Development of a Physically-Based Distributed Watershed Scale Model

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Abstract

This talk presents the conceptual design, numerical methodology, and progress of a new watershed model named SRH-W. It is developed to simulate event-based runoff and soil erosion processes in order to predict sediment erosion and delivery to rivers and reservoirs. It is physically-based, process-oriented, and mesh-distributed. The model mesh can be Cartesian or polygonal; the mesh may be very coarse while fine-scale features may be represented through local mesh refinement. Terrain resolution can be finer than the mesh and is taken into account in the water storage and budget computation. The overland soil-erosion module incorporates the recent developments in sheet and rill erosion research. The presentation will focus on the methodologies of the model along with the preliminary results of a case study.

Introduction

Waterways are facing crises worldwide due to frequent occurrence of extreme weather (drought or flood), increased population (demand of water consumption), and worsening water quality (in particular, nutrient and contaminant). Many do not meet the safe water standard established for streams. In the United States, for example, over 40% of the assessed waters did not meet the water quality standard established under the 1977 Clean Water Act (NRC, 2001). This occurred even though the required level of pollution control technology was installed at point source pollution locations. The polluted waterways represented over 20,000 river segments, lakes, and estuaries, covering about 300,000 miles of rivers and shorelines and 5 million acres of lakes. The data in 2010 did not show significant improvement. The US Environmental Protection Agency (EPA) estimated that 53% of the assessed rivers and streams and 69% of the assessed lakes, ponds, and reservoirs were impaired (USEPA, 2010). The EPA Total Maximum Daily Load (TMDL) program, as a result, has become a foundation for the nation's efforts to meet the water quality standards by the states. The federal law requires that states should establish priority rankings for waters on the impaired list and develop TMDLs for them. A TMDL specifies the maximum amount of point and non-point source pollutant a water body can receive and still meet the water quality standard. By law, EPA must approve or disapprove the state lists and TMDLs. Point source loads, such as loading from sewage treatment plants, have received much attention over the years and significant reductions have been achieved. Major violations of TMDL today come primarily from non-point sources. In fact, the non-point source pollution was the primary reason that 40% of the assessed water bodies in the United States were unsafe for basic uses such as fishing or swimming (NRC, 2001). For non-point source pollution, sediment has been identified as the number one pollutant that impairs water (NRC, 2001). Most sediments in rivers, lakes, reservoirs, wetlands, and estuaries come from two sources: soil erosion from watersheds and bank erosion from streams. This shows the need to understand the sediment detachment and movement processes at the watershed scale and along the stream banks.

In addition to TMDLs, sediment supply and management are also critical to many infrastructures on the watersheds or streams. For example, sediment directly impacts the sustainable use of reservoirs due to increased sedimentation, required release for water quality reason, and aquatic and riparian habitat for endangered species. With a large number of man-made facilities and structures on the rivers in the world, the sediment supply, movement and storage can only be measured at limited locations and over a limited time period. Few feasible ways are available to obtain the sediment delivery information in ungauged, non-point source areas. Further, the future impacts of manmade projects are difficult to estimate as historical data are limited. Therefore, there is a wide range of needs for the use of numerical models that are becoming important alternatives. Numerical models may provide additional watershed scale data for assessment and predict future trends and impacts due to implemented projects. Hydrological watershed models have been routinely used by project managers and engineers to assess and evaluate the impact of watershed management and mitigation strategies as well as the impact of floods on facilities. There is little disagreement regarding the usefulness of watershed scale numerical models for understanding hydrologic systems and erosion and sediment transport issues (Sharika et al., 2000). Numerical modeling is widely utilized as a complementary research methodology to theory and experiment (Post and Votta, 2005).

Another potential use of watershed models is for flood prediction. Due to climate change, extreme hydrologic events will likely be more frequent than before. An estimate by the European Environment Agency (EEA, 2010) found that floods have led to 1,126 deaths and 60 billion Euro economic loss in Europe alone between 1998 and 2009. This category of watershed model usage is gaining attention in recent years as the interest in developing flood forecasting and warning systems has increased. For example, the European Commission launched the development of a pan-European Flood Awareness System to improve disaster risk management through early warning (Bartholmes et al., 2009).

