Assessment of Two Physically-Based Watershed Models Based on Their Performances of Simulating Water and Sediment Movement

Latif Kalin, Mohamed M. Hantush

Abstract

Two physically based watershed models, GSSHA and KINEROS-2, are evaluated and compared for their performances on modeling flow and sediment movement. Each model has a different watershed conceptualization. GSSHA divides the watershed into cells, and flow and sediments are routed through these cells in a cascading fashion. Conversely, KINEROS-2 divides the watershed into sub-watersheds and channel segments having uniform properties. GSSHA requires much longer simulation times depending on what is simulated. KINEROS-2, on the other hand, entails relatively less data and effort. Simulations were performed with each model over a small watershed for several events. Models were calibrated using the same events and the differences in estimated parameters were discussed. Both models have resulted in different calibration parameters although the underlying physics are similar. The differences in model behaviors are discussed.

Keywords: sediment, distributed models, watershed, GSSHA, KINEROS-2

Introduction

Hydrologic models are useful tools in understanding the natural processes in a watershed. For instance, one practical application is analyzing the effect of land use changes, such as urbanization, on runoff and sediment yield. There are numerous watershed scale hydrologic models varying from lumped such as the unit hydrograph concept (Sherman 1932) to highly complex distributed models such as MIKE-SHE (Refsgaard and Storm 1995). Each of those models has their own advantages and disadvantages. Depending on needs, sometime a simple lumped model might suffice. However, to achieve TMDL targets and implement BMPs, use of distributed models is inevitable. The availability of high power computers relaxed the burden of long simulation times. Among the distributed models the physically based ones always have edges over the empirical ones, since the model parameters have physical meanings and can be measured in the field. When measurements are not available model parameters can be still be deduced from published data in literature based on topography, soil and land use maps. When flow is concerned, to our knowledge three models seem to be the most physically based and separate themselves from others: GSSHA (Downer and Ogden 2002), KINEROS-2 (Smith et al. 1995) and MIKE-SHE (Refsgaard and Storm 1995). In this study we examined and compared the former two. In what follows is a brief discussion of each model.

GSSHA

Gridded Surface Subsurface Hydrologic Analysis (GSSHA) is a reformulation and enhancement of CASC2D (Downer and Ogden 2002). The CASC2D model was initiated at Colorado State University by Pierre Julien as a two dimensional overland flow routing model. In its final form, it is a distributed-parameter, physically-based watershed model. Both single event and continuous simulations are possible. The U.S. Army Waterways Experiment Station considered this model as very promising and therefore fully incorporated this model into

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Kalin is an ORISE Postdoctoral Researcher and Hantush is a Research Hydrologist, both at the United States Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, OH 45268. E-mail: kalin.latif@epa.gov.

Watershed Modeling System(WMS). Watershed is divided into cells and water and sediment is routed from one cell to another. It uses one and two-dimensional diffusive wave flow routing at channels and overland planes, respectively. Although only Hortonian flows were modeled by employing Green-Ampt (G-A) infiltration model in the initial versions, GSSHA considers other runoff generating mechanisms such as lateral saturated groundwater flow, exfiltration, stream/groundwater interaction etc. GSSHA offers two options for long-term simulations: G-A with redistribution (Ogden and Saghafian 1997) and the full Richards' equation. The latter requires tremendous amount of simulation time and is very sensitive to time step and horizontal and vertical cell sizes (Downer and Ogden 2003). Modified Kilinc and Richardson equation (Julien 1995) is used to compute sediment transport capacity at plane cells. A trap efficiency measure is used to determine how much material is transported from the outgoing cell. Details on theory and equations used can be found in Julien et al. 1995, Johnson et al. 2000, and Downer and Ogden 2002.

