RIVER AND WATERSHED MODELING: CURRENT EFFORT AND FUTURE DIRECTION

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ABSTRACT

This paper discusses the current effort and experience of the development and application of a computer model, GSTAR-W, for flow and sediment modeling of river systems and watersheds. Many existing models are limited by various assumptions and intended uses. They are often used beyond their applicability range. This paper will review the current status of river and watershed modeling and presents experience and knowledge gained when applying GSTAR-W to field cases. Current effort in the model development is reported, limitations of different numerical methods are assessed, and future direction for river and watershed modeling is discussed.

1. INTRODUCTION

Water and sediment supply, and their management, are critical to many hydraulic project operations. They directly impact sustainable use of reservoirs, water quality, and riparian habitat for endangered species. However, limited tools and methods are available to understand the future impacts of a project to the river system. In addition, water and sediment supply has been measured only at limited locations and over a limited time period; there are few feasible ways to obtain the sediment delivery from ungaged non-point sources. For these and other needs, a predictive numerical model provides a viable alternative and is gaining popularity in recent years.

In developing a numerical model, one has to realize that river and reservoir systems rarely act alone and often interact with their surroundings such as floodplains and watersheds. Traditional approaches often treat each process separately and models lack the ability to simulate river system and their surroundings together. In view of this, Reclamation initiated a project to develop a new model that treats different systems according to their physics - each with the most suitable technology - but in a coupled manner. The model is named GSTAR-W, Generalized Sediment Transport for Alluvial Rivers and Watershed. This paper reports the progress made and experience gained so far.

GSTAR-W may be used to predict water and sediment delivery to project facilities at a watershed scale; it may also be used for river corridors. In watershed applications, a thorough review of existing watershed models has been reported by Yang et al. (2003) and Lai and Yang (2004). It is found that most watershed models are empirically based and region specific. Among distributed models, most are limited to field scales or small watersheds and suffer various other

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shortcomings. Two popular distributed models in the United States are the Water Erosion Prediction Project (WEPP, Nearing et al. 1989) and the CASCade of planes in Two Dimensions (CASC2D, Julien et al. 1995 and Johnson et al. 2000). However, WEPP is limited to spatial scales less than a few square miles while CASC2D has a number of restrictions such as on the overland and channel coupling (Lai 2006). Both are watershed models and have limited capabilities in river system modeling. In river corridor applications, on the other hand, many existing models are either purely one-dimensional (1D), e.g., HEC-RAS (USACE 2002) and GSTAR-1D (Yang et al. 2004), or purely two-dimensional (2D), e.g., MIKE21 (DHI 1996) and RMA2 (USACE 1996). A channel network is most efficiently treated with a 1D model while the floodplain and adjacent areas are best simulated with a 2D model. Few existing models can take advantages of both 1D and 2D to efficiently solve river corridor problems.

GSTAR-W adopts a hybrid zonal approach for coupled modeling of channels, floodplains, and watershed; and it incorporates both benefits of 1D and 2D modeling. Conceptually, GSTAR-W divides a watershed or a river corridor into zones. A zone may represent a 1D channel reach or a 2D feature that may be solved with suitable models and solvers. There are two major modules: the 2D model for rivers, floodplains or watersheds and the 1D model for channel reaches. A seamless integration between the two is achieved. Major features are briefly described below:

<u>Hybrid Zonal Modeling:</u> GSTAR-W divides a watershed or a river corridor into zones where each zone is solved with the most suitable models and algorithms. The layered hybrid approach facilitates the use of most appropriate models and solvers for each zone; it also extends the model to larger spatial and time scales. Flow routing includes diffusive wave and dynamic wave equations and numerical solvers provide a choice of explicit or implicit scheme, in addition to various process models.

<u>Geometry Representation:</u> The arbitrarily shaped element method (ASEM) of Lai (2000) is adopted for geometry representation. Such a flexible meshing strategy facilitates the implementation of the hybrid zonal modeling concept and allows the use of most existing meshing methods. For example, it allows a natural representation of a channel network in 1D or 2D, as well as the surroundings (flood plains or watersheds). With ASEM, a tight integration between watershed and channel system is achieved and a truly mesh-convergent solution may be obtained.

<u>Channel Network Modeling:</u> GSTAR-W provides a 1D diffusive wave routing model for a channel network, in addition to the 2D model. It also incorporates the recently developed dynamic wave model, GSTAR-1D (Yang et al, 2004), as an option. With the use of a comprehensive channel network model such as GSTAR-1D, GSTAR-W is capable of simulating larger watershed scales than many existing distributed models. GSTAR-1D is a dynamic wave model using arbitrary channel cross-sections, alluvial channel evolution with bank erosion, and extensive sediment modeling.

GTSAR-W is an on-going project. This paper focuses on applications to water flow and runoff only. Erosion and sediment issues will be reported in future papers.

2. GSTAR-W FLOW ROUTING METHOD

Development of rainfall-runoff numerical models has received much attention since the early 1970s. Earlier models used simple methods to quantify various hydrological components such as the unit hydrograph method, empirical/statistical relations, lumped method and analytical equations. As computing power increases, more complex distributed models have been developed.

