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A SATURATION EXCESS EROSION MODEL

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ABSTRACT

Scaling up sediment transport has been problematic because most sediment loss models (e.g., the Universal Soil Loss Equation) are developed using data from small plots where runoff is generated by infiltration excess. However, in most watersheds, runoff is produced by saturation excess processes. Therefore, scaling up requires a hydrology model that accurately predicts the location and extent of runoff source areas. These runoff predictions can then be used for simulating sediment concentrations. We base sediment predictions on a simple, well-tested distributed saturation excess hydrology model, which calculates surface runoff, interflow, and baseflow. Surface runoff originates from bottom lands that become saturated during the rainy season or from severely degraded lands with little or no storage capacity. Baseflow and interflow are generated from the remaining parts of the landscape. Interflow comes from the shallow soils over an impermeable surface and base flow results from percolation below the impervious layer. To obtain the sediment concentrations, we assume that during surface runoff, there is a linear relationship between runoff velocity and sediment concentration, but baseflow and interflow are sediment free. Thus only the runoff component of stream discharge is involved in active erosive work compared to baseflow and interflow that contribute minimally to watershed sediment yield. To show the general applicability of the Saturation Excess Erosion Model (SEEModel), the model was tested for watersheds located 10,000 km apart, in the United States and in Ethiopia. In the Ethiopia highlands, we simulated the 113 ha Anjeni watershed, the 400 ha Enkulal watershed and the 180,000 km2 the Blue Nile basin. In the Catskill Mountains in New York State, the sediment concentrations were simulated in the upper 493 km^2 Esopus Creek watershed. Daily discharge and sediment concentration were well simulated over the range of scales with comparable parameter sets. The Nash Sutcliffe values for the daily stream discharge were greater than 0.80 and the daily sediment concentrations had Nash Sutcliffe values of 0.65 using only two calibrated sediment parameters and the subsurface and surface runoff discharges calculated by the hydrology model. The model results suggest that correctly predicting both amount of surface runoff and subsurface flow is an important step in simulating the sediment concentrations.

KEYWORDS. Variable source areas. partial area hydrology, sediment, monsoon climates, USLE

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Introduction

The success of soil and water conservation practices depend on the understanding of the processes involved in the generation and transport of sediment (Ciesiolka et al, 1995). Many models use the Universal Soil Loss Equation for predicting sediment loads, which assumes that rainfall intensity is one of the main driving forces for causing erosion. Although this might be a reasonable assumption for areas with limited infiltration capacity and/or extremely high intensity storms, it is not applicable for humid climates, where soils are well structured and rainfall intensities are usually less than the infiltration capacity of the soil. In these areas runoff is generated from saturated areas of the landscape and the amount of runoff is a function of the precipitation depth and available soil storage. The objective of this research is to develop an alternative to the USLE for humid monsoonal climates and test if this method also applies to humid temperate climates.

SATURATED EXCESS EROSION MODEL(SEEMODEL) DEVELOPMENT

In this section, the amount of erosion is predicted as a function of the (daily) amounts of surface runoff, interflow, and baseflow. These fluxes are obtained from a relatively simple hydrology model (Steenhuis et al. 2009; Tesemma et al. 2011). In this simple model, the watershed is divided into three zones: two surface runoff zones consisting of areas, one that becomes saturated during the wet monsoon period and the other the degraded hillsides. The remaining hillsides are the third zone where the rainwater infiltrates and becomes either interflow (zero order reservoir) or base flow (first order reservoir) depending on its path to the stream. A daily water balance is kept for each of the zones using the Thornthwaite Mather procedure where actual evaporation has a linear relationship with the available water storage in the root zone. At maximum storage, S_{max}, actual evaporation is equal to the potential evaporation (Steenhuis and van der Molen, 1986). More information about the hydrology model can be found in Steenhuis et al (2009) and Tesemma et al (2011). Erosion originates from the runoff producing zones. Erosion is negligible from the non-degraded hillsides because almost all water infiltrates before it would reach the stream.