KINEROS-2

This is the improved version of KINEROS (Woolhiser et al. 1990). It is event based since it lacks a true soil moisture redistribution formulation for long rainfall hiatus and more importantly it does not consider evapotranspiration (ET) losses. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds. Smith et al. 1995 suggest watershed size smaller than 1,000 ha for best results. Runoff is calculated based on the Hortonian approach using a modified version of Smith- Parlange (Smith and Parlange 1978) infiltration model. KINEROS-2 requires the watershed divided into homogeneous overland flow planes and channel segments, and routs water movement over these elements in a cascading fashion. Mass balance and the kinematic wave approximations to the Saint Venant equations are solved with implicit finite difference numerical scheme in a 1-D framework. KINEROS-2 accounts for erosion resulting from raindrop energy and by flowing water separately. A mass balance equation is solved to describe sediment dynamics at any point along a surface flow path. Erosion is based on maximum transport capacity determined by Engelund-Hansen equation (1967). The rate of sediment transfer between soil and water is defined with a first order uptake rate. A detailed description of the model and the equations used can be found in Smith et al. 1995 and at the official URL of the model: http://www.tucson.ars.ag.gov/kineros.

Data

The data used in this study comes from a small USDA experimental watershed named W-2, which is located near Treynor, Iowa. It is approximately 83 acres. Figure 1 depicts the location and topography of this watershed. This watershed is one of the 4 experimental watersheds established by USDA in 1964 to determine the effect of various soil conservation practices on runoff and water-induced erosion. Runoff and sediment load has been measured since then. There are two rain gauges (115 and 116) around the watershed. W-2 has a rolling topography defined by gently sloping ridges, steep side slopes, and alluvial valleys with incised channels that normally end at an active gully head, typical of the deep loess soil in MLRA 107 (Kramer et al. 1990). Slopes usually change from 2 to 4 percent on the ridges and valleys and 12 to 16 percent on the side slopes. An average slope of about 8.4 percent is estimated, using first-order soil survey maps. The major soil types are well drained Typic Hapludolls, Typic Udorthents, and Cumulic Hapludolls (Marshall-Monona-Ida and Napier series), classified as fine-silty, mixed, mesics. The surface soils consist of silt loam (SL) and silty clay loam (SCL) textures that are very prone to erosion, requiring suitable conservation practices to prevent soil loss (Chung et al. 1999). Corn has been grown continuously on W-2 since 1964.

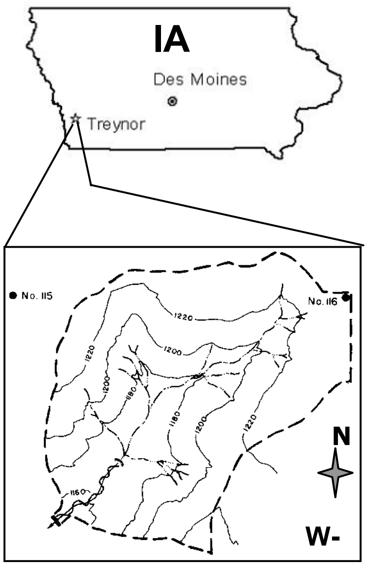

Figure 1. Study watershed.

Methodology

KINEROS-2 was already calibrated for W-2 watershed in a previous study using 3 rainfall events (Kalin and Hantush 2003). In that study average values were used for net capillary drive, G (35,20 cm), pore size distribution index, λ (0.6,0.6), porosity, ϕ (0.47,0.50), and median particle size diameter, D_{50} (7 μm). The two values given in parentheses represent SCL and SL soil types, respectively. Table 1 lists the parameter sets used after calibration of KINEROS-2. In the table, n is Manning's roughness, K_s is saturated hydraulic conductivity, I is interception depth, S_i is initial saturation, C_g is soil cohesion coefficient and C_f is rainsplash coefficient. For simplicity channel and overland roughness were assumed to be same. Since corn has been grown on W-2, the parameters n, C_g and C_f were allowed to vary with season where C_g and C_f were assumed to decay exponentially with the growing season. This assumption was justified over four independent verification events (see Kalin and Hantush 2003).