Distributed models range from the simple kinematic wave model to the full dynamic wave model (Woolhiser, 1996). Singh and Frevert (2002a, b) provided a listing of available hydrological models in which six distributed models were described. It was recognized that flow routing with the dynamic wave model accounting for micro-topographic characteristics was computationally intensive. Attempts were made to adopt simplified equations. It was Henderson and Wooding (1964) who first applied the kinematic wave theory to simulate overland flows. Later, a detailed analysis was carried out by Woolhiser and Liggett (1967) on the kinematic wave criteria. Since then, the kinematic wave model has been very popular and used by many runoff models. In an attempt to overcome some limitations of the kinematic wave model, some recent models adopted the diffusive wave approximation. Examples include Di Giammarco et al. (1996), CASC2D (Julien et al. 1995; Johnson et al. 2000), and GSSHA (Downer 2002). The diffusive wave model is more accurate in taking the backwater effect into account while the added computational complexity and cost remain relatively low. This advantage makes the diffusive wave model suitable also for problems with flatter terrains.

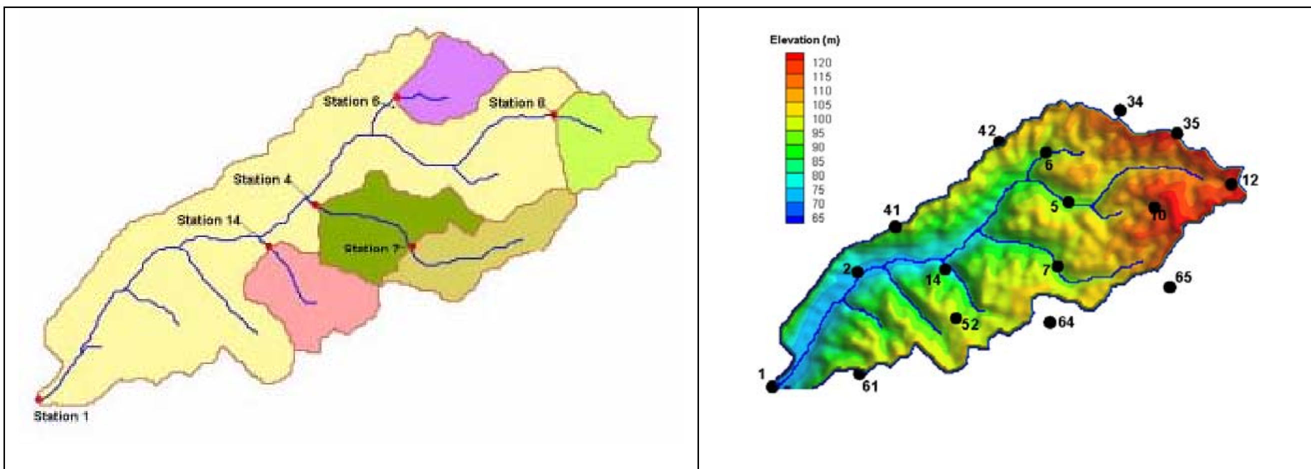
GSTAR-W offers both the diffusive wave and the dynamic wave solvers for water flow as it intends to extend the modeling capability beyond overland flows to river systems. It also offers both explicit and implicit solvers for solution efficiency and robustness. Such choices become feasible, and also make sense, due to the hybrid zonal modeling concept adopted. A detailed description of the mathematical formulation and the numerical methods has been reported by Lai and Yang (2004) and Lai (2006) and is not repeated here.

3. CASE STUDIES

3.1 Goodwin Creek Experimental Watershed

The first case uses the watershed modeling capability of GSTAR-W and the model is applied to the Goodwin Creek experimental watershed. This watershed is located in Panola County, Mississippi, near Batesville. It has a size of 21.3 km^2 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 diffusive wave solver is used as it is sufficient for such applications. Comparison is made between the GSTAR-W, CASC2D and the measured data for the hydrographs at six outlet stations shown in Figure 1a. Experiences gained with regard to the explicit versus implicit method, raster mesh versus arbitrarily shaped element mesh will be discussed.



(a) Six Hydrograph Stations | (b) DEM, Channel Network and Rain Gages

Figure 1 Goodwin Creek Watershed DEM, Channel Network, Rain Gages and Hydrograph Stations

Event Simulated and Input Data: The storm event on October 17, 1981 was chosen for simulation. This event began at 9:19pm and had rainfall duration of 4.8 hours. Precipitation data were taken from sixteen of the thirty-two rain gages that are located within and just outside the watershed. The Digital Elevation Model (DEM), the delineated channel network and locations of sixteen rain gages are displayed in Figure 1b. 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. Readers should consult Lai and Yang (2004) and Lai (2006) for a detailed description of these input data. It is noted that the same set of input parameters were used by Sanchez (2002) in applying CASC2D to the same watershed. No attempt has been made in this study to calibrate parameters to fit the field measured data.