Many watershed models have been developed in the past and a large body of literature exists. Reviews have been reported by, e.g., Ewen et al. (2000), Daniel et al. (2010), Devi et al. (2015), Mello et al. (2016), and Lai et al. (2019). Review and discussion of existing models are omitted herein. Despite continuing advances in watershed modeling, however, the ability to predict multi-year hydrologic responses in large-scale watersheds is still limited as most models are primarily developed for agricultural uses. In this study, a new watershed model, SRH-W, will be developed which is an extension of the river simulation model of SRH-2D (Lai, 2010). The model will incorporate the current runoff and soil erosion research results and address some limitations of the existing models. Key SRH-W features are as follows:

- An event-based, process-oriented, and mesh-distributed watershed model for runoff and soil erosion simulation;
- Initial application targets are for flood prediction and sediment delivery to streams and reservoirs owing to a relatively large precipitation event although the model theory is generally applicable to many other applications;
- Applicable to both small and large watersheds;
- Use of special meshing technology allowing both coarse and refined mesh simulations;
- Finite-volume discretization method, explicit and implicit schemes, and diffusive wave routing equation;
- Flexibility to use different erosion models: both empirical and processes-based soil erosion models.

The Numerical Model

The spatial representation of a watershed needs to be specified first with a watershed model. SRH-W adopts the meshed approach so that model parameters, variables and governing equations of the underlying physical processes may be represented on the mesh. The meshed approach is most flexible in watershed model applications. Almost all model parameters and state variables may represented and stored in the Geographical Information System (GIS), and they may be easily mapped onto the mesh for modeling. The meshed model, however, needs to solve more sophisticated process-based governing equations which may potentially increase the computing time.

SRH-W is designed to simulate a wide range of watershed sizes, from small (<10 km^2) to large (>1,000 km^2). For small watersheds, a fine-resolution mesh may be used; detailed local process features may be represented using the first principle governing equations. For large watersheds, a coarse-resolution mesh may be used; parameterized relationships from large-area-averaged data may be used for selected processes. This dual-scale model capability means that appropriate mathematical equations should be selected for the relevant spatial scale of the watershed, along with the associated model parameters. SRH-W consists of the following modules: terrain, atmospheric forcing, land use (vegetation), soil type, infiltration, overland runoff, overland erosion, and channel network. Only selected overland processes are discussed below.

The terrain module reads and processes the watershed terrain information for the spatial representation of a watershed. Terrain data of the finest possible resolution is used by SRH-W. First, a mesh is generated to represent the spatial features such as terrain, land use, soil type, etc. Two meshing options are offered: the polygonal mesh and the Cartesian mesh. The polygonal mesh adopts the method of SRH-2D (Lai, 2010). The benefit of the polygonal mesh is that different spatial resolution may be used in different zones; a primary drawback is that the solution algorithm is complex leading to increased computing time. The Cartesian mesh adopts the rectangular or square mesh cells. This mesh is generated automatically based on the user inputs of the watershed boundary, breaklines, hard points, and the mesh cell size. The Cartesian mesh has the benefit of increased computing efficiency; but the drawback is the difficulty of varied spatial resolution. Local mesh refinement will be developed to overcome this drawback. A locally refined storage (LRS) procedure is to be developed that may offer an increased accuracy when the mesh resolution is coarser than the terrain. LRS uses locally refined computation of volumes and areas of mesh cells based on the terrain data. The objective is to maintain the local volumes and flow areas even when the 2D mesh is progressively coarsened.