Table 1. Parameter sets used in KINEROS-2.

event	n	K_s *	I **	S_i	C_g	C_f
6/13/83	0.055	(1.8,6.5)	2.0	(0.44,0.27)	0.15	160
5/30/82	0.040	(1.5,6.0)	0.0	(0.90,0.86)	0.25	200
8/26/81	0.080	(2.0,7.0)	1.0	(0.84,0.60)	0.05	100

* K_s: mm/hr
** I: mm

Flow simulations

GSSHA was run with the above events. KINEROS-2 values were directly substituted for parameters common to both models i.e. λ, ϕ, n, I, S_i, and K_s. Other parameters were adjusted accordingly. The infiltration scheme in GSSHA is the Green-Ampt (G-A) model, whereas KINEROS-2 uses Smith-Parlange infiltration model. G-A capillary head (Ψ) needs to be provided in GSSHA. We approximated Ψ as equal to G in KINEROS-2. Figure 2 shows the comparison of the simulation results for flow with two models. It is clear that both models behave very differently when similar parameter sets are used as inputs. The most striking observation is that, in all cases GSSHA generates later responses and lower peak flows than KINEROS-2. For instance, the difference in time to peaks for the event 8/26/81 is around 25 minutes which is very significant considering the fact that the base time is around 150 minutes. Similarly, the peak flow generated by KINEROS-2 is about 45 % larger than the peak flow generated by GSHHA. One possible rationale to this might be the different watershed conceptualizations involved in each model. Flow routing in GSSHA is only in x-y directions. In other words, flow from a cell is allowed only in the four principal directions. Diagonal neighboring cells can not be receivers which well might be the reality. This results in overestimation of the travel lengths of water particles which might be up to 41 %. On the other hand, the travel paths used to compute the average travel lengths of each element in KINEROS-2 were determined based on the D-8 methodology using the TOPAZ algorithm (Garbrecht and Martz 1999) which allows flow in 8 directions. Considering the fact that flow in the study watershed is mostly diagonal, the overestimation of travel lengths by GSSHA resulted in longer travel time leading to more resistance to flow, and consequently lower and retarded peaks.

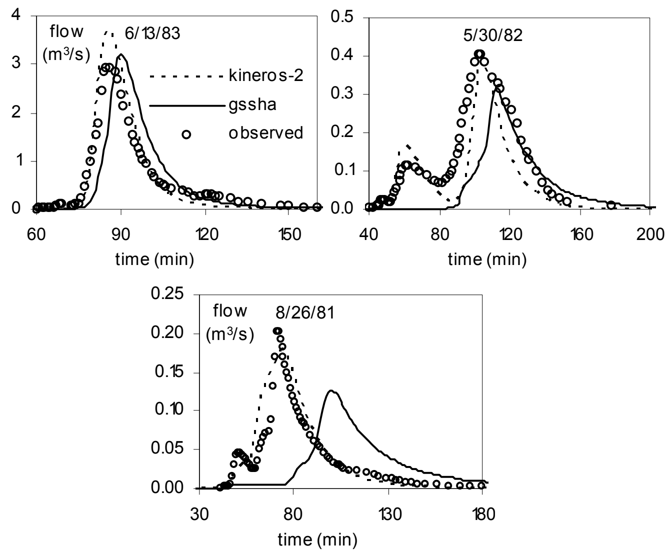

Figure 2. Comparison of hydrographs generated with GSSHA and KINEROS-2 based on KINEROS-2 calibrated parameters.

The differences in flow volumes do not seem to be significant. With this set of parameters KINEROS-2 seems to simulate events having multi-modal shapes, such as the one in 5/30/82, better than GSSHA. In fact GSSHA completely misses the first and second humps in 5/30/82 as opposed to KINEROS-2. KINEROS-2, to some extent, performs better than GSSHA in simulating the small hump seen on the observed data of 8/26/81.