In calculating the erosion from runoff producing area, we are assuming that rate of erosion depends on the stream power (Ω) per unit area.. The maximum concentration of sediment that a stream can carry (called the transport limiting capacity C_t *(g/L)*) can be derived from the stream power function as shown by Hairshine and Rose (1992); Siepel et al. (2002); Ciesiolka et al. (1995) and Yu et al. (1997)

:

$$C_t = a_t q_r{}^n \tag{1}$$

Where q_r (mm/day) is the runoff rate per unit area from each runoff producing region, a_t (g L mm^{-n}day^n) is a variable derived from the stream power. The variable a_t is a function of the slope, Manning's roughness coefficient, slope length, and the effective depositability (Yu et al 1997). As water depth increases a_t essentially becomes independent of the runoff rate per unit area and can be taken as a constant (Yu et al, 1997). The exponential, n, that takes a value of 0.4 assuming both a wide channel and a linear relationship between sediment concentration and velocity (Ciesiolka et al 1995 and Yu et al 1997). In this paper where the smallest watershed considered is 113 ha, the water in the channel is sufficiently deep so that a_t is constant.

For erosion of cohesive soils, the sediment concentration will not always reach the transport limit. Only in cases where, for example, the rills are formed in newly plowed soils, the transport capacity will be met. Tebebu et al (2010) found that once the rill network has been fully established, no further erosion will take place and the sediment source becomes limited and, the concentration, C, will fall below the transport limit. For the cases when the sediment concentration becomes lower than the transport limit, C_t', Ciesiolka et al. (1995) found based on the work of Hairsine and Rose that the sediment concentration will not decline below the "source limit", C_s (g/L):

$$C_s = a_s q_r{}^n \qquad 2$$

where a_s is the source limit and is assumed to be independent on the flow rate for a particular watershed (as compared to plots). Introducing a new variable, *H*, defined as the faction of the runoff producing area with active rill formation, the concentration of sediment from the runoff producing area can then be written as:

$$C_r = [C_s + H(C_t - C_s)] \qquad 3$$

Combining Eq. 3 with Eqs. 1 and 2, the concentration from the runoff producing area becomes

$$C_r = [a_s + H(a_t - a_s)]q_r{}^n \qquad 4$$

Finally, in the calculation of the daily concentration, baseflow and interflow play an important role. In a monsoon climate, baseflow can be at the end of the rainy season a significant portion of the total flow. Thus, in the last part of the rainy season the subsurface flow dilutes the peak storm sediment concentration from the runoff producing zones when simulated on a daily basis. It is therefore important to incorporate the contribution of baseflow in the prediction of sediment concentration.

Next we will calculate the concentration of the sediment yield in the stream. Since the interflow and baseflow are sediment free the sediment load per unit watershed area, *Y* (g $m^{-2}day^{-1}$), can be obtained by multiplying C_r in Eq. 4 by the relative area and the flux per unit area, e.g.,

$$Y = A_1 q_{r_1} \left[[a_{s_1} + H(a_{t_1} - a_{s_1})] q_{r_1}{}^n \right] + A_2 q_{r_2} \left[[a_{s_2} + H(a_{t_2} - a_{s_2})] q_{r_2}{}^n \right] \qquad 5$$

where $q_{r_1}$and q_{r_2} are the runoff rates expressed in depths units for contributing area A_1 (fractional saturated area) and A_2 (fractional degraded area), respectively. Assuming that the saturated and the degraded zones have the same values for transport and source limiting capacities, the concentration of sediment in the stream can be obtained by dividing the load *Y* (Eq. 5) by the total watershed discharge

$$C = \frac{\left(A_1 q_{r_1}{}^{n+1} + A_2 q_{r_2}{}^{n+1}\right)[a_s + H(a_t - a_s)]}{A_1 q_{r_1} + A_2 q_{r_2} + A_3(q_b + q_i)} \qquad 6$$

Where q_b (mm/day) is the base flow and q_i (mm/day) is the interflow per unit area of the non-degraded hillside, A_3 where the water is being recharged to the subsurface (baseflow) reservoir.