The mathematical equations presented below follow the same ones reported by Sanchez (2002) and details are documented in Lai et al. (2019). The overland runoff module resorts to the first principle governing equations for overland routing that transforms rainfall excess into overland flow depth. The diffusive wave equation is solved as follows:

$$\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(\frac{h^{\beta}}{n\sqrt{S}}\frac{\partial z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h^{\beta}}{n\sqrt{S}}\frac{\partial z}{\partial y}\right)+e \qquad (1)$$

In the above, h is overland flow depth (m); x, y are the Cartesian coordinates (m) projected onto the horizontal plane; t is time (s); e is rainfall excess rate (m/s) (rainfall minus the intercept, storage and infiltration), z is water surface elevation, n is Manning's roughness coefficient, $\beta = 5/3$ is a constant, and S is computed by:

$$S = \sqrt{S_{fx}^2 + S_{fy}^2} \tag{2a}$$

$$S_{fx} = \frac{\partial Z}{\partial x}; \qquad S_{fy} = \frac{\partial Z}{\partial y} \tag{2b}$$

Soil eroded from an overland may come from sheet, rill erosion, and gully erosions. Only the sheet and rill erosions are considered. The detachment and sediment transport are treated as separable and independent processes. A number of sediment size classes may be used to represent the soil particles such as clay, silt, sand, and aggregates. Each soil size class is described by its density, fall velocity and percentage of presence (composition). The non-equilibrium sediment routing is adopted: sediment concentration does not equal the sediment transport capacity in transport. This is in contrast to the commonly used Exner equation method - an equilibrium model that assumes instant exchange between the transported sediment and the bed sediment. The non-equilibrium sediment routing equation is expressed on an overland as:

$$\frac{\partial AC}{\partial t} + \frac{\partial UAC}{\partial x} + \frac{\partial VAC}{\partial y} = \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(AD\frac{\partial C}{\partial y}\right) + S_C \tag{3}$$

In the above, C is volume concentration of a size class, A is the flow area per unit width (m), U and V are the flow velocity components (m/s) in x and y directions, respectively, D is dispersion coefficient, and S_C is the sediment exchange between the sediment in water and that on the bed (m/s). The sediment exchange rate is computed by:

$$S_C = E_C - D_C \tag{4}$$

where E_C is the detachment rate (m s^{-1}) and D_C is the deposition rate (m s^{-1}). The deposition rate for loose sediments in suspension is computed by:

$$D_C = ahC \tag{5a}$$

$$a = \frac{\omega}{\zeta h} \tag{5b}$$

where ω is the sediment fall velocity and ζ is the adaptation constant ranging from 0.1 to 1.0.

The detachment rate is computed by:

$$E_C = E_{Cr} + E_{Cf}$$

where E_{cr} and E_{cf} are the rates due to splash and flow runoff, respectively. Such a bi-linear relation was used by, e.g., KINEROS and CATFLOW-SED (Scherer and Zehe, 2015). The detachment rate due to rainfall and leaf drip (E_{Cr}) may be computed by the empirical equation of Wicks and Bathurst (1996) that was adopted by SHETRAN.

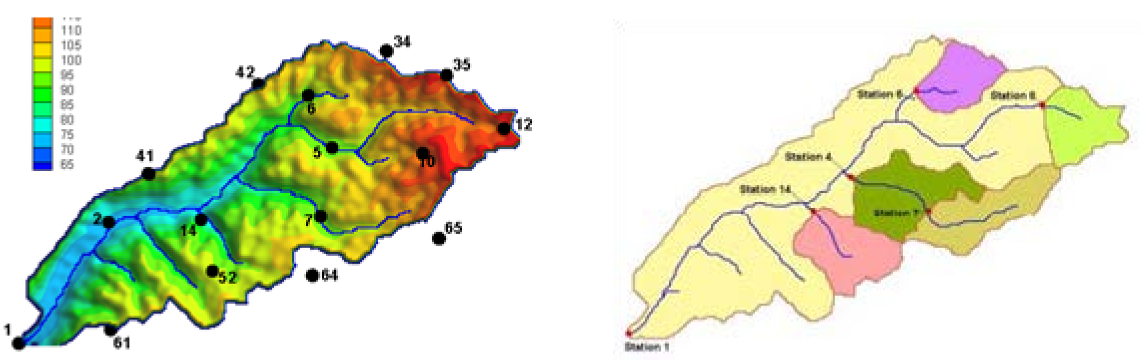
The flow runoff rate (E_{Cf}) may adopt several approaches. The first is the shear stress based method that uses the rate equation of Ariathurai and Arulanandan (1978). The second is the velocity based method adopting the modified Kilinc-Richardson equation (Julien, 1998; Velleux et al., 2005). And the third is the unit stream power based method (Yang, 1996).

