WATERSHED SIMULATION WITH AN ENHANCED DISTRIBUTED MODEL

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INTRODUCTION

Distributed watershed hydrological and erosion modeling is gaining popularity in recent years due to increased computing power and availability of detailed spatial hydrological data. Models of this type are widely believed to provide greatest opportunities to examine hydrologic impact of land use change and climate change (Sharika et al. 2000); they also have immense utility to forecast the movement of pollutants and sediments (Beven 1985). So far, quite a number of distributed models have been developed, and many were reviewed by Yang et al. (2003) and Lai and Yang (2004). Among them, WEPP (Nearing et al. 1989) and CASC2D (Julien et al. 1995; Johnson et al. 2000) are the two leading models used in the US.

Despite the consensus for their potential use and the need to develop distributed models, there have been a number of concerns. Ewen et al. (2000) pointed out three major outstanding issues: (1) True capabilities of distributed models are yet to be demonstrated in a convincing way; (2) Some important physical processes have not been included or modeled properly; and (3) There exists the so-called "scale problem" with the distributed models. Unrealistic results may be obtained when mesh size is too large, and a calibrated model at smaller-scale watersheds may not be extended to larger-scale ones.

This paper presents an enhanced distributed model, GSTAR-W (Generalized Sediment Transport for Alluvial Rivers and Watersheds), that is partially motivated by the scale issue. The model is based on the concept of CASC2D due to its popularity, ease of use and efficiency; but a number of improvements are made to extend the capability. One of the objectives is to partially address the scale problem. It is accomplished by developing a proper solution algorithm that guarantees mesh convergent solutions and a hybrid zonal modeling concept that allows mixed use of process models to achieve model scale-up.

MODEL CONCEPT AND METHOD

A significant departure from CASC2D is the geometric representation of a watershed. CASC2D uses the raster mesh while GSTAR-W adopts the zonal representation. With GSTAR-W, a watershed is partitioned into zones or polygons first. A zone may represent a sub-watershed or an arbitrary polygon, with the channel network as a special zone. Zonal partition lines may represent natural features based on topography, land use or soil types; or they may be arbitrary. Channel banklines are used as the partition lines in general applications and they form the channel network zone. This representation provides a more accurate coupling between overland and channel network in water and sediment exchange. In contrast, channels are 'approximated' in CASC2D by the raster mesh cells. The zonal modeling concept allows hybrid modeling: different methodologies or process models may be used in different zones. For example, one zone may use simple empirically based lumped modeling while another may select a physically based distributed modeling. In this regard, each zone may be viewed as a "building brick" of the model and each zone may be modeled and validated separately. This provides an opportunity to alleviate scale issue number two discussed in the Introduction.

For a two-dimensional (2D) distributed zone, the zone is further divided into discrete mesh cells. Hydrological and erosion processes are modeled in detail on each mesh cell. The meshing strategy adopts the arbitrarily shaped element method of Lai (2000). Such a flexible mesh facilitates the implementation of the hybrid zonal modeling concept and encompasses most existing meshing methods in use. For example, the raster mesh is a special mesh representation. In addition, such a mesh allows a tight integration between watershed and channel network and a truly mesh convergent solution is achievable.

GSTAR-W offers both the diffusive wave and the dynamic wave solvers for water flow as it intends to extend the modeling capability beyond overland flows to river systems. It also offers both explicit and implicit solvers for solution efficiency and robustness. A detailed description of the mathematical formulation and the numerical methods has been reported by Lai and Yang (2004) and is not repeated here.