These equations are only as good as the experimental data. Therefore Eq. 6 is tested in three watersheds in the Ethiopian highlands and one in New York State, The areas range from 113 ha (Anjeni, Ethiopia) to 180,000 km^2 (entire the Blue Nile Basin in Ethiopia). The other watersheds are Enkulal (400 ha) in Ethiopia and Esopus Creek (493 km^2) in New York state.

Watershed descriptions

The Anjeni watershed covers an area of 113 ha with elevations ranging between 2405 and 2507m and is cropped. It is located in the sub-humid northwestern part of Ethiopia near Debre Markos 370 km NW of Addis Ababa. The mean annual rainfall is 1690 mm, which lasts from the middle of May to the middle of October. There is a large active gully in the upper part of the watershed. Both discharge and sediment concentrations were measured during storm events. Daily average discharge and sediment concentrations were calculated. Rainfall, potential evaporation, stream discharge and sediment concentrations were collected from 1988 to 1997. In 1990 soil and water conservation practices were installed resulting in a decrease in soil loss for two years. Periods in which there is incomplete data) were excluded. The model was calibrated for the years 1988 and 1990 for discharge, and was validated for the years 1989, 1991-1993 and 1997. Only three years were available for sediment concentration: The year 1990 was used for calibration and 1992 and 1993 for validation.

The Enkulal catchment is a small tributary of Gumara watershed, located approximately 80 km northeast of Bahir Dar. Enkulal watershed covers an area of 400 ha. Elevation ranges from 2306 to 2528 m. The average annual rainfall is 1577 mm. Most of the rainfall is concentrated from June to September. More than three quarter of the watershed is in low yielding oxen-plowed agriculture. Discharge and sediment concentration data were available twice a day at 6 a.m. and 6 p.m. for the year 2010. Especially at the end of the rainy season many storms occurred at night and the peak flows were not recorded. The rivers in the watershed are stable and in the lower part run over bedrock

The last watershed modeled in Ethiopia is the entire Blue Nile Basin in Ethiopia. It is 180,000 km^2 and encompasses the Anjeni and the Enkulal watersheds. It is said that the source of the Blue Nile is a spring located about 100 km south of Lake Tana at an elevation of 2,900 m. This spring is the beginning of the Gilgil Abbay, which flows into Lake Tana. After Lake Tana the Nile flows through a 1 km deep gorge to the Sudanese border mostly over bedrock. The Blue Nile leaves the highlands near the western border of Ethiopia, and enters the Sudan at an elevation of 490 m. The annual rainfall varies from less than 1000 mm near the Sudanese border to over 1800 mm in the highlands south of Lake Tana. Three years of discharge and sediment data were available at the Sudanese border (1997, 2003 and 2004). The year 1997 was used for calibration and 2003 and 2004 for validation. Tesemma et al (2010) found that the degraded soils had increased by 10% during a 25 year time span. For that reason the degraded hillslope was increased by 3% from 1997 to 2003 and 2004.

The final watershed is The Esopus Creek watershed located in the Catskill region of New York State drains 493 km2 and is dominated by forests, which occupy more than 90 % of the watershed area. The elevation of the watershed ranges from 194 m near the watershed outlet at Coldbrook to 1275 m at the headwaters. Widespread stream channel erosion of glacial clay deposits has been identified as the primary cause of high levels of turbidity. For the Esopus Creek watershed, measured daily stream discharge from the USGS gauging station at the watershed outlet near Coldbrook was used. Turbidity measurements were taken at intervals between 15 min and 1 hr using a YSI water quality sonde from which flow-weighted average daily values were calculated. The measured stream discharge was separated into base flow and surface runoff components using a base flow filter program (Arnold and Allen, 1999). The values for surface runoff region (A1 and A2) and hillside recharge region (A3) were derived as the long-term (1931-2011) mean proportions of runoff and base flow to total stream flow. Observed daily turbidity and daily stream discharge from the March 2003 to March 2004 period were used for calibration of the sediment of the SEEModel and a power function and data from March 2007-2008 period were employed for validation. The Esopus Creek is at times fed by a diversion tunnel operated from the nearby Schoharie reservoir that contributes to stream discharge. Therefore all calculations were confined to days when the tunnel contribution of stream discharge was insignificant.