Results and Discussion

SRH-W is still under development to achieve its full capabilities. At present, only a preliminary version has been completed with a number of test cases. In this paper, model verification is reported using a set of measured data at the Goodwin Creek Experimental Watershed located in Panola County, Mississippi. The model domain for this watershed has a size of 21.3 km^2, and is situated in the bluff hills of the Yazoo River basin of northern Mississippi. The watershed is under research management by the National Sedimentation Laboratory, Agricultural Research Service. The current preliminary SRH-W can solve the diffusive wave equation on a Cartesian or hybrid quadrilateral-triangle mesh with explicit or explicit time discretization scheme. Capabilities such as the local mesh refinement and LRS (locally refined storage) are yet to be developed.

The digital elevation model (DEM) at the 30-meter resolution was used and processed to obtain a depressionless DEM by Sanchez (2002). The channel network was delimited from the smoothed 30-meter DEM as shown in Figure 1a. These data were made available to us in the model testing of the present study. Note that the channel network routing is carried independent of the 2D overland runoff and the coupling between the two is achieved with a one-way approach as described in Sanchez (2002). The water runoff simulation is carried out first and is discussed next.

The storm event that occurred on October 17, 1981 is simulated. The storm started at 9:19pm and lasted for 4.8 hours. Precipitation data were recorded by rain gages distributed within the watershed and the rain data from a total of sixteen gages are used (the locations of the sixteen rain gages are plotted in Figure 1a). Input data include DEM, channel network geometry and hydraulic properties, rainfall intensity at sixteen gages, soil type and land use class maps and the associated infiltration, Manning's roughness coefficients and rainfall interception parameters. For a more detailed description of the input data, the reader is referred to Sanchez (2002) who simulated the same event using the CASC2D model. No attempt has been made in this study to calibrate the input parameters to fit the measured data. Comparisons between the model results and the measured data are mostly at the six outlet locations shown in Figure 1b.



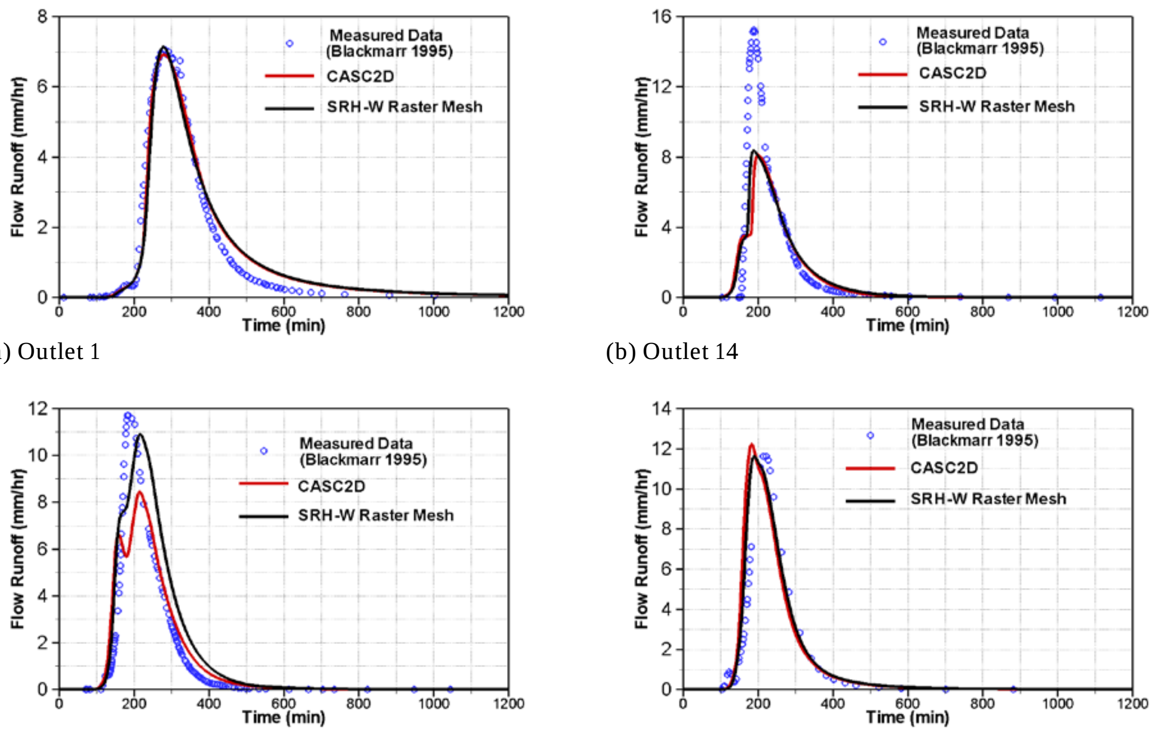
(a) Model domain, channel network and rain gages