CASE STUDIES

Two-Dimensional Surface Runoff: A 2D runoff case is simulated which has an approximate analytical solution and previous numerical results for comparison. The geometry is displayed in Fig.1 in which a V-shaped overland is connected to a channel. The overland plane has a slope of 0.05 and the channel has a slope of 0.02 and a width of 20 m. The depth of the channel varies linearly from 1 m at the upstream end to 20 m at the downstream end. An unstructured mesh shown in Fig.2 is used. Simulation has been carried out under a constant rainfall intensity of 10.8 mm/hr and zero infiltration with the rainfall duration of 1.5 hr. The Manning's roughness coefficient is 0.015 for the overland and 0.15 for the channel. A number of simulations have been carried out using GSTAR-W with explicit or implicit schemes. Essentially identical solutions are obtained and they are compared with previous results in Fig.3. Note that DiGiammarco et al. (1996) used a central difference scheme that leads to an 'overshoot' of the solution during the rising limb of the hydrograph; while CASC2D used a first-order upwind scheme that is too dissipative. Overall, it is shown that GSTAR-W agrees with the analytical and previous numerical results quite well, indicating that the right equation has been solved.

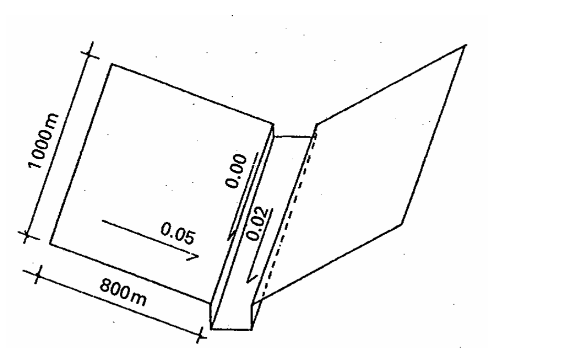


Figure 1 Geometry of the V-Shaped Catchment

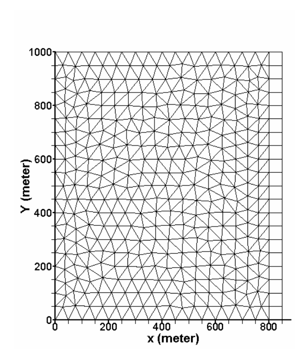
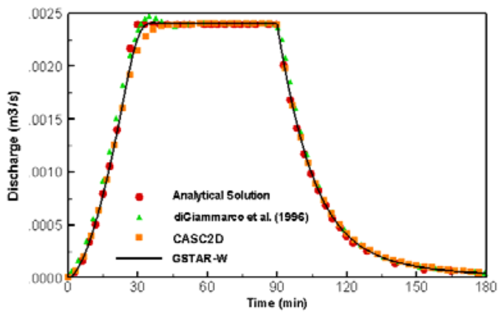
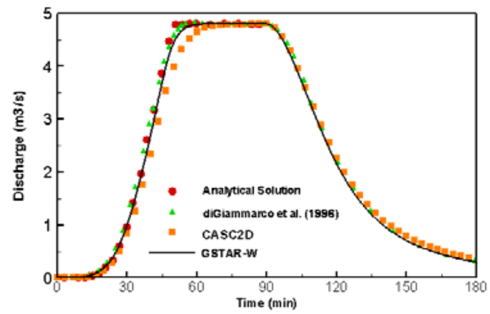


Figure 2 Unstructured Mesh Used



(a) at the Overland Exit into the Channel



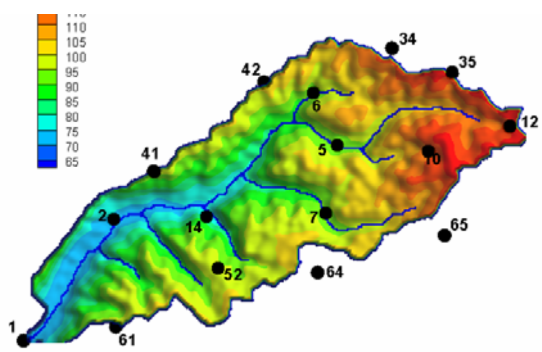
(b) at the Channel Exit

Figure 3 Comparison of Discharges for the 2D Runoff Case

Goodwin Creek Experimental Watershed: The runoff and erosion model is applied to the Goodwin Creek Experimental Watershed. Comparison is made between the GSTAR-W, CASC2D and the measured data at six gage stations shown in Fig.4a. A detailed presentation of the case is available in Lai and Yang (2004) with regard to the watershed and inputs to the model such as the digital elevation model, soil types, land use, precipitation, and others. They are only briefly described next while focus will be on the results and comparisons.

The digital elevation model (DEM) is available at 30-meter resolution and data are preprocessed first using TOPAZ to obtain a depressionless DEM (Sanchez 2002). The channel network and watershed are then delimited from the smoothed 30-meter DEM. Figure 4b shows the DEM and the channel network. Seven soil types are used based on the soil characteristics study by Blackmarr (1995). The land use is reclassified as forest (includes planted forest), pasture (includes idle land), water, and cultivated.

(a) Six Hydrograph Stations

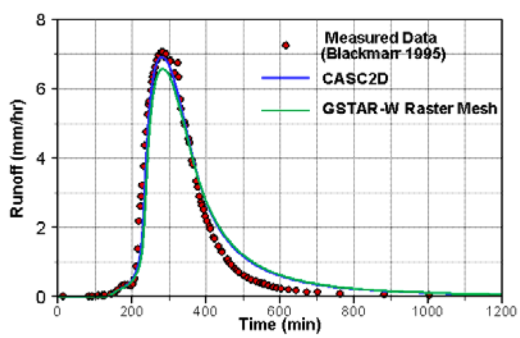


(b) DEM, Channel Network and Rain Gages

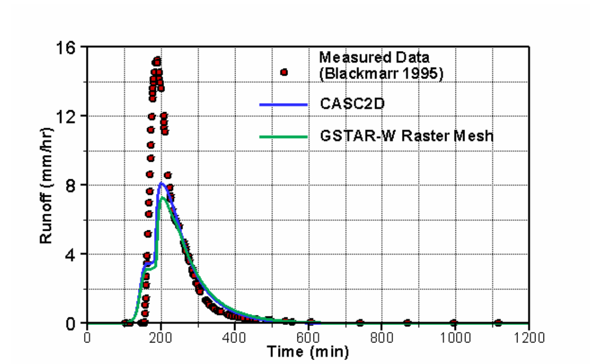
Figure 4 Goodwin Creek Watershed Information

The storm event of October 17, 1981 is chosen for simulation as the same event was also simulated by Sanchez (2002) with CASC2D. This event began at 9:19 pm and had a total rainfall duration of 4.8 hours with very little rainfall preceding this event. Precipitation data were taken from sixteen rain gages (see Fig.4b) that are located within and just outside the watershed. The entire watershed is divided into two zones: the overland zone solved with the distributed method and the channel zone with the 1D diffusive wave solver. Two meshes are used: 30m-by-30m raster mesh the mixed element unstructured mesh. All input data and parameters used are the same as those of Sanchez (2002) unless otherwise stated. No attempt has been made to calibrate the parameters to fit the field measured data.

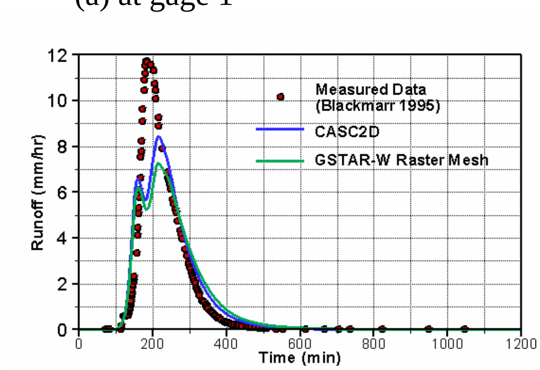
The first comparison in Fig.5 is between GSTAR-W and CASC2D with the raster mesh for flow hydrographs at four gage stations. The following are found: (1) The same results are predicted by GSTAR-W with the explicit and implicit solvers and with different time steps. Only one curve, therefore, is plotted with GSTAR-W; (2) Results from GSTAR-W and CASC2D are close but GSTAR-W results are consistently smaller than those of CASC2D. This may be attributed to the different resistance equations used. Smaller flow resistance was used by CASC2D even if the Manning's coefficients are the same for the two models; (3) It is noticed that a significant under-prediction of the peak occurred for stations 6 and 14. These are the smallest sub-catchments within the watershed (see Fig.4a) and therefore, errors may be attributed to sources such as the accuracy of precipitation and the delineated channel.



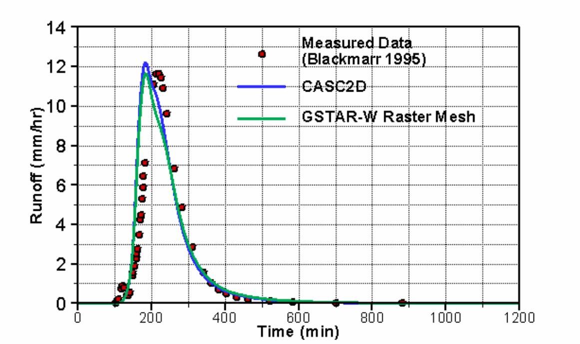
(a) at gage 1



(b) at gage 14



(c) at gage 6

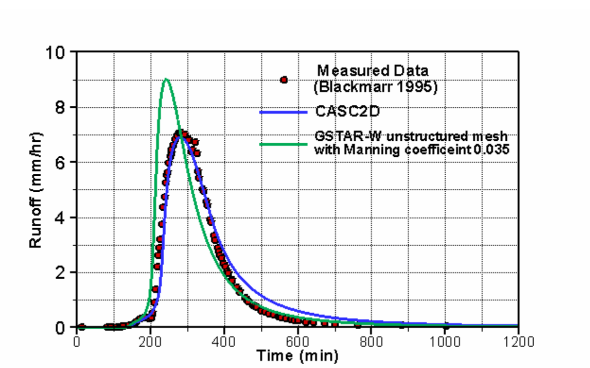


(d) at gage 7

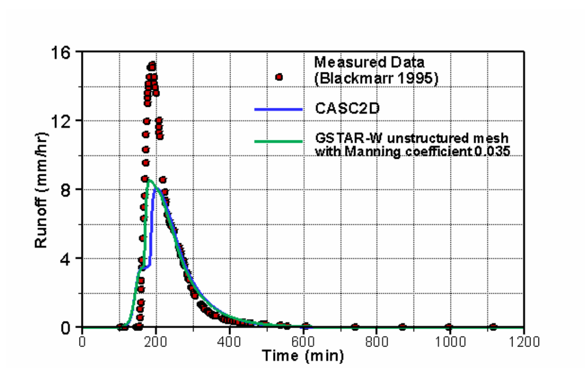
Figure 5 Comparison of Hydrographs with the 30-meter Raster Mesh.

The second set of comparisons is between the raster mesh and the mixed element unstructured mesh in order to see the difference between two mesh representations. Figure 6 shows the comparison when the channel Manning coefficient fixed at 0.035 for both mesh. It is seen that the predicted hydrograph at the watershed exit (station 1) is way off the measured one for the unstructured mesh, though the results are fine at other stations. It is found that this discrepancy is not due to the failure of the model but to the difference in channel representation of the two models. With the raster mesh, the channel is represented by the zigzagging mesh cells and as a result, the channel length is longer than that of the unstructured mesh. If the channel length for each reach is increased for the unstructured mesh to the same value represented by the raster mesh, simulation results are obtained. This points out that the channel Manning coefficient was calibrated by the raster mesh using the wrong channel length! If the Manning coefficient is re-calibrated with the correct length, the Manning coefficient of 0.06 is obtained. Such re-calibrated results are shown in Figure 7. It is seen that agreement between the two meshes is much better. The difference at station 6 is hard to explain and it may be due to the difference of mesh size and density for the subcatchment. It is worthwhile to point out that the roughness coefficient of 0.06 is probably a more realistic value as the same roughness coefficient was found and used in applying the 1D CONCEPTS model to the channels of the Goodwin Creek watershed (Langendoen 2000). The above results show that a correction should be carried out to the channel length when a raster mesh is used to represent the channel. Without the correction, the calibrated roughness coefficient may be in error.