Results

The model calibration over a wide range of scales has some remarkable similarities (Table 1). Especially the fraction of surface runoff zones in the three watersheds, which is between 0.3 to 0.4. Only in the Anjeni watershed the surface runoff area is equal to 15% of the watershed. The size of permeable hillside increases with watershed size. The small watersheds are located in the top of the watershed and some of the subsurface water passes under the gaging station and provides water for springs below. The hillside area is especially small for the Enkulal watershed, which is in accordance with the data from piezometers readings that indicated that the top part of the watershed contributed mainly to baseflow. The maximum storage of water in the root zone varies among the watersheds. However, the model is relatively insensitive to the S_{max} values since it only affects the amount of surface runoff in the beginning of the rainfall season. Variations in these values between watersheds are therefore not significant with the exception of the maximum storage for the hillside and saturated area of the whole Blue Nile Basin that is larger.

Table 1: Calibrated model parameters and model efficiencies for the four watersheds

Component	Description	parameters	Unit	Calibrated Values			
				Anjeni	Enkulal	Blue Nile	Esopus
Hydrology	Saturated area	Area A_1	fraction	0	0.1	0.2	-
		S_{max} in A_1	mm	-	50	200	-
	Degraded area	Area A_2	fraction	0.15	0.2	0.2	0.32
		S_{max} in A_2	mm	10	10	25	-
	Hillside	Area A_3	fraction	0.5	0.3	0.6	0.68
		S_{max} in A_3	mm	100	50	250	-
	Subsurface	$t_{½}$	days	70	120	80	-
		τ*	days	10	100	200	-
Sediment transport limit		a_t	see text	4.5	17	6.9	-
Sediment Source limit		a_s	see text	3	5	4	0.63
Nash Sutcliffe Efficiencies	Time step		days	1	7	10	1
	Hydrology	calibration	none	0.84	0.75	0.95	-
		validation	none	0.80		0.92	-
	Erosion	calibration	none	0.70	0.76	0.86	0.63
		validation	none	0.75		0.72	0.66

There are two parameters that determine the subsurface flow: Interflow and baseflow. While the baseflow contribution to streamflow decreases slowly depending on the amount of water in the aquifer, the interflow remains constant for a particular storm and stops after a time, t^*. As expected t^* increases with watershed size, because more deep flow paths are intercepted by the river. The larger than expected t^* for the Enkulal watershed is likely a consequence of missing most of the peak flows especially later in the rainy season (due to the sample collection timing). The half-life, $t_{½}$, for the aquifer system is almost independent of watershed size, indicating that there is not a large aquifer. With the Nile flowing over bedrock this should not be a surprise. Finally, the hydrology model could not be fitted very well to the Esopus Creek watershed discharge data, because in a temperate climate the snowmelt requires another subroutine and with the large height differences in the watershed, the snowmelt is spatial variable. The proportion of surface runoff zone and permeable hillsides were derived statistically from the discharge data. The simple SEEM model was able to simulate the discharge pattern quite well in the watersheds.

The Nash Sutcliffe efficiencies in Table 1 for validation for the daily discharge data in the Anjeni watershed was 0.80 (Table 1) and for the 10-day average discharge in the entire Blue Nile in Ethiopia was 0.92. The simple SEEmodel was able to simulate the discharge pattern quite well in the watersheds. The predicted and observed discharge for 1989 validation year for the Anjeni watershed is shown in Figure 1a. In Anjeni daily the peak flows were underestimated likely because saturated areas were forming near the river for the high flows and they were not included in the model. The data