(b) Six outlet locations

Figure 1. General information of the Goodwin Creek Watershed

Four model options are used to simulate the runoff event; they are the Cartesian mesh with a spatial resolution of 30 meters with both the explicit and implicit schemes and the hybrid quadrilateral-triangle mesh with both the explicit and implicit methods. The results of CASC2D by Sanchez (2002) are also reproduced for comparison with the SRH-W results. Note that CASC2D model is limited to the Cartesian square mesh and the explicit solver only.

The flow hygrograph results from the Cartesian mesh are compared with the measured outlet data in Figure 2. The SRH-W explicit and implicit model results are found to be almost the same (so only one curve plotted in Figure 2.), which demonstrates that the discretized equations are solved correctly by both solvers. It is noted that a significant under-prediction of the peak runoff occurs at outlet 6 and 14. The two are the smallest sub-watersheds (see Figure 1b) and the under-prediction may be attributed to the inaccuracy of the precipitation input and the delineated channel network.

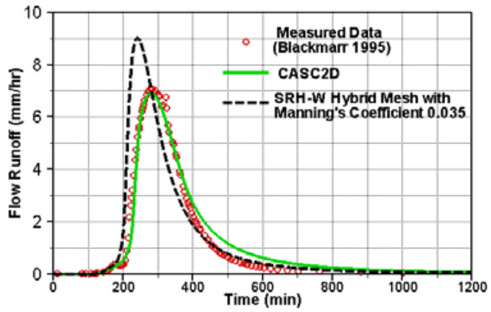


(a) Outlet 1 (b) Outlet 14

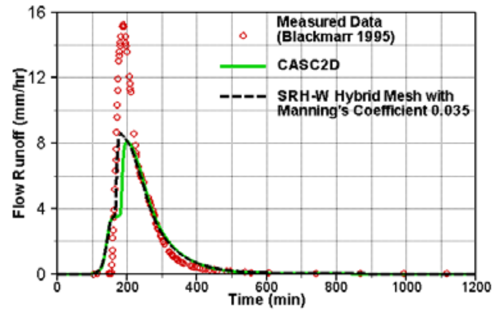
(c) Outlet 6 (d) Outlet 7

Figure 2. Comparison of results with the Cartesian mesh

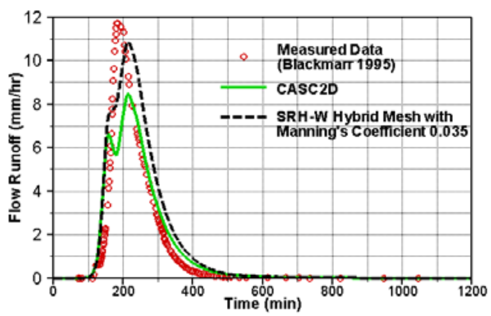
Next, the flow runoff results from the hybrid mesh are compared (Figure 3). The predicted runoff hydrograph at the watershed exit (Outlet 1) deviates significantly from the measured data although the comparisons at other outlets are good. This discrepancy is not the failure of the model; it is caused by the difference in channel