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EVALUATION OF THE STORM EVENT MODEL DWSM ON A MEDIUM-SIZED WATERSHED IN CENTRAL NEW YORK, USA

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Abstract: DWSM is a dynamic watershed simulation model that predicts distributed hydrograph and associated sediment discharge graph (sedigraph) of a watershed for a given storm event. Its performance, however, is not extensively tested in medium and large watersheds. Here, we applied DWSM to Upper Oneida Creek watershed located in central New York, USA with an area of 311 km² by dividing it into topographically connected 42 overland elements and 21 channel sections. Field-measured water discharge and sediment concentration data during two storm events, one on 9/30/2010 and the other on 6/28/2010, were used to test the performance of DWSM. Model simulation was performed by calibrating the key adjustable parameters in the input file till the best outcomes were achieved. The final results showed that during calibration for the 9/30/2010 event, DWSM successfully predicted the peak water discharge and its arriving time with the errors of –3.3% and 0%, respectively, and peak sediment discharge and its arriving time with the errors of –0.6% and –0.03%, respectively. For the whole event, DWSM under-predicted total water volume and event sediment load by 10.7% and 22.3%, respectively. Sensitivity analysis indicated that DWSM is most sensitive to the curve number adjustment factor, as well as factors representing flow resistance and flow detachment ability. During validation using the 6/28/2010 event, DWSM showed even better performance in predicting not only the peak values, but also event total values. These results showed that DWSM has the potential of successfully predicting event hydrology and sediment transport in the study watershed.

Keywords: Watershed modeling, DWSM, Sediment transport, Model calibration, Model validation

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INTRODUCTION

The complex transport processes of suspended sediment at the watershed scale may be more efficiently characterized by physically-based watershed models (Borah and Bera, 2004; Singh and Frebert, 2006). Among various existing watershed models, Dynamic Watershed Simulation Model (DWSM) is the one of relatively high efficiency with a relatively simple model structure that involves a set of overland elements and the connected stream segments (Borah, 2011; Borah and Bera, 2004). It uses several mathematical equations to characterize various surface and subsurface hydrological processes, and sediment entrainment and transport processes both on hillslopes and in stream channels during a single rainfall event. Spatial variations of topographic, soil, and land use and land cover characteristics are simplified by assigning single values to each of the divided elements. By routing water and sediment discharges through the divided elements, DWSM predicts both hydrograph and sediment discharge graph (sedigraph) of the watershed at the outlet for a given rainfall event. Although DWSM has been very successful in predicting suspended sediment transport during storms of small watersheds (Borah et al., 2002), it has not been widely tested for watersheds with relatively big sizes in various climatic regions. In this study, we applied DWSM to a medium-size watershed in central New York, USA. Using measured data of water discharge and sediment concentrations for two events of 2010 (one in summer and the other in fall), we tested its abilities of predicting (1) peak water and sediment discharges and (2) event total water volume and sediment yield, and performed sensitivity analysis for the key adjustable model parameters to investigate the behavior of DWSM in the study watershed.

METHOD

Study watershed

Oneida Creek watershed is one of seven sub-watersheds discharging to Oneida Lake of central New York, USA. Its main stream, Oneida Creek originates from the southwestern side of the watershed, flows southeast and then turns to north till reaching Oneida Lake (**Fig. 1**). Its main tributary, Sconondoa Creek extends upstream to the southeast of the watershed. Topographically, the downstream part of the watershed is quite flat, while the middle- and upper-stream ones vary greatly in elevations ranging approximately from 120 to 570 m.

The Oneida creek watershed has a typical continental climate with moderate temperatures and rainfalls in summers and cold, intensive snowfalls in winter. Its mean annual precipitation is more than 1270 mm. With more than half of the area used for agriculture (e.g., dairy farms and cultivated lands) and urbanization, the watershed supplies significantly high sediment loads than other sub-watersheds to Oneida Lake and serves as the main source of sediment pollution to the Lake. Quantifying sediment load and its variation is essential for the design and implementation of sediment-related best management practices (BMP). The middle and upper sections of the Oneida Creek watershed were selected as the study watershed (**Fig. 1**) to take advantage of hydrological data available in a gauging station established by United State Geological Survey (USGS) near the outlet and to capture the topographic diversity of the area. The study watershed has the area of 311 km^2, and thus is a medium-sized watershed (Singh, 1995).

Data preparation

Stage recording and water sampling were performed through a long-term monitoring station established at the outlet of the study watershed. The monitoring station involves an automatic pumping sampler installed at the outlet of the study watershed that consists of a marine battery to supply power to the sampler, a pressure transducer to record stages of the flowing water, and a sampling tube to collect suspended sediment samples by sucking sediment-laden water into a series of 24 sample bottles.

The stages of the flow were constantly recorded at 15-minute intervals. When a pre-determined threshold value of flow stage was exceeded, the sampler began to collect sediment-laden flow samples every three or four hours and stopped when the stage dropped below the threshold at the end of the rainfall event.

Fig. 1 The studied watershed

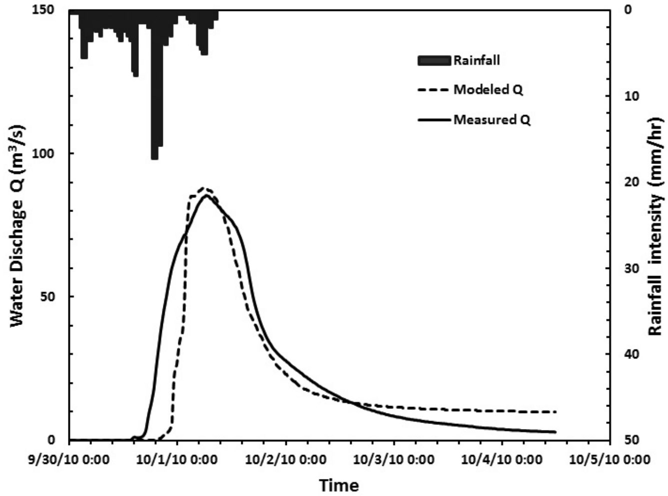

Fig. 2 Comparison of measured with modeled hydrograph and sedigraph of the 9/30/2010 event

The samples were subsequently taken back to the Physical Geography Laboratory at Syracuse University for analysis to obtain sediment concentrations (*C*). Water discharges (*Q*; hydrograph) of the event were determined in terms of the correlation between measured *Q* at the outlet and the associated *Q* recorded at the USGS gauging station (**Fig. 1**). A sediment rating curve was subsequently established using the measured pairs of *C* and *Q*. Sediment discharge, Q_s, was then calculated by $Q_s = QC$ and used to determine the event sediment yield by summing Q_s over the time period of the event (Gao and Josefson, 2012a).

The study watershed was spatially divided into 42 overland elements and 21 stream segments using the ArcHydro technique (Maidment, 2002) for modeling. Each element or segment was assigned a set of parameters to represent its physiographic and land use and land cover (LULC) conditions. The basic input parameters, such as slope and slope length, overland area, and stream segment length were determined based on the DEM data with the resolution of 10 × 10 meter. Soil and LULC parameters were determined using GIS in terms of available GIS layers. Four different median sizes of sediment fractions and their corresponding percentages were determined based on particle size analysis for several samples collected at the outlet of the studied watershed. These values were entered into the input data file. Rainfall information of the modeled events was obtained from the National Oceanic and Atmospheric Administration (NOAA) website by email request. Model calibration and validation were performed by adjusting a set of parameters that will be elaborated in the sensitivity analysis section.

DWSM has two different methods of simulating rainfall excess. The first is the SCS runoff curve number (CN) procedure in which the rainfall excess (direct runoff rate) is calculated from CN values of overland elements and breakpoint cumulative precipitation data (Borah 1989). The second is the interception-infiltration procedure in which the rate of rainfall excess is calculated by subtracting rainfall losses in interception (both tree canopies and ground covers) and infiltration from rainfall intensity (Borah et al., 2002). The first method has been commonly and successfully used in modeling both *Q* and Q_s because of its simplicity and hence is adopted in this study. Using the prepared input data, DWSM was conducted to predict the hydrograph and the corresponding sedigraph of the selected events that can fit observed ones as accurate as possible.

RESULTS

Model calibration

The September 30, 2010 storm event generated a single-mode hydrograph with peak water discharge (Q_{peak}) of 85.35 m^3/s (**Fig. 2**). The modeled Q_{peak} value is 88.15 m^3/s, 3.3% higher than the measured one. The predicted arriving time of Q_{peak} is only 15 minute later than the measured one. Associated with the hydrograph is a single-mode sedigraph with the peak sediment discharge (Q_{speak}) of 89.29 kg/s. The modeled Q_{speak} value is 89.76 kg/s, merely 0.6% more than the measured one. Furthermore, the modeled arriving time Q_{speak} is one hour earlier than the measured one. These results demonstrated clearly that DWSM is capable of simulating both magnitude and timing of Q_{peak} and Q_{speak}.

The modeled rising limb of the hydrograph is steeper than the measured one, while the modeled falling limb follows along the measured one first and then decreases with a gentler slope than the measured one giving rise to higher predicted *Q* values than the measured ones toward the end. Overall, the total volume of storm water (V_w) generated by the event is 8.38×10^6 m^3 whereas the modeled one is 7.49×10^6 m^3, about 10.7% less than the measured one. This under-estimation is mainly caused by the delayed but fast increased storm flows predicted by DWSM during the rising limb of the event. Nonetheless, the small predicted percent errors for Q_{peak} and V_w further indicates that DWSM successfully captures the hydrological behavior of the storm event.

Simulated sediment discharge values generally agreed well with the measured ones. The under-estimation over the lower section of the rising limb is primarily caused by the under-estimation of *Q* during the same period. Although DWSM correctly predicts Q_{speak} both in magnitude and timing, it does not simulate sediment discharge values very well for the earlier section of the falling limb (**Fig. 4**). However, the predicted event sediment yield, SSY_e is 4465 ton, which is only 22.3% less than the measured SSY_e (5748 ton).

Given the complexity of sediment transport processes, this predicting error is very well acceptable. These results showed that DWSM correctly characterizes physical processes controlling water movement and suspended sediment transport in the study watershed and hence is capable of predicting both Q_{speak} and SSY_e.

Sensitivity analysis

In the DWSM input file, there are two types of parameters. The first are those determined in terms of watershed topographical features, channel morphology, and sediment information, such as slope length and area of overland element or channel segment, coefficients of the relationship between wetted perimeter and flow area, and percentages of sediment sizes in three different ranges. These parameters are not adjustable once determined. The second are those representing watershed surface conditions, land use and land cover, and soil characteristics, such as uniform curve number adjustment factor for model calibration (CNAF), Manning's roughness coefficient of overland and channel (FRICO and FRICC), and interception storage capacity for a typical ground cover (VOG). These parameters are adjustable. Modeling event-based hydrological response and sediment transport is essentially identifying a set of values for these parameters that can generate the results best fit the measured Q and Q_s values. Therefore, understanding the sensitivity of these parameters to the predicted hydrological and sediment values is critical for examining the predictability of DWSM.

We tested the sensitivity of main adjustable parameters that may affect predicted Q and Q_s values. For Q, the percent changes of Q_{peak} and event total water volume (V_w), as four main parameters change (i.e., CNAF, FRICO, FRICC, and VOG), are shown in **Fig. 3**. Modeled Q_{peak} and V_w results are considerably sensitive to CNAF (the reason that both curves end at –30% change of CNAF is because no values are generated when CNAF is reduced more than 30%). A 10% increase of CNAF could cause 500% and 50% increase of Q_{peak} and V_w, respectively (**Fig. 3**). In addition to CNAF, both FRICO and FRICC also have significant influence on predicted Q_{peak} and V_w values, but at a less degree than CNAF is. As FRICO decreases by 60%, both Q_{peak} and V_w increase by 31% and 17%, respectively. On the other hand, as FRICO increases, Q_{peak} almost remains the same, but V_w decreases gradually with no more than 14% when it is increased by 60% (**Fig. 3**). The different response of Q_{peak} and V_w to variable FRICO suggests that increasing FRICO largely increases the modeled Q values for the lower part of the falling limb, but has no obvious impact on Q_{peak}. FRICC has a similar pattern of sensitivity to FRICO, but its degree of sensitivity is less than that of FRICO suggesting that overland elements are more influential than channel segments on the output. Change of VOG does not have a significant impact on both Q_{peak} and V_w values. In addition to these five main adjustable parameters, we further tested others such as initial interception storage (VIN) and ratio of the interception storage capacity of a typical canopy cover to that of a typical ground cover (VOR). Their changes do not have significant impact on Q_{peak} and V_w values. Although not showing in **Fig. 3**, our analysis also indicated that the arriving time of Q_{peak} is significantly affected by the change of CNAF, FRICO, and FRICC. Therefore, the most important parameters controlling the modeled hydrological behavior of an event are CNAF, FRICO, and FRICC, the first reflects the comprehensive effect of soil, land use and land cover on surface runoff and subsurface flow, and the other two represent the different surface resistance due to overland and channel bed and banks.

Modeling sediment discharges of an event mainly requires adjustment of two parameters: rainfall detachment coefficient (RDC) and flow detachment coefficient (FDC). We performed sensitivity analysis for both Q_{speak} and SSY_e with respect to these two parameters (**Fig. 4**). As RDC changes (either reduces up to 60% or increases to 100%), Q_{speak} does not vary significantly, while SSY_e changes in an approximate linear fashion. However, the percent changes (either increase or decrease) are all less than 0.5%. The arriving time of Q_{speak} always remains the same as RDC changes. These results suggest that RDC is not quite sensitive to the predicted sediment discharges. The magnitudes of the modeled Q_{speak} and SSY_e values are very sensitive to the change of FDC. Increase of FDC by 100% could lead to 79% increase of Q_{speak} and 94% increase of SSY

Table 1 Comparison of six key variables between modeled and measured values for the 6/28/2010 event

	Measured	Modeled	Error
Q_{peak} (m^3/s)	37.10	37.32	0.6%
Arriving time of Q_{peak} (min)	1425	1395	2.2%
V_{water} (m^3)	3.04×10^6	2.91×10^6	–4.5%
Q_{speak} (kg/s)	36.12	32.42	10.2%
Arriving time of Q_{speak} (min)	1425	1395	2.2%
SSY_e (ton)	1723	1561	–9.4%

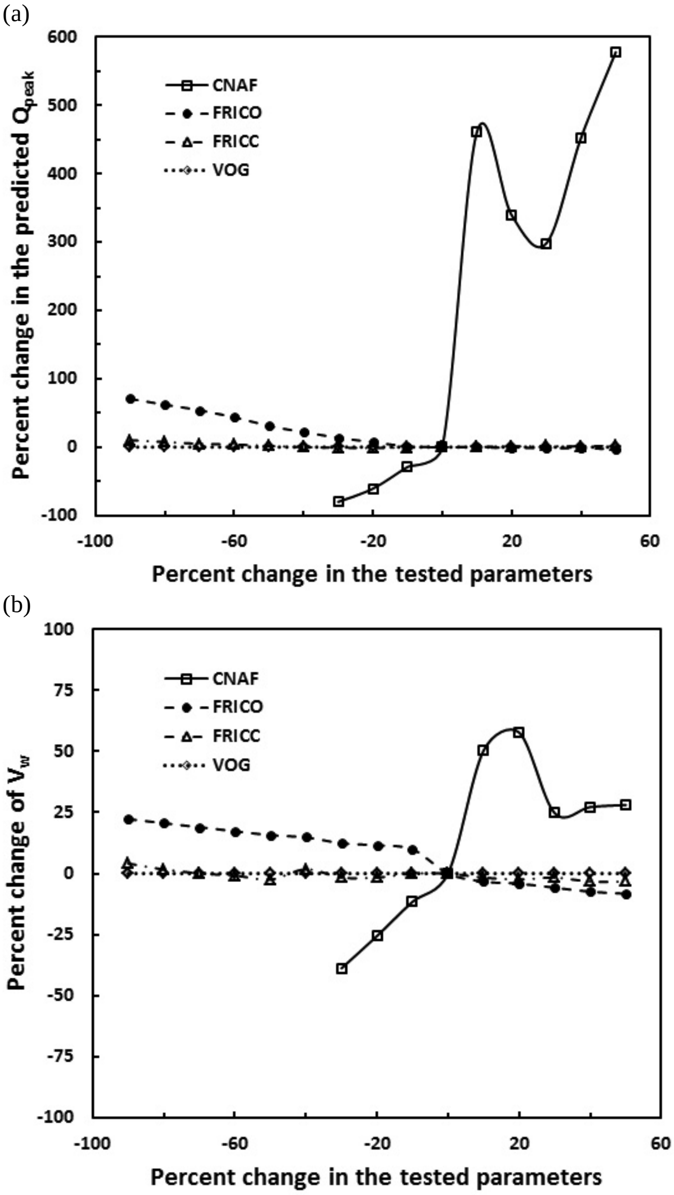

Fig. 3 Hydrological sensitivity analysis for the four main parameters. (a) Q_{peak}; (b) V_w.

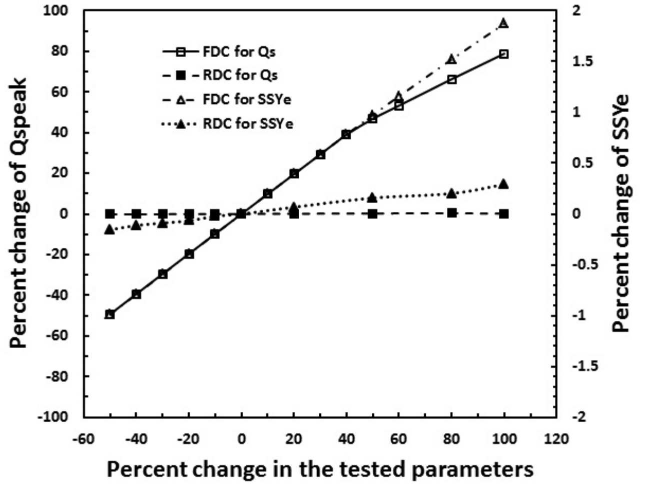

Fig. 4 Sediment sensitivity analysis for the two relevant parameters

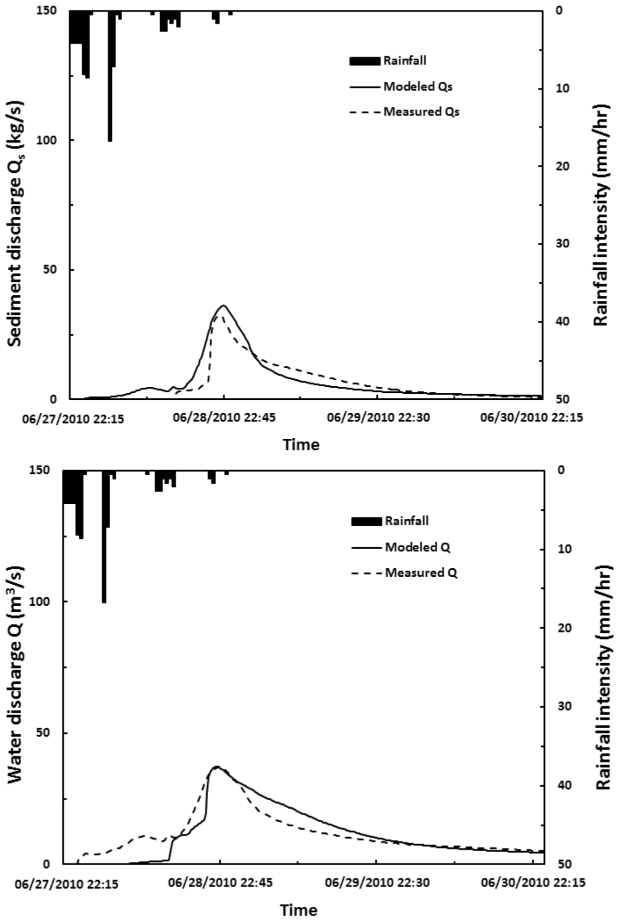

Fig. 5 Comparison of measured with modeled hydrograph and sedigraph of the 6/28/2010 event

(**Fig. 4**), though the arriving time of Q_{speak} still does not affected. This clearly shows that suspended sediment transport in the study watershed is more controlled by hydraulic forces caused by surface runoff than by impact energy generated by rainfall drops.

Model validation

To assure model performance, DWSM is subsequently validated using a different storm event occurred on June 28, 2010. Both modeled and measured hydrograph and sedigraph are shown in **Fig. 5** where modeled ones agree generally well with the measured ones. The detailed values of key output variables for both water and sediment discharges and the relative predictive errors are demonstrated in **Table 1**.

DWSM only over-predicted Q_{peak} by 0.6% with the arriving time being over-predicted by 2.2%, but it under-predicted V_{water} by 4.5%. For sediment transport, Q_{speak} was only over-predicted by 10.2% and SSY_e was under-predicted by 9.4%. Predictions on the event hydrology are generally better than those on event sediment transport. However, the largest error is only 10.2% for Q_{speak}, much less than the largest error of SSY_e for the first event. Thus, the numerical results in **Table**

1 confirm the visual observation shown in **Fig. 5**. DWSM successfully predicted water discharges and sediment transport rates in the second event, which validate the ability of DWSM in characterizing event-based processes controlling water movement and sediment transport in the study watershed. Comparing values of the sensitive adjustable parameters between this and the previous events showed that all of them except CNAF are the same in the two events. The different values of CNAF (0.84 for the 9/30/2010 and 1.24 for the 6/28/2010 events, respectively) are reasonable because the two events had different rainfall intensities and amounts.

DISCUSSION

Although DWSM is a watershed model aiming at simulating event-based sediment transport processes, the first and critical step is to adjust parameters, such that it predicts a well fitted event hydrograph. The exact values of these parameters are not known a priori and need to be determined by an iterative process. Because of the complicated inter-connection among mathematical equations adopted in DWSM, The initial values of these parameters often fail to lead to the final correct ones. Therefore, selection and change of parameter values based partially on their concepts would increase the possibility of modeling success. For instance, FRICO by definition should be greater than FRICC because resistance to flow induced by hillslope surface is generally much greater than that due to stream channels. This hydraulic nature suggests that we should assign a higher value to FRICO than to FRICC. In our case of modeling the first event, the best fitting was achieved by using FRICO = 0.115 and FRICC = 0.023. Given that channel segments of Oneida Creek ranges from bed-rock channel with water fall to gravel-bed channels with well vegetated banks, the final value of FRICC is a reasonable representation of overall flow resistance from all these channel segments. Once the best fit for a hydrograph is determined, modeling sedigraph is a relatively easy task of mainly adjusting FDC.

The change of CNAF adjusts runoff curve numbers determined for the 42 overland elements (ranging from 60 to 73) uniformly. The high sensitivity of CNAF to the model outputs suggests that curve number is a parameter sufficiently reflecting main hydrological response of watershed to a rainfall event and thus is the key parameter to adjust. However, the impact of CNAF to the model outputs shows an abnormal trend (**Fig. 3**) that is, as CNAF increases from 10% to 30%, both Q_{peak} and V_w decrease. This apparent contradiction implies that the structure of DWSM may become unstable for some values of parameters. Thus, searching for the appropriate values of parameters to achieve the best model prediction is practically challenging.

The accuracy of model prediction to a large degree depends on the accuracy of input data. In this modeling, rainfall data were obtained from a station near the studied watershed by NOAA. Although its daily accumulation is consistent with those obtained from the sites within the watershed by an independent group, its hourly distribution may not be very accurate. This uncertainty serves as a source of errors in the model outputs. The success of modeling sediment transport of one event does not guaranty its achievement for modeling other events. Further modeling work is necessary for assuring the performance of DWSM in the study watershed in general.

CONCLUSIONS

In this study, DWSM, a Dynamic Watershed Simulation Model, was employed to predict both water and sediment discharges in the Upper Oneida Creek watershed, a medium-sized watershed in central New York. The predicted results for the two events in 2010, one for calibration (9/30/2010) and the other for validation (6/28/2010), indicated that DWSM can reasonably well reproduce the measured hydrograph and sedigraph of the events, which suggests that DWSM may capture the synoptic effect of complex processes controlling water movement and sediment transport in this medium-sized watershed. The fact that values of adjustable parameters except CNAF are the same for the two events occurred in different seasons (summer vs. fall) implies that the difference of land use and land cover and soil conditions in these two different seasons may be simply accounted for by using different values of CNAF. Because these two events are relatively big comparing with other events occurred in 2010 (Gao and Josefson, 2012b), the model should be further evaluated for small events to assure its reliability. Performing DWSM modeling under a variety of storm events at different times of a year will provide further guidance towards estimating parameter values and enhancing versatility of this relatively simple physically-based model with only a small number of adjustable parameters.

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