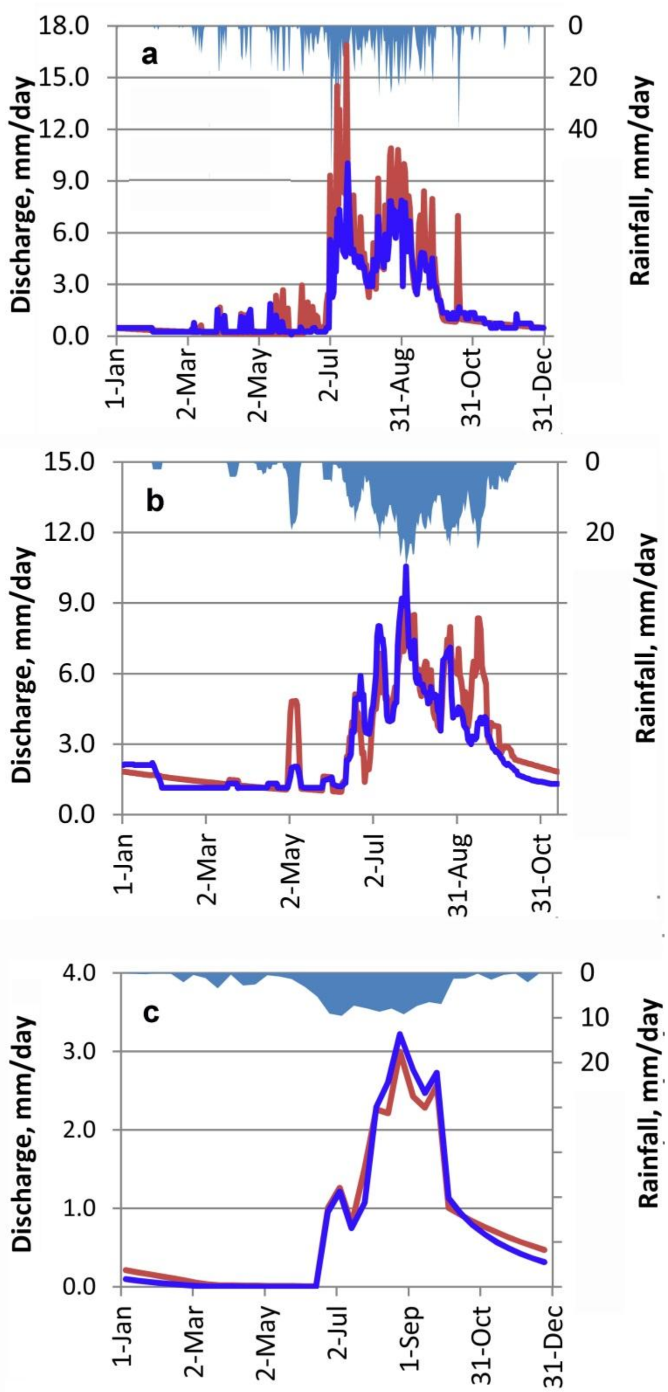

Figure 1. Predicted (red line) and observed (blue line) discharge data for a) Anjeni validation for daily discharge in 1989; b) Enkulal calibration running weekly average discharge in 2010; c) Validation for the Blue Nile at the Ethiopian-Sudan border in 2003.

for the Enkulal watershed was only collected in 2010 and weekly running averaged discharge in 2010 is compared in Figure 1b. The fit is not great and is partly caused by the uncertainty of the peak flows. The Blue Nile validation is shown for the year 2003 in Figure 1c. The NSE values were improved over the Collick et al. (2009) spreadsheet model and comparable to the SWAT-WB model in Easton et al (2010) for Anjeni and the entire Ethiopian Blue Nile basin. The good fit of the hydrology model is a consequence that the model recognizes that before the watershed discharge can respond to precipitation after the dry season, the soils need to be filled to field capacity or saturation.

