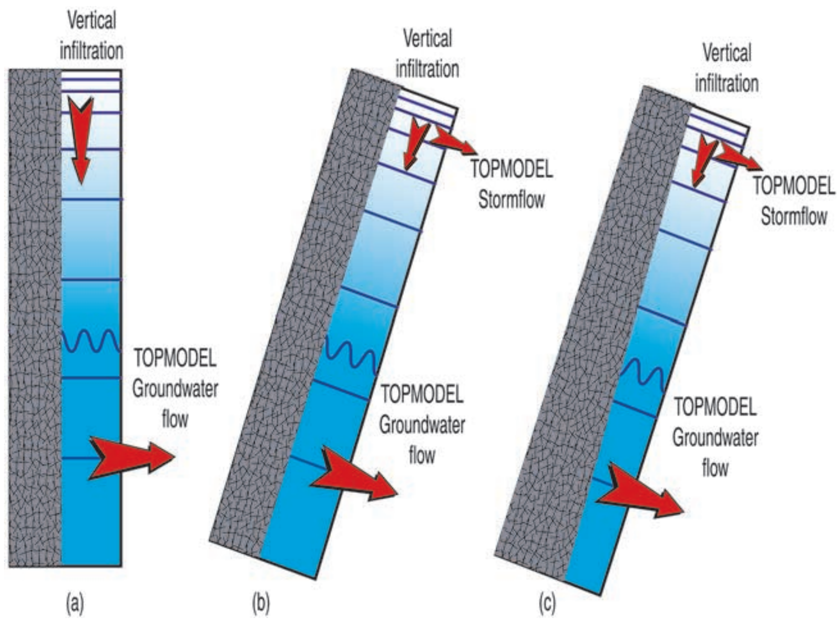

Figure 2. Schematic of the subsurface storm flow and MSCP modifications. (a) Baseline model soil column with a fixed level of porosity and field capacity with depth. Porosity and field capacity are represented jointly by the open areas of the column; solid soil is represented by the hatched brick filling the left of the column; in this version, vertical infiltration recharges the water table raising groundwater flow. (b) Model with subsurface storm flow. Gravity directs a component of the recharge laterally generating subsurface storm flow. (c) Model with subsurface storm flow and the MSCP, as for Figure 2b) but with reduced porosity and field capacity with depth (represented by the expanding hatched brick).