It is important to keep in mind that all these observations are based on simulations with the parameters calibrated for KINEROS-2. Therefore, we recalibrated the GSSHA parameters for the same events. This time each event was calibrated individually and parameters were compared to KINEROS-2 calibrated parameters. We accept that we did not follow the traditional model calibration/ verification methodology. However, we need to mention that the aim of this study is basically a comparison of the two models rather than a model calibration effort. Keeping this in mind, we kept I, S_i and the overland plane roughness (n_p) same and recalibrated channel roughness (n_c) and K_s. Figure 3 shows the hydrographs after calibration. For the event 6/13/83 both model performs equally. For 5/30/82 GSSHA is still underestimating the first and second humps, but interestingly it does a better job than KINEROS-2 in representing the shape. Although KINEROS-2 could not simulate the first (the smallest hump in the figure) happening approximately at 45 minutes, GSSHA does a fairly good job in catching the both humps. Finally, when we look at the last event we see that GSSHA almost perfectly reproduces the observed hydrograph shape while KINEROS-2 suffers to simulate the first peak.

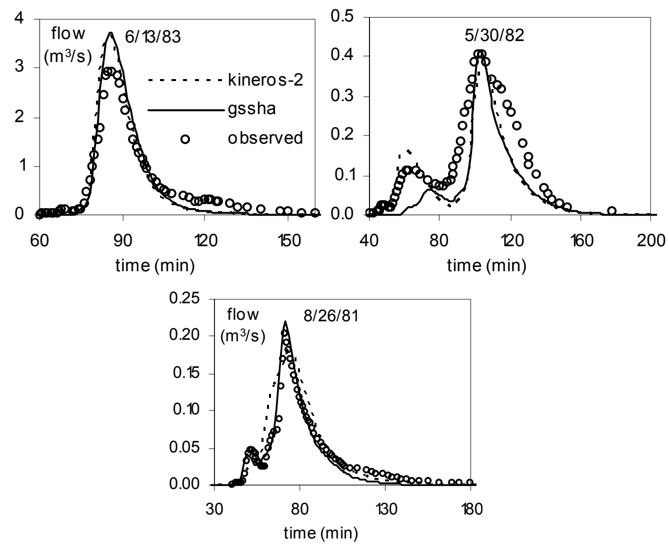

Figure 3. Comparison of hydrographs generated with GSSHA and KINEROS-2. GSSHA is recalibrated.

The recalibrated parameters for GSSHA are summarized in Table 2. In the table C is the USLE crop factor which will be discussed later. The value of n_c had to be decreased dramatically for each event that is clearly expected from Figure 2 as GSSHA generated later responses in each case. One remarkable observation is that n_c values are very close to each other which confirms the comments of Larry Kramer (personal communication) who has extensive experience on Treynor watersheds. He stated that channels are covered with bromegrass and they are cultivated such a way that channel roughness can be assumed invariable year around. K_S values are very close to KINEROS-2 values.

Table 2. Calibrated parameters with GSSHA.

event	n_c	K_s (mm/hr)	C
6/13/83	0.025	(2.0, 7.7)	0.042
5/30/82	0.020	(1.5, 6.0)	0.150
8/26/81	0.025	(1.8, 6.5)	0.050

Erosion simulations

GSSHA requires silt and sand percentages for sediment computations. Assuming that D_{50} is 0.25 mm for sand, 0.016 mm for silt and 0.003 for clay, compositions of each soil class were determined as sand % (10,25) and silt % (56,61) so that the overall average D_{50} is 7 mm, which is the value used in KINEROS-2. The sediment routine in GSSHA is based on the USLE concept that requires three parameters K, C and P. It is not practical to infer estimates of these parameters from the KINEROS-2 soil parameters; i.e., C_g and C_f. Therefore, by keeping KP product constant C was calibrated for each event, since it is only the product of K, C, and P that matters. The values of K and P are (0.37,0.48) and (0.01,0.01), correspondingly. The estimated C values are listed in Table 2. The pattern observed in KINEROS-2 that is erodibility decreases with the growing season, is not observed between the C values here. The C values obtained for the event 8/26/1981 is unexpectedly high, even higher than the value of 6/13/83. Figure 4 compares the sedimentographs obtained by KINEROS-2 and GSSHA. The general observation is that GSSHA generates narrower sedimentographs than KINEROS-2 generates. We do not have a clear reasoning for this. Further, this can not be attributed to flow, since such a behavior is not monitored in Figure 3.