In simulating the sediment losses, we first define the form of the function of *H*, indicating the fraction of plowed land with active gully formation. Tebebu et al (2010) and Zegeye et al. (2011), found that the erosion is the greatest just after plowing and stopped after rills were formed in the field. Cultivation begins after the first rainfall and then continues for approximately a three to four week period. Therefore, in the model we assume that the concentration from the runoff areas is at the transport limit (i.e., H=1) for the first four weeks after the first rainfall event. Then for another month a few more fields are being prepared and the H decreases from 1 to zero. Around August 1 the sediment concentration from the runoff areas is at the source limit except for the Esopus Creek watershed where the sediment remains at its transport limit due to the unstable banks.

The sediment concentration shown in Figure 2 are calculated according to Eq 6 by using the H values as specified above and the discharges predicted by the hydrology model. The value for n was 0.4 as it theoretically should be for a wide field (Tilahun et al, 2010). The coefficients a_t and a_s in Table 1 were calibrated for first year of data and then validated with the remaining years of data. The observed and predicted values for the validation of two watershed with multiple years of data fit well (Table 1; Figures 2a and 2c. The transport limiting concentration, a_t , for Anjeni and the Blue Nile, are surprisingly similar (Table 1). The transport limiting capacity, a_t, for Enkulal watershed is the greater than the other two watersheds. Both the slopes are steeper and the soils in this watershed are sandier than in the Anjeni watershed and the Blue Nile Basin. The source limits for all three watersheds spanning a range of scales in Ethiopia are similar.