representation. The channel network is represented with the overland mesh cells by CASC2D. The channel is thus represented by a zigzag 2D cells which artificially lengthens the channel length. The hybrid mesh, however, follows the natural channel network longitudinally without distortion. If the channel network longitudinal length of the hybrid mesh is arbitrarily increased to match the length used by CASC2D, it is confirmed that the runoff at Outlet 1 is almost the same between the two meshes. This shows that the channel representation of the Cartesian mesh needs to be modified. In addition, it suggests that the calibrated channel Manning's coefficient used with the CASC2D modeling is based on the longer channel length, which is incorrect. The Manning's coefficient should be re-calibrated with the hybrid mesh modeling. This would show that the coefficient should be 0.06 instead of 0.035. New SRH-2D hybrid mesh results are shown in Figure 4 with the new Manning's coefficient. It is seen that the agreement between the two meshes is much closer. The difference at Outlet 6 may be due to the difference of mesh size and resolution within that sub-watershed. The roughness coefficient of 0.06 is probably a realistic value as the same roughness coefficient was calibrated and used by Langendoen (2000) in applying the 1D CONCEPTS model to the channels of the Goodwin Creek watershed.



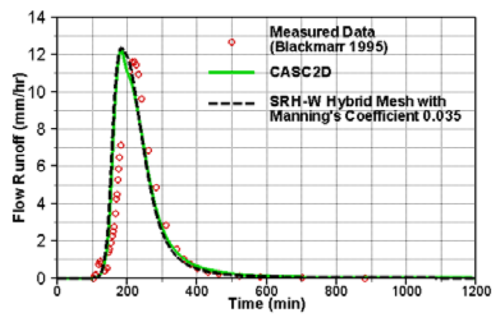
(a) Outlet 1



(b) Outlet 14

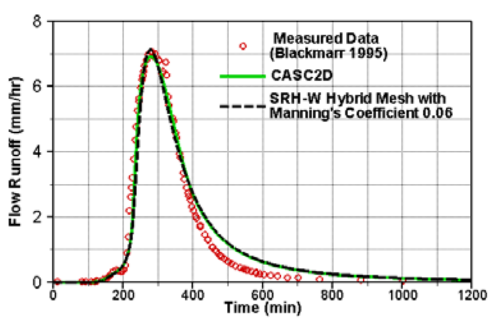


(c) Outlet 6

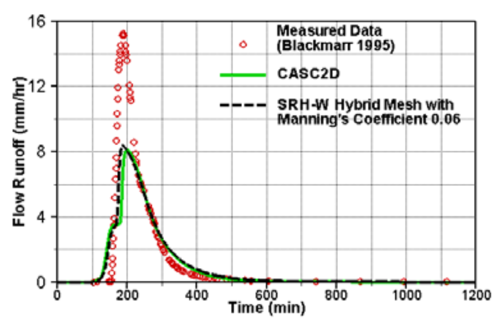


(d) Outlet 7

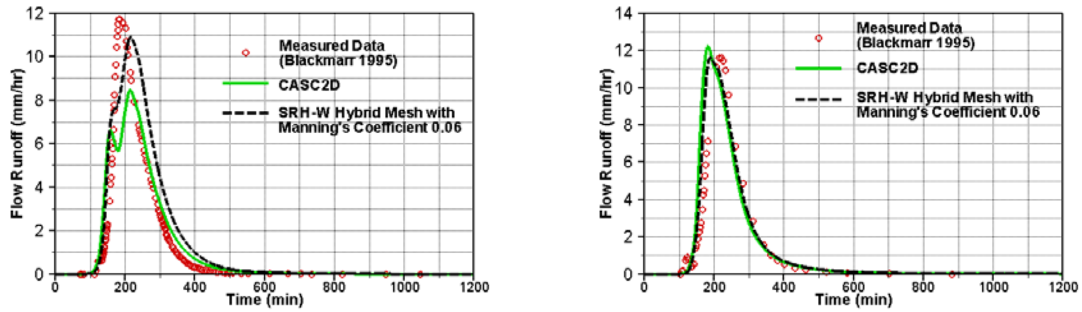
Figure 3. Comparison of results with the hybrid mesh (n=0.035).