It is interesting to note that the erosion parameters, c_f and c_g, found after calibration for KINEROS-2 are well above the recommended values given in Woolhiser et al. (1990) and the calibrated C parameters for GSSHA are well below the literature values. What this means is that when literature values are used, GSSHA overestimates erosion compared to KINEROS-2. Slope is an important factor in both models' erosion formulation. The smaller the computational element, which is the grid size for GSSHA and the average length of overland flow planes in KINEROS-2, the greater the erosion. Because, as the element size increases the tendency of smoothing the topography increases, and this results in loss of areas with steep slopes meaning reduction in erosion. KINEROS-2 uses far less elements than GSSHA, thus leading to loss of local slope information in the former. This probably elucidates the difference in estimates of soil erosion. A very good discussion on this topic can be found in Rosalia 2002.

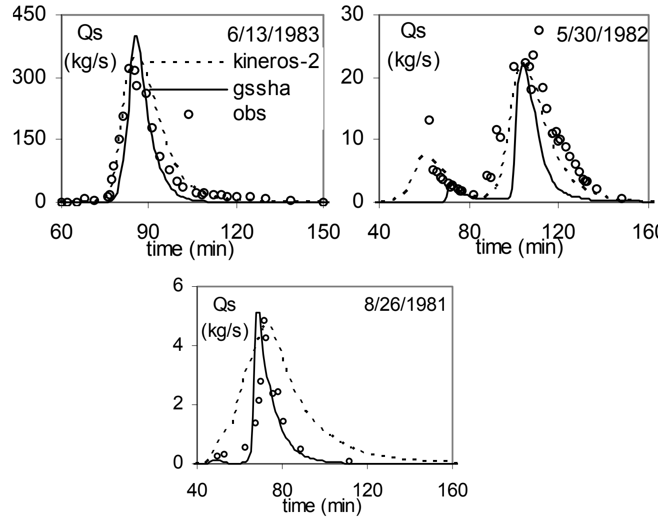

Figure 4. Comparison of sedimentographs generated with GSSHA and KINEROS-2.

Discussions and Conclusions

It is known that in numerical solutions involving finite difference schemes, as the grid size decreases the required time interval should also decrease. In fact, this is reflected in the Courant Condition as a stability criteria which can be stated as $U<\Delta x/\Delta t$ where U is velocity, and Δt and Δx are time and space increments, respectively (Chapra 1997). The grid size used for W-2 in GSSHA simulations was 10 m. This is an unusually small grid size for such simulations. In fact, 5 m horizontal resolution DEM data is also available for this area, but because of the interaction between Δt and Δx we decided to use 10 m. Using coarser grid size than 10 m would lead to inaccurate representation of the watershed since it is only 83 acres. In a review of several watershed scale hydrologic and non-point source pollution models, Borah (2002) refers to a study on CASC2D, the older version of GSSHA, where Molnar and Julien (2000) found that for a 150 m grid size the required time step was about 5 seconds. This number decreased to 1 second when the grid size was reduced to 30 m. The smallest time interval allowed by GSSHA is 1 second which is the value used in our simulations. This might have introduced additional uncertainty.

One of the deficiencies of the GSSHA is that erosion in channels is not transport limited. GSSHA can generate sediment which has a volume larger than flow. This is physically impossible; however there is nothing in the GSSHA formulation to prevent this from happening once sediment reaches the channels (Downer, personal communication). When we initially used the literature values for C, K, and P parameters we observed this effect. Eventually we had to decrease these parameters dramatically to get more realistic results. This itself is enough to claim that the sediment routine in KINEROS-2 is more robust than the routine used in GSSHA. In fact, there is a contract between US Army Corps of Engineers and Fred Ogden, University of Connecticut, one of model developers, to completely reformulate the sediment routine of GSSHA (Downer and Ogden, personal communication). It would be interesting to redo this whole exercise once that project is completed.

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