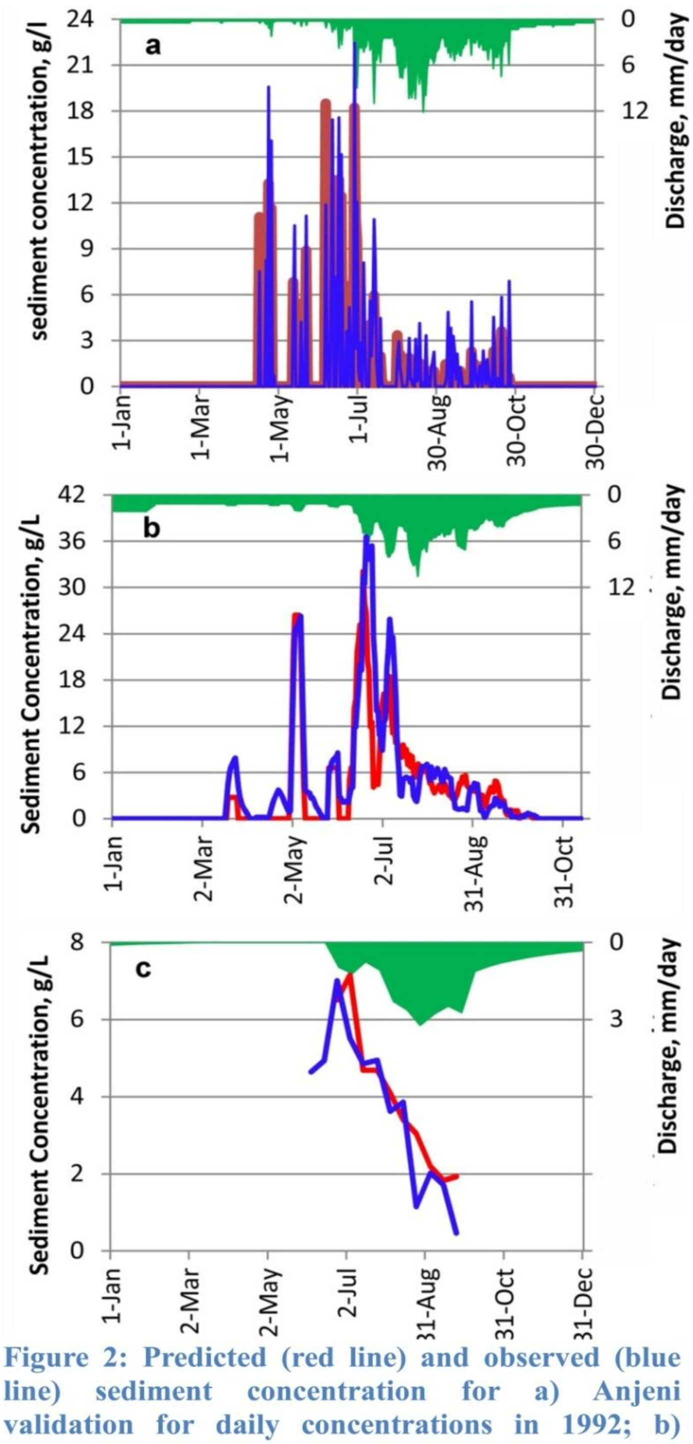

Figure 2: Predicted (red line) and observed (blue line) sediment concentration for a) Anjeni validation for daily concentrations in 1992; b) Enkulal calibration running weekly average concentrations in 2010; c) Validation for the Blue Nile at the Ethiopian-Sudan border in 2003. Discharge expressed in mm/day is the solid green area chart hanging from the top of figure

For the Esopus Creek we could not use the model employed for Ethiopia because of the inability to simulate snow melt accurately. Therefore, based on the long-term statistical analysis the average area contributing to base and interflow (A_3 in Eq 6) was found to be 0.68 and therefore (A_1 + A_2) was 0.32. The *H* value was kept constant at 0. We left the exponential term n= 0.4 and calibrated the value of the transport limiting capacity, a_s as 0.63 (Figure 3). This was much lower than in the Nile basin, likely because the watershed was completely forested. The Nash Sutcliffe efficiency was 0.61 for calibration. A simple power function rating curve (using two calibration parameters using data from the same period had as expected a better NS efficiency of 0.83 . However, during the validation period the one parameter model (Eq 6) performed better (NS efficiency of 0.66) than the rating curve (NS efficiency of 0.40). Unlike the rating curve the SEEModel was able to capture the variability in stream discharge- turbidity relationship to a certain extent (Figure 3).

CONCLUSIONS

Sediment concentrations in the stream were monitored in four watersheds. The SEEModel was developed by assuming that the concentration in the stream was the transport limiting capacity at the time the fields were plowed and then became equal the source limit once the rill network in the field were fully developed. The Nash Sutcliffe efficiencies are remarkably good for such a simple model over such a wide range of scales and better than most values reported in the literature for the Blue Nile Basin. Although the hydrology model could not be used in temperate climate where most runoff is produced during snowmelt, the sediment relationships seemed to apply as we

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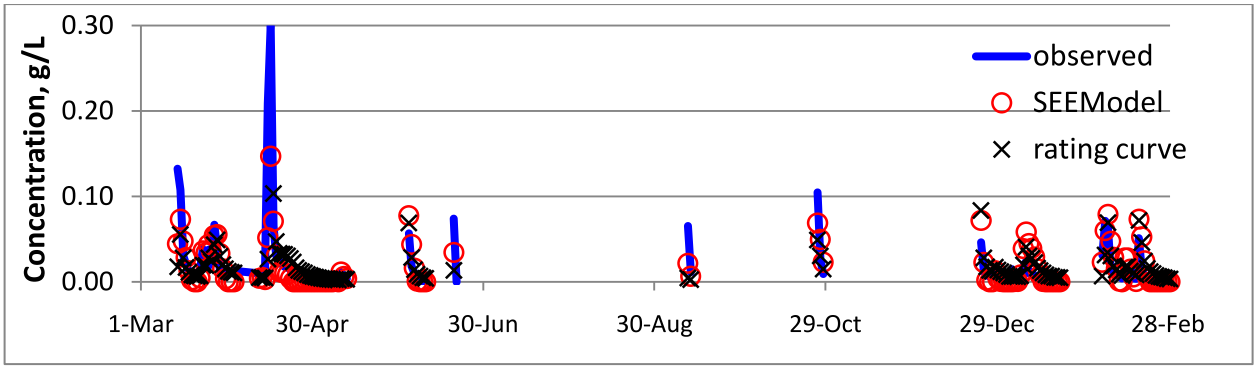

Figure 3: Esopus creek watershed 2007-2008 validation

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