(a) Outlet 1



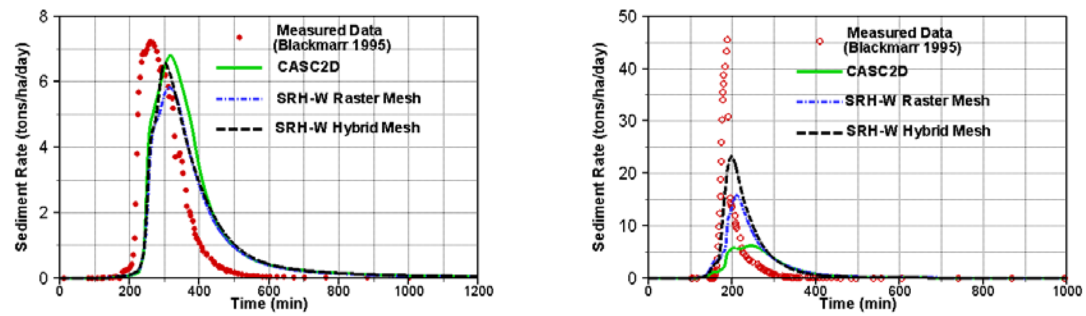
(b) Outlet 14



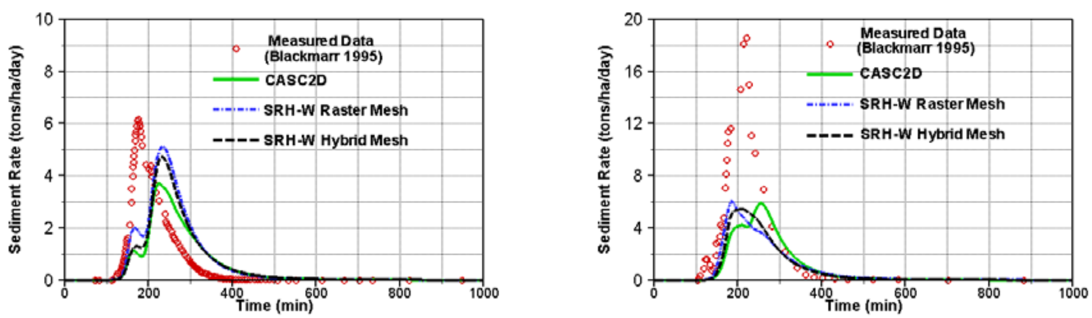
(c) Outlet 6 (d) Outlet 7

Figure 4. Comparison of results with the hybrid mesh (n=0.060).

Finally, soil erosion and sediment transport are also simulated. The simulated and measured sediment discharge rates are compared in Figure 5. The simulated sediment transport rates by SRH-W are similar to CASC2D, as essentially the same input parameters and the same transport capacity equations have been used. In comparison with the measured data, it is noted that significant under-prediction at outlets 7 and 14 is observed. The reason is unclear and possibilities may be various. One reason may be that bank erosion and mass failure in the channel or gully erosion on the sub-watershed may have occurred that are not simulated by the model.



(a) Outlet 1 (b) Outlet 14



(c) Outlet 6 (d) Outlet 7

Figure 5. Comparisons of sediment rates at four outlets.

Conclusion

An event-based, processes-oriented, mesh-distributed runoff and soil erosion watershed model is developed. The preliminary results show that the model works well as intended. The Cartesian mesh may potentially be efficient but the channel network representation has to be redesigned for modeling accuracy. The hybrid mesh is accurate and robust but the simulation time is larger than the Cartesian mesh. In future, new capabilities will be developed. Primary developments include the use of the local mesh refinement with the Cartesian mesh, local refined storage technique by which the finer terrain data may be used even when the model mesh is coarse, and the development of a new channel network solver that is based on the dynamic wave equation.

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