MODELING WETLANDS IN A MULTI-DIMENSIONAL HYDROLOGIC MODEL

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Abstract: GSSHA is a two-dimensional finite difference hydrologic model that has been used mostly in research of watershed flooding. Major processes that GSSHA is capable of modeling include overland flow (2D), stream flow (1D), infiltration (1D), groundwater (2D), and evapotranspiration. Recently a capability to model flows through wetlands was added to GSSHA. The wetlands hydrodynamic capabilities of GSSHA are described. A study to determine how useful the wetland hydrodynamics are in a practical engineering application was done on the Rio Grande river. This study uses GSSHA's diffusive wave overland flow equations to simulate the Rio Grande River to the end that proposed wetlands could be evaluated on the banks of the Rio Grande River. The study concludes that GSSHA is able to be used to both evaluate the hydrologic effects of wetlands placement and also to discover where wetlands could be placed to have a greater chance of wetlands sustainability.

INTRODUCTION

The U.S. Army Corps of Engineers hydrologic model Gridded Surface Subsurface Hydrologic Analysis (GSSHA) has been used traditionally in hydrologic settings to predict runoff of precipitation driven flooding events in watersheds. The U.S. Army Corps of Engineers has a national mission to regulate the waters of the United States, including wetlands, for the benefit of all and includes areas of waterborne transportation and environmental sustainability. Wetland hydrodynamics have recently been added to the GSSHA model in order to more adequately model their impacts on the hydrologic response of a watershed. It is clear that, in addition to hydrologic modifications, wetlands perform a vital role in environmental sustainability and habitat availability. This paper is a result of investigating how GSSHA can model wetlands for current USACE projects.

The paper will first discuss the wetlands hydrodynamics that GSSHA uses and then it will describe a demonstration project on the Rio Grande River. This project site was selected not only because of current wetlands restoration activity but also because it is a significant project dealing with habitat restoration along the river.

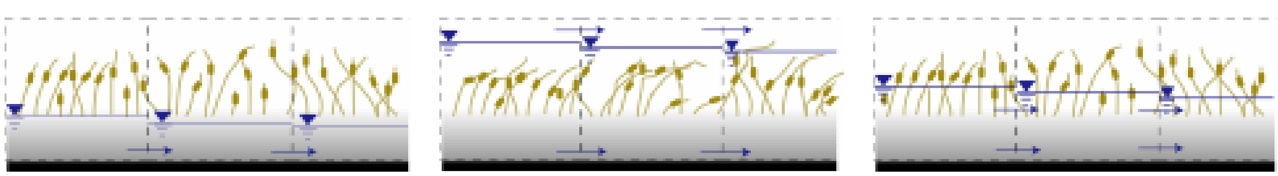
WETLANDS MODEL

Wetlands protection and restoration represents a source of contentious public debate in many communities. A new wetland module has been added to GSSHA that provides the engineer with an ability to model the wetland flow physics in detail. GSSHA currently has the capability to model small lakes and detention basins, and at first glance wetlands may appear to require an approach that would be similar to the lakes and detention basins, but the flow dynamics are actually very different due to the vegetation and peat or muck layer that is commonly present. A wetland in GSSHA is envisioned to act as a system that has properties of both overland flow and seepage approximated by a combination of Manning's formula and Darcy's law. The wetland algorithm implemented is not allowed to modify the channel network as the lakes and detention basins are. The extent of the wetland system is static and not allowed to change in size.

Modified Darcian System: Wetlands are complex systems that have flow properties of both groundwater and surface runoff. The exact mechanism that is dominant at any particular time is most accurately defined as a function of the vegetative height and flow depth. In particular the wetland dynamics are conceptualized by the three different flow scenarios as shown in Figure 1. From a physical point of view, wetlands are conceptualized by a peat or muck layer that is overlain by a vegetative layer. The first scenario considered in Figure 1-a is the flow depth being less than or equal to the user specified