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

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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

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.

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 \( \ln(a/\tan b) \), where \( \tan b \) 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.

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 \( \tan b \); (2) the saturated hydraulic conductivity falls off exponentially with depth;
2. Discharge Response

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.

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.

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.

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.

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.

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; Stiegitz 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.

These model discharge biases reflect inappropriate levels of groundwater flow generation. Within the TOPMODEL framework, groundwater discharge is determined
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,
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 \( z \), determined from the soil column model, and local water table depth at any location \( x \)

\[
z_{x} = z - 1/f \left[ \ln \left( \frac{a}{\tan b} \right)_{x} - \lambda \right]
\]

where \( \ln \left( \frac{a}{\tan b} \right)_{x} \) is the local topographic index at location \( x \); \( \lambda \) is the mean watershed value of \( \ln \left( \frac{a}{\tan b} \right) \), 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

\[
\ln \left( \frac{a}{\tan b} \right)_{x} \leq \lambda + fz
\]

[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

\[
Q_{b} = AK_{s} \left( z = 0 \right) e^{-\lambda z} e^{-fz}
\]

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.
This combined approach to modeling the land surface has been validated at several watersheds, ranging in scale from 2.2 km² [Stieglitz et al., 1999] to 570,000 km² [Ducharne et al., 2000].

4. Approach

4.1. Conceptualization of Subsurface Storm Flow

Within our hydrology model, field capacity ($q_{fc}$) is taken from the empirical analysis of Hillel [1977], which found infiltration to initiate at 70% of the volumetric moisture retained within soils at -33 kPa [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 $q_{fc}$. 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.

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 layer $i$ upward:

$$s_{wi} = z_{bi} - \left( \frac{\theta_i - 0.7\theta_{fc}}{\phi_i - 0.7\theta_{fc}} \right) \Delta \theta_i, \quad \theta_i > 0.7\theta_{fc}. \quad (4)$$

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 $i$ ($Q_{Swi}$). (d) Subsurface storm flow for layer $i$ ($Q_{Si}$) is the difference between $Q_{Swi}$ and $Q_{Swi}$. 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 ($Q_{B}$).
a) Measured Runoff vs. Baseline Modeled Runoff. 
- Low snowmelt discharge
- High recession discharge
- No quickflow response

b) Measured Runoff vs. Model Simulation with Stormflow.

c) Measured Runoff vs. Model Simulation with the MSCP.

d) Measured Runoff vs. Model Simulation with Both Stormflow and the MSCP.
where $sw_i$ is the subsurface storm flow water table in layer $i$, $zb_i$ is the bottom boundary of model layer $i$, $\theta_i$ is the volumetric soil moisture in layer $i$, $\theta_{fc,i}$ is the field capacity in layer $i$, and $\phi_i$ 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 ($Q_{Swi}$). This second value is subtracted from the first, leaving only the flow within the layer in question.

$$Q_S = Q_{swi} - Q_{Swi}$$

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.

$$Q_S = \sum Q_{Si}$$

[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)

[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 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 Hydrographa

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<th>Subsurface Storm Flow</th>
<th>MSCP Only</th>
<th>Subsurface Storm Flow and the MSCP</th>
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</thead>
<tbody>
<tr>
<td>RMS Error</td>
<td>0.00144</td>
<td>0.00125</td>
<td>0.00149</td>
</tr>
<tr>
<td>Correlation Coefficient (r)</td>
<td>0.8596</td>
<td>0.8975</td>
<td>0.8711</td>
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<tr>
<td></td>
<td>0.00125</td>
<td>0.9039</td>
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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 were calibrated for best fit of hydrograph. These parameters 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.

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.

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).

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.

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

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 1 m below the surface in the depressional areas. Soils in the lowland areas are more organic than upslope, but bulk
and the smaller storms subsequent. The baseline model run fails to simulate this flood event, was broken in September by Hurricane Floyd (Figure 6a). Consequently, the third shortcoming, poor wet to dry conditions. Warm winter conditions precluded groundwater discharge is high during transitions from dry condition storm events are not depicted. Two of the three shortcomings apparent in the Sleepers rockier and possesses shallower soils than Sleepers River. This circumstance is due in part to differences in parts. 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 basin 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. 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. 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.

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. 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

Further illustration of the impacts of subsurface storm flow and the MSCP can be seen from examination of modeled, mean water table depth. Figure 8 presents comparisons of the three new model simulations with the baseline run for the Sleepers River catchment. 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). 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.
Coefficient ($r$) is in units of m/d.

6. Discussion

6.1. Evaluation of Subsurface Storm Flow

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.

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.

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.

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-

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<th>Table 2. Black Rock RMS Error and Correlation Analyses, Comparing Model Simulations to the Measured Hydrographa</th>
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<td>Subsurface Storm Flow and the MSCP</td>
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<tr>
<td>Baseline</td>
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<tr>
<td>RMS Error 0.00396</td>
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<tr>
<td>Correlation Coefficient ($r$) 0.5961</td>
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aAnalyses are based on all years of simulation (1998 – 2000). RMS error is in units of m/d.
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)

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

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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.
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.

Our sensitivity analyses show that differences in catchment response to the MSCP exist. The steeper catchment of Black Rock with its shallower upland 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.

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

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.

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.

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

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.

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.

The new modeling strategies have been applied to two experimental watersheds 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.

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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).