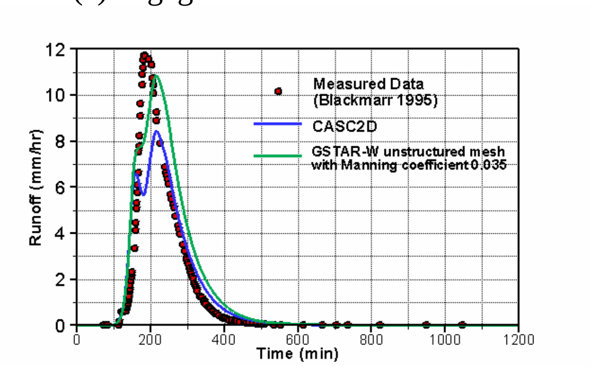
Next, predicted and measured sediment discharges at the six gage stations are compared in Figure 8. Overall the GSTAR-W results are similar to those of CASC2D by Sanchez (2002) as essentially the same input parameters and the same transport capacity equations have been used. In comparison with the field data, it is noted that significant under prediction at station 7 and 14 is observed. The reason is unclear and possibilities may include several. One of them may be that bank erosion and slide in the channel or gully erosion on the sub-catchment may occur that are not modeled.



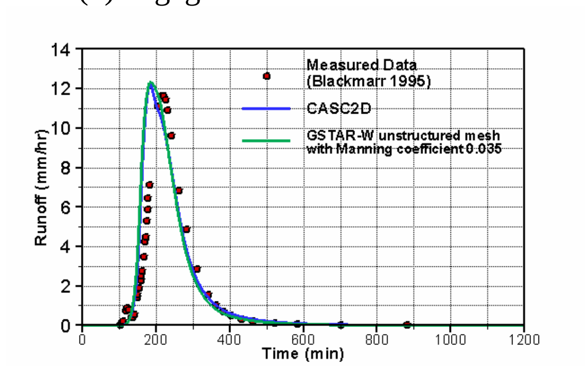
(a) at gage 1



(b) at gage 14

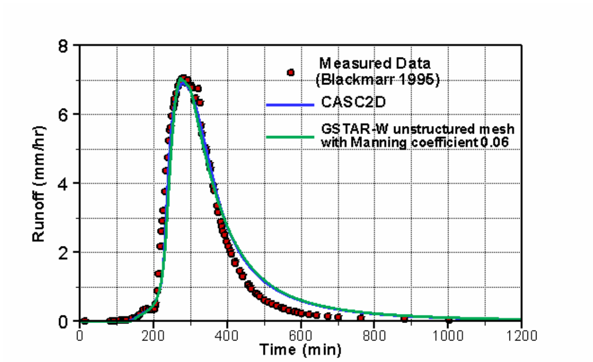


(c) at gage 6

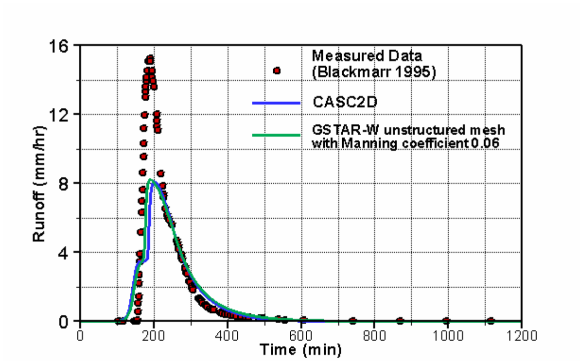


(d) at gage 7

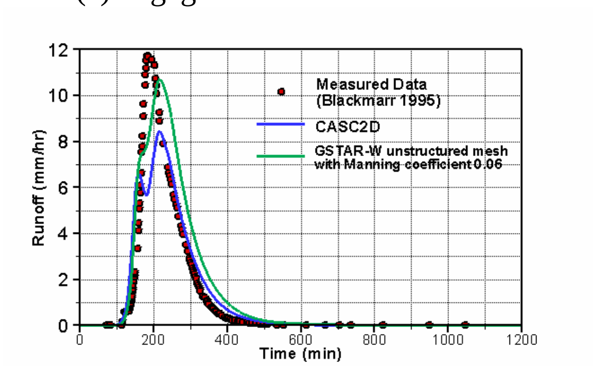
Figure 6 Comparison of Hydrographs with the Unstructured Mesh, n=0.035



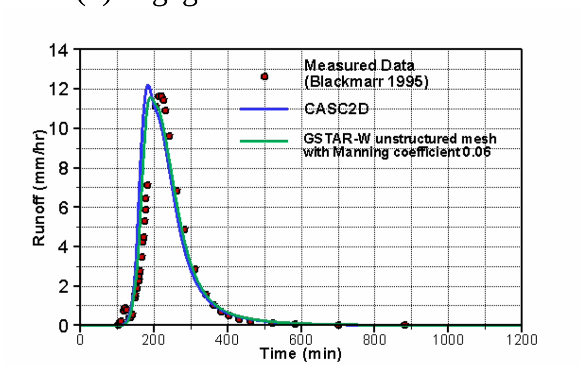
(a) at gage 1



(b) at gage 14

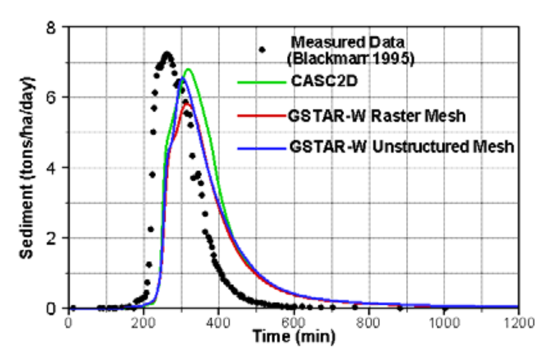


(c) at gage 6

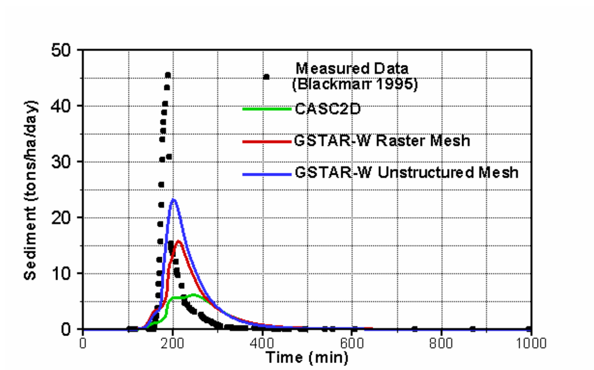


(d) at gage 7

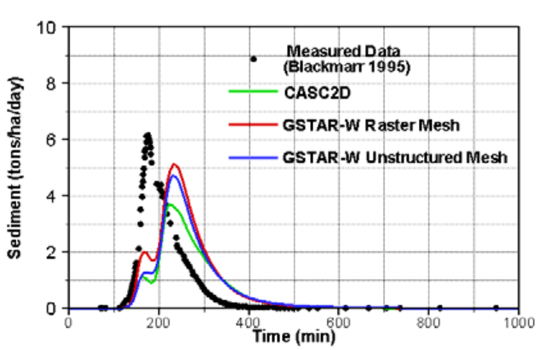
Figure 7 Comparison of Hydrographs with the Unstructured Mesh n=0.06



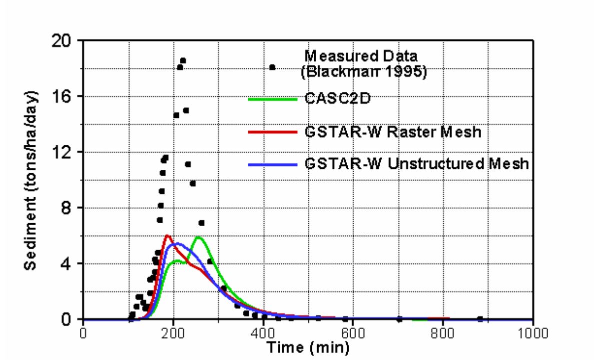
(a) at gage 1



(b) at gage 14



(c) at gage 6



(d) at gage 7

Figure 8 Comparisons of Sediment Graphs between CASC2D and GSTAR-W

One of the benefits of distributed modeling is its ability to predict flow and the erosion and deposition patterns. Such information may be used to assist the erosion management assessment and plan. The predicted water depth at 210 minutes and the predicted erosion and deposition pattern at 300 minutes after the storm event are displayed in Fig.9 and Fig.10. It clearly demonstrated the usefulness of the modeling as high erosion area could be identified graphically.

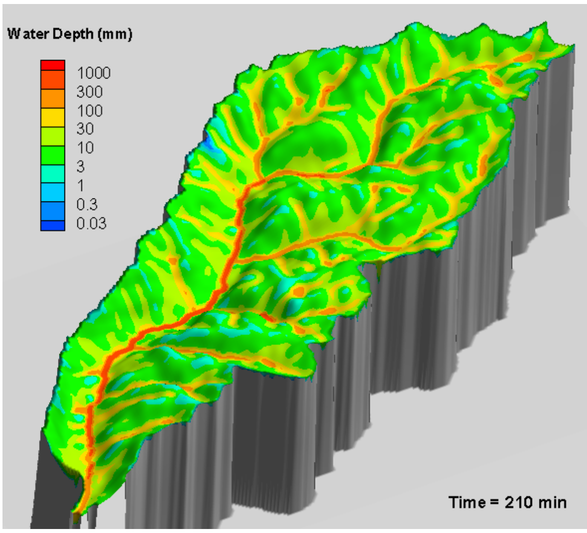


Figure 9 Water Depth at 210 Minutes

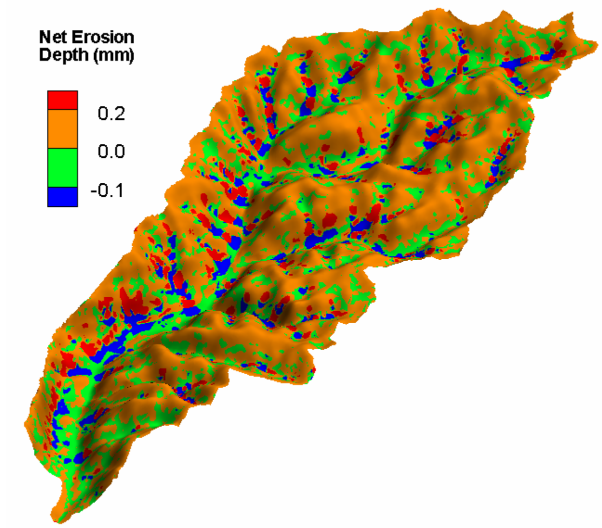


Figure 10 Net Erosion Depth at 300 Minutes

CONCLUDING REMARKS

An enhanced distributed model, GSTAR-W, has been developed to model the water runoff and soil erosion on watershed. The hybrid zonal modeling concept is proposed that is a major departure from the single zone raster mesh approach of most existing models. In addition, unstructured and implicit solution method is developed for the distributed zone that is more general and flexible than the raster mesh and more robust than the explicit method. Selected test cases of the model verify the model. Future work will focus on the demonstration of the hybrid zonal modeling capability and the ability of the model to resolve the scale issue, at least partially.

ACKNOWLEDGEMENTS

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