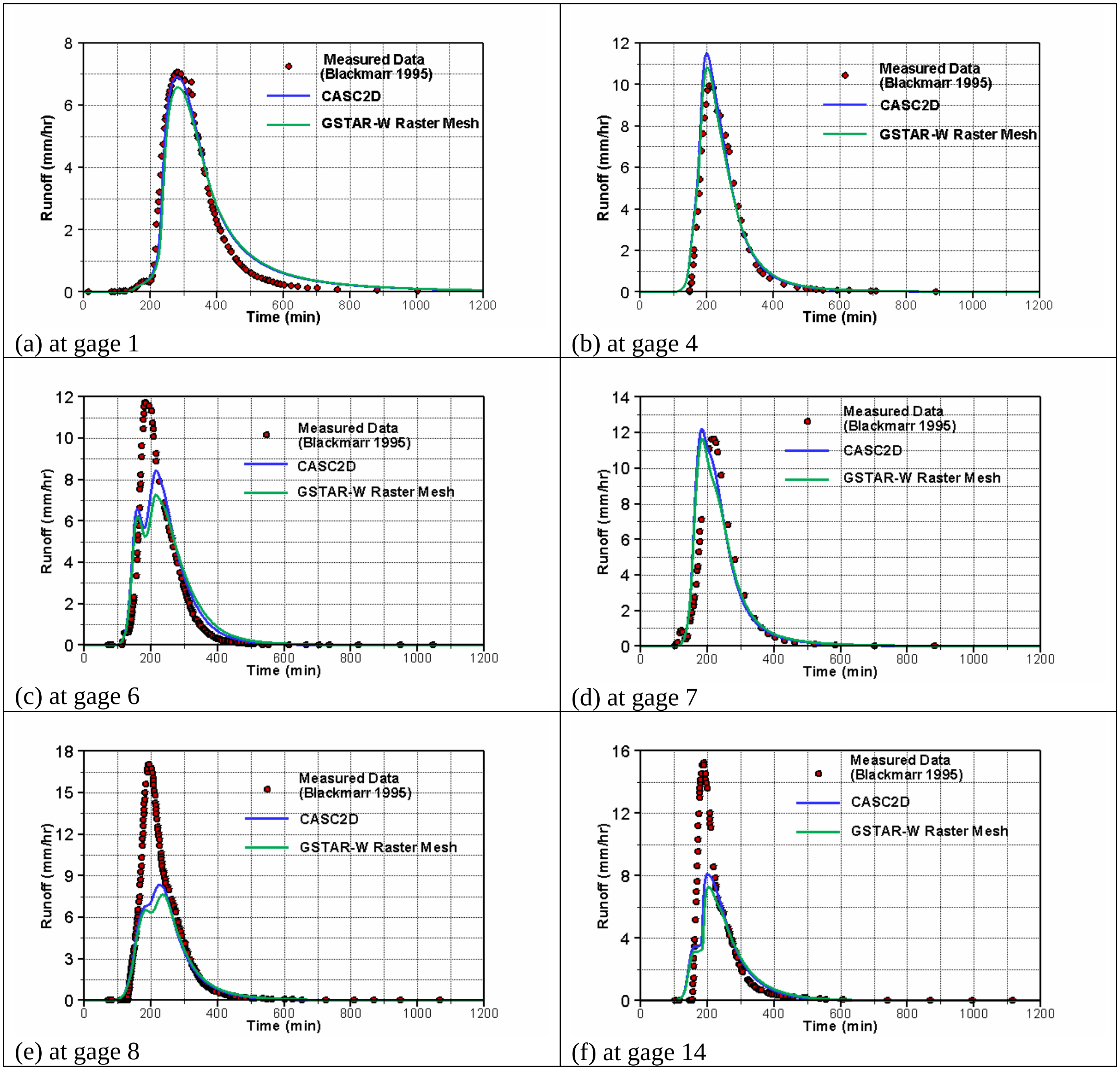
Description of Mesh Topologies: A number of meshes and solver options are used to simulate the storm event. They are: (1) 30m-by-30m raster mesh with CASC2D; (2) 30m-by-30m raster mesh with GSTAR-W, both explicit and implicit solvers; (3) the mixed element unstructured mesh with GSTAR-W, both explicit and implicit solvers.

CASC2D is limited to the raster mesh and the explicit solver only. Channel network representation of CASC2D is the same as the diffusive wave channel solver option offered in GSTAR-W. That is, overland mesh elements are used to represent the network. Such a channel network representation has limitations when the raster mesh is used. Firstly, such a representation is not feasible when a channel width exceeds the element size (30m for the present case). This limits the minimal mesh size that may be used. Next, such a representation makes the channel actually zigzag along the raster mesh instead of the natural river alignment. A consequence is that the actual reach length is not accurately modeled. With the CASC2D simulation, the time step was chosen to be *dt*=0.5s as *dt*=1.0s was found to lead to divergence. The same time step (0.5s) was also used by Sanchez (2002) in her modeling.

Next, the same raster mesh is also used by GSTAR-W with both explicit and implicit solvers. The major difference from CASC2D is that only active elements that cover the watershed are used by GSTAR-W and inactive elements are ignored. With GSTAR-W, different time steps may be used for the overland runoff simulation and the channel network simulation. With the diffusive wave channel network solver, *dt*=0.5s is used for all channel simulations. For overland simulation, up to *dt*=5s may be used with the explicit scheme while up to *dt*=300s may be used with the implicit scheme.

Finally, a mixed element unstructured mesh is created for GSTAR-W simulation. This is the most general and flexible mesh topology and is the intended use of GSTAR-W for practical applications. With this mesh, 1D quadrilateral mesh is used first to represent the channel network with its natural alignment. The rest of the watershed is then filled with elements of triangles and quadrilaterals; this may be done automatically. The average size of each element is maintained approximately at 30 meter resolution though there is quite a spread. Note the important difference between the unstructured mesh and the raster mesh in that the channel may be represented more accurately eliminating the limitations of the raster mesh discussed earlier. For the unstructured mesh, the time step for the diffusive wave channel network solver is fixed at 0.5s while varied time steps are used for the overland simulation. The explicit scheme used the time step up to 2.5s while the implicit scheme was up to 120s.

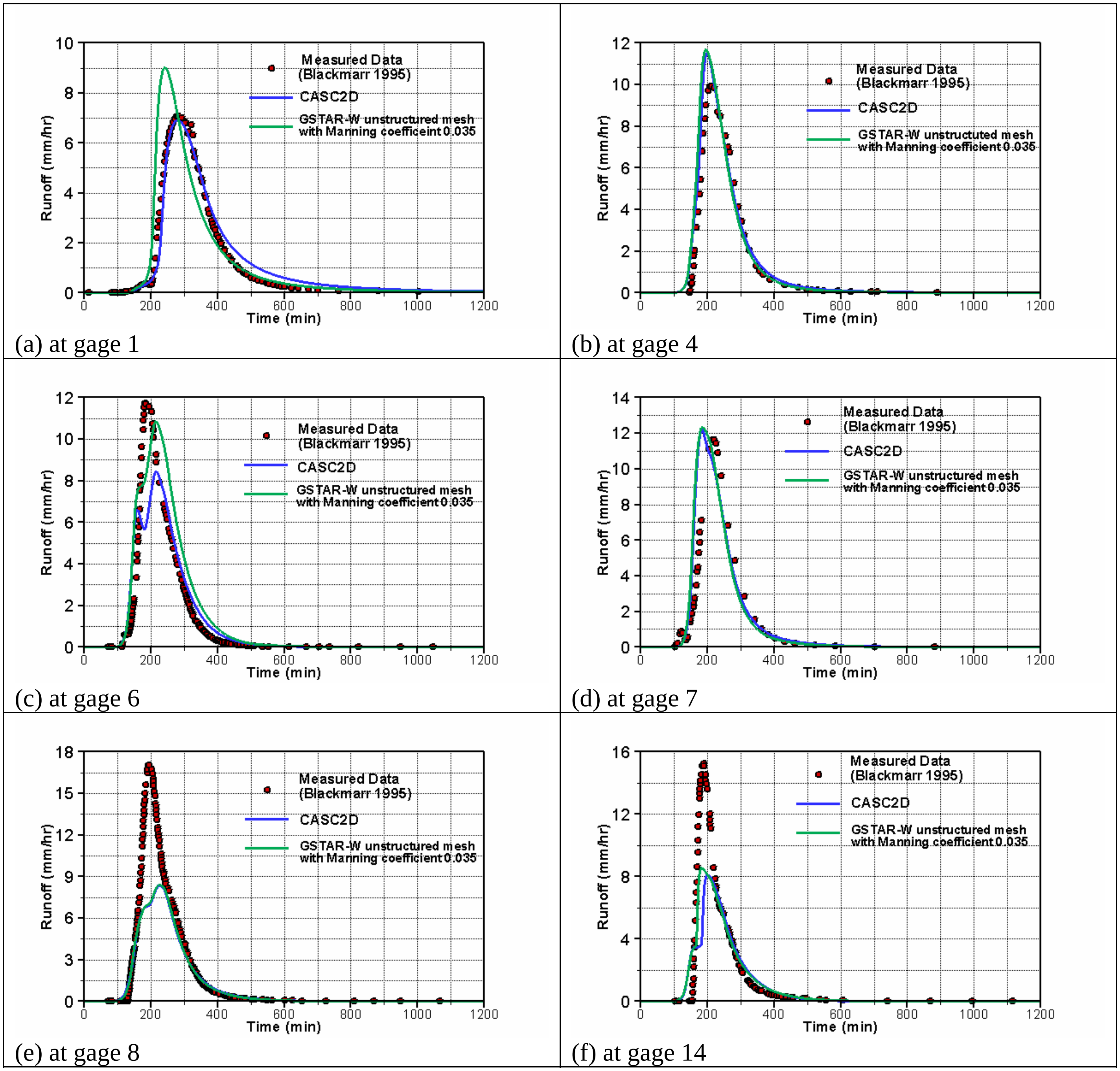
Results and Discussion: The first comparison is between GSTAR-W and CASC2D with the raster mesh, shown in Figure 2, for flow hydrographs at six gage stations. The following findings are observed: (1) the same results are predicted by GSTAR-W with the explicit and implicit solvers and with different time 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 is effected 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, 8 and 14. These are the smallest sub-catchments within the watershed (see Fig.1a) and therefore, the errors may be attributed to sources such as the accuracy of precipitation and the delineated channel.



(a) at gage 1
(b) at gage 4
(c) at gage 6
(d) at gage 7
(e) at gage 8
(f) at gage 14

Figure 2 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 3 shows the comparison when the channel Manning coefficient is 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. Recall that the channel represented by the raster mesh zigzags 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 found to agree with each other. 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 reach length, the Manning coefficient of 0.06 is obtained. Such re-calibrated results are shown in Figure 4. 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).



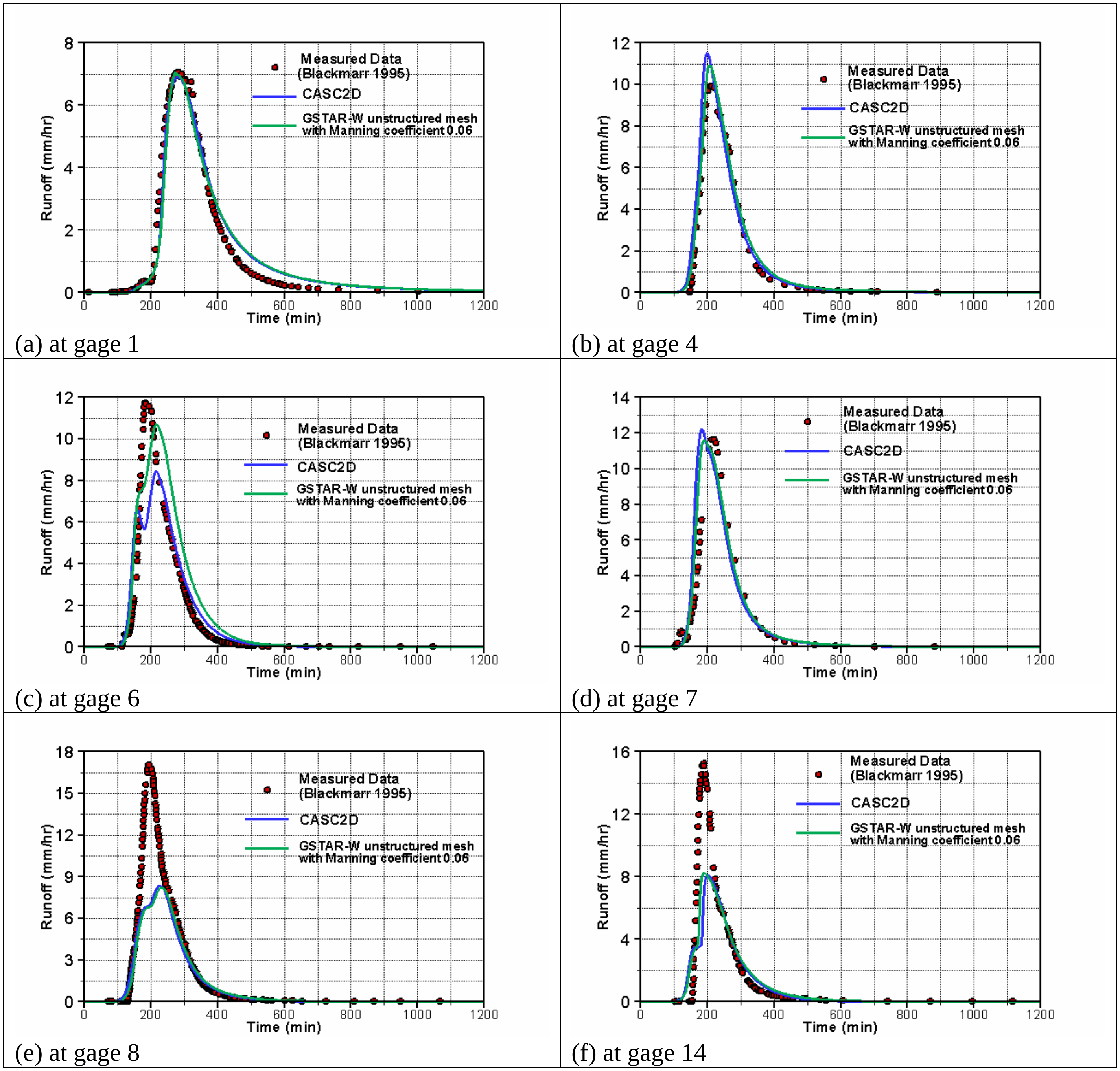
(a) at gage 1 (b) at gage 4

(c) at gage 6 (d) at gage 7

(e) at gage 8 (f) at gage 14

Figure 3 Comparison of Hydrographs with the Unstructured Mesh, n=0.035.

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.



(a) at gage 1 (b) at gage 4

(c) at gage 6 (d) at gage 7

(e) at gage 8 (f) at gage 14

Figure 4 Comparison of Hydrographs with the Unstructured Mesh, n=0.06.

3.2 Savage Rapids Dam

The second case is the application of GSTAR-W to a river system, i.e., the Savage Rapids Dam. The dam is located in southwestern Oregon on the Rogue River, five miles upstream from the city of Grants Pass. It is owned and operated by Grants Pass Irrigation District and has been used for diverting irrigation flows since 1921. The full removal of the dam and construction of a new pumping station are under design by the Bureau of Reclamation, due to lack of compliance of the existing fish ladders and screens to the current National Marine Fisheries Service criteria. GSTAR-W is used to simulate various scenarios to provide design data and assistance. Only the calibration and verification study is reported below.

Topography and Mesh: The simulation reach extends from the Savage Rapids Park, 0.5 mile upstream of the dam, to about 0.45 mile downstream of the dam. The topography for the reach is reconstructed from a number of survey data conducted between 1999 and 2005 (Bountry and Randle 2003). A quadrilateral mesh is developed that consists of 20,145 elements and 20,468 nodes with a typical element size of 5 by 12 feet. A 3D view of the topography and part of the mesh is displayed in Figure 5.

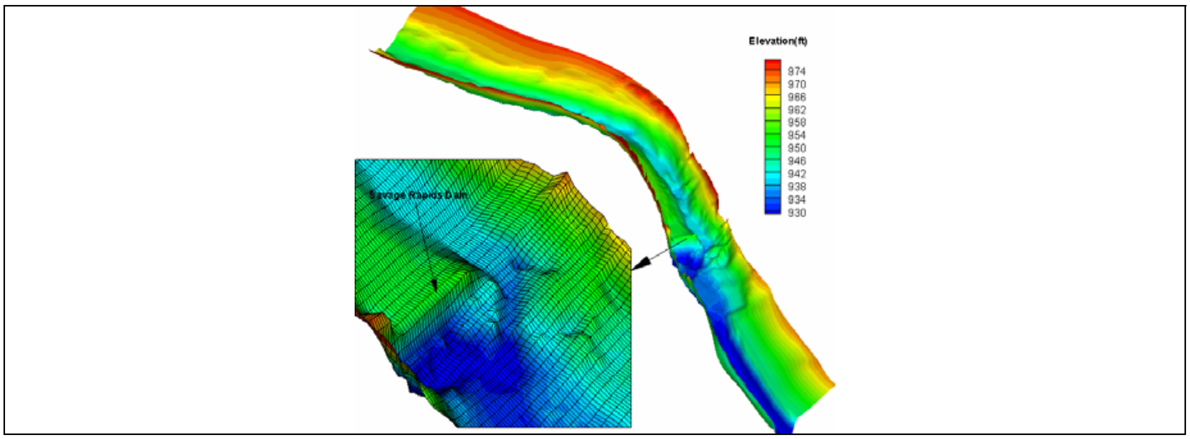


Figure 5 A Perspective View of the Topography of the Modeled River Reach.

Case Modeled: The measured data, water surface elevation and velocity vectors, during the April 2002 survey (Bountry and Randle 2003) was chosen to calibrate and verify the GSTAR-W model. This case represents a drawn-down flow with a discharge of 2,800 ft^3/s. All flow was through the two radial gates near the left side of the dam. The measured water surface elevation is used to calibrate the Manning roughness coefficient that is assumed to be uniform throughout the reach. Once calibrated, the model results are then compared with the measured velocities and flow patterns. Both diffusive wave and dynamic wave solutions are obtained so that a comparison may be made between the two solvers.

Boundary Conditions and Other Parameters: A water surface elevation of 935.53ft was specified at the downstream boundary. This elevation was obtained from the calibrated one dimensional HEC-RAS model as described by Bountry and Randle (2003). At the upstream boundary, a flow discharge of 2,800ft^3/s was applied where a uniform distribution of velocity is assumed with the flow normal to the boundary. The calibrated flow loss coefficient is 0.05 for the diffusive wave model and 0.04 for the dynamic wave model. Finally, the depth-averaged parabolic model is used for the turbulence viscosity used by the dynamic wave model (Rodi 1993).

Comparison of Water Surface Elevation: The calibrated model results are compared with the measured water surface elevation along the thalweg in Figure 6. Both the diffusive wave and the dynamic wave model agree with the measured elevation well. Major discrepancy between the two models is mostly limited to an area near the radial gates where a hydraulic jump exists due to the dam. As anticipated, the dynamic wave model predicts the existence of the jump, while the diffusive wave model is incapable of simulating the hydraulic jump. The diffusive wave model tends to predict a smooth variation of elevation over the jump. Based on experiences with other applications of GSTAR-W, it is recommended that the jump area should be modeled with a higher loss coefficient in order to predict the water elevation change, although the uniform coefficient works fine for the Savage Rapids Dam application.

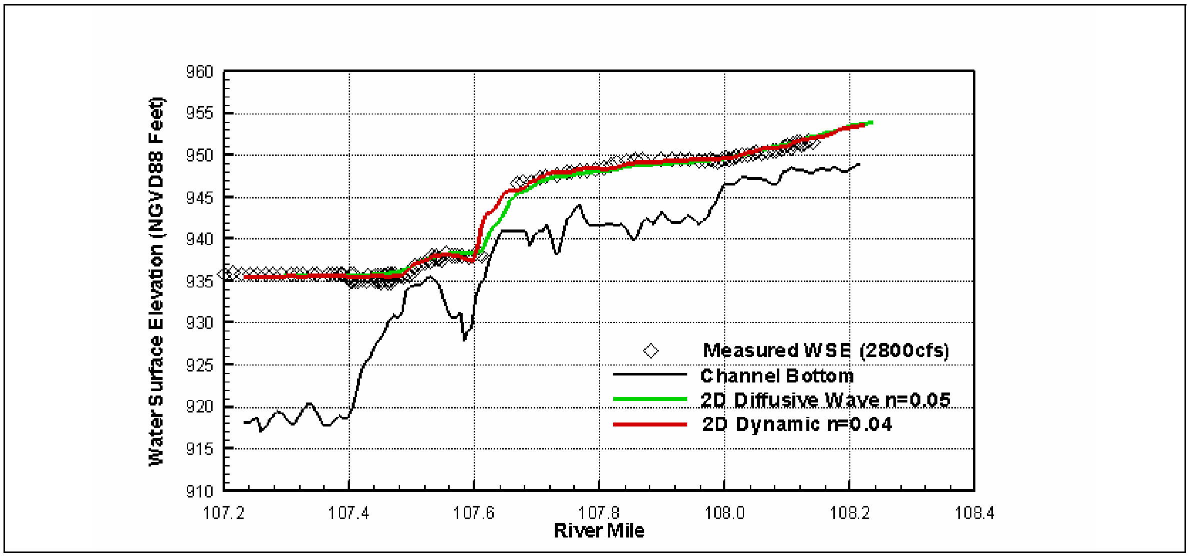


Figure 6 Comparison of Predicted and Measured Water Surface Elevations.

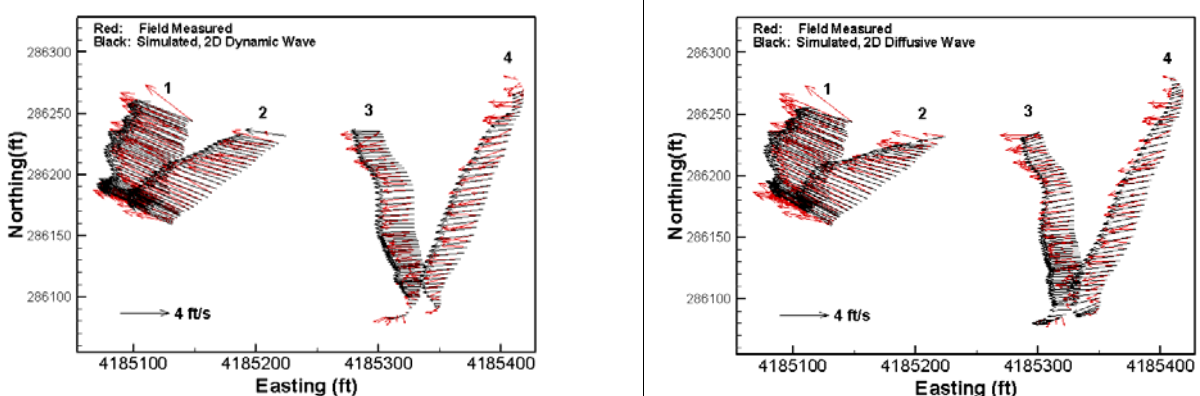
<u>Comparison of Velocities and Flow Patterns:</u> Next, the computed velocity vectors and flow patterns are compared with the measured data so that the flow hydraulics may be compared in greater detail. It is noted that a good prediction of the water surface elevation does not guarantee a good prediction of velocities and flow patterns.

The ADCP-measured and depth-averaged velocity data are available and the measurement points are displayed in Figure 7. Upstream of the dam, eight cross sections were surveyed and they are numbered consecutively in the figure. Downstream of the dam, two areas are compared: One is immediately downstream of the dam but near the right side; another is downstream of the excavated channel from the radial gates. Complex eddies were formed at the time of survey in both areas.

Figure 7 Velocity Measurement Points for the Simulated River Reach (Points are Shown in Red).

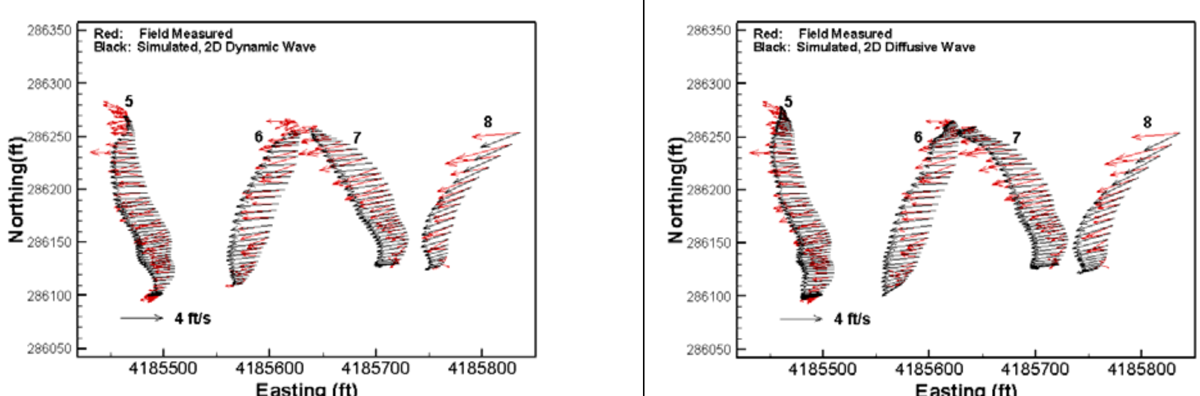
A comparison of predicted and measured velocity vectors at eight cross sections upstream of the dam is displayed in Figures 8 and 9. Agreement is favorable for both models except at a few locations. Overall, the difference between the dynamic wave and the diffusive wave solutions is not appreciable. The dynamic wave model is capable of predicting the flow separation on the left bank of cross sections 3 and 4 while the diffusive wave model is not.

A comparison of velocities and flow patterns is shown downstream of the dam in Figure 10. It is clear that the diffusive model is incapable of predicting any eddies and therefore, the velocity results in such areas are in gross error. On the other hand, the dynamic wave model is quite good in predicting the eddy structures. It is noted that the two-eddy structure on the right of the jet stream from the excavated channel is well predicted both in terms of size and location. In addition, the eddy on the left of the jet stream is also predicted. These results indicate that the dynamic wave model has to be used if eddies or flow separation are of interest.



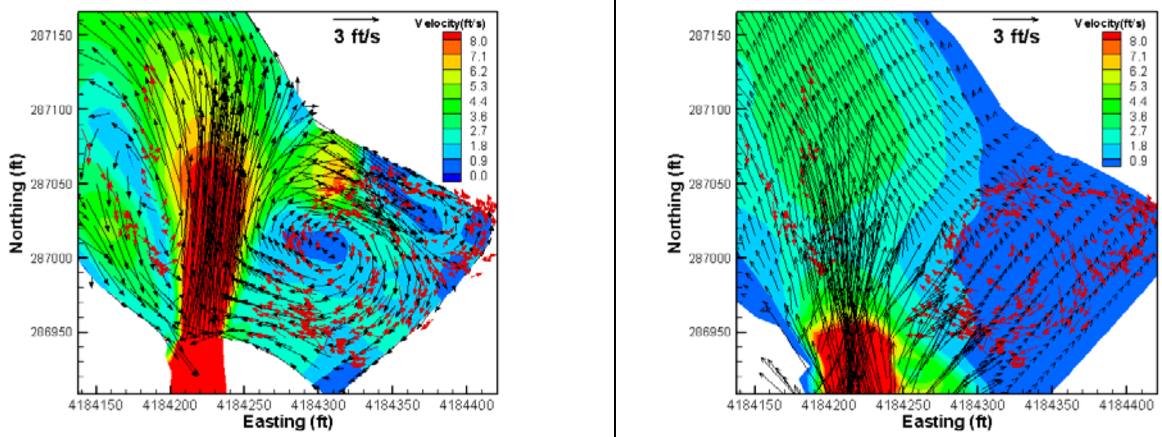
(a) Dynamic Wave Solution (b) Diffusive Wave Solution

Figure 8 Comparison of Predicted and Measured Velocity Vectors at Cross Sections 1 to 4.



(a) Dynamic Wave Solution (b) Diffusive Wave Solution

Figure 9 Comparison of Predicted and Measured Velocity Vectors at Cross Sections 5 to 8.



(a) Dynamic Wave Solution

(b) Diffusive Wave Solution

Figure 10 Comparison of Velocity Vectors and Flow Patterns downstream of the Dam.

4. CONCLUDING REMARKS AND FUTURE DIRECTIONS

Based on the development and its applications of GSTAR-W, the following findings and recommendations are obtained:

a. When the raster mesh is used for the watershed runoff simulation, one has to be aware of the limitations of the channel network representation. The width of the channel may limit the minimal mesh resolution used and the channel length may be longer than the actual size. The Manning coefficient may be wrongly calibrated for such cases.

b. Experience with GSTAR-W has indicated that the implicit solver is more efficient and robust for majority of the applications. The explicit solver may be more suitable only for special cases where the accuracy dictates that a small time step be used.

c. The diffusive wave solver is suitable for many applications that require the water surface elevation, water depth and bulk velocities. But the dynamic wave solver has to be used if eddies and flow separations are the interested outputs. For the diffusive wave solver, the Manning roughness coefficient should be interpreted as the energy loss coefficient as extra losses due to eddies, separations, and hydraulic jumps are lumped together with the coefficient. So the coefficient used for the diffusive wave solver is usually higher than that for dynamic wave solver. Hydraulic jump can only be simulated with the dynamic wave model and a smooth transition will be predicted by the diffusive wave solver. If details around a jump are not important, the diffusive wave solution may still be used even if there are hydraulic jumps.

Future directions of the model development include the following:

a. One of the biggest challenges with the watershed modeling is the so-called “scale problem”. This may mean different things by different researchers. Inherent are two problems: one is that unrealistic results may be obtained when mesh size is too large; and the second is that a calibrated model that works for a smaller scale watershed can not be extended to larger scales. Care should be taken to ensure that (1) the numerical method should guarantee mesh-convergent solutions (GSTAR-W satisfies this condition); (2) avoid to use scale-dependent process models unless they are intended for a customized use; (3) a more comprehensive and robust channel network model is needed for extension to larger watersheds (such as incorporation of GSTAR-1D into GSTAR-W); (4) a sufficiently fine mesh needs to be used; (5) a few measured points for physical properties as inputs may not be extended for use to larger scales.

b. Future development and application should focus on the hybrid zonal modeling capability. It is widely known that rivers and watersheds are working together as one dynamic system. Disturbances at one reach may lead to a system wide response. This requires modeling of larger scales even if only a local problem is addressed. Larger scale modeling inevitably requires simpler modeling for larger scales and more detailed comprehensive modeling for smaller scales. The hybrid zonal modeling capability explored in GSTAR-W provides such a tool for a more systematic simulation in future.

c. Recent soil research is shifting to the analysis of spatial dynamics of soil surface characteristics and runoff and erosion patterns. Most model performances, however, have been tested using the watershed outlet data only and erroneous predictions of flow and erosion patterns may be predicted and go undetected. Analysis has shown that runoff on cultivated land is often directed along linear landscape features (e.g., tillage lines) and this has a major impact on erosion patterns (Kirkby et al. 2005). There is no doubt that the kind of flow routing methods used will become important when accurate patterns need to be simulated. Preliminary results discussed in this paper indicate that the dynamic wave model may be needed in selected zones to predict the flow pattern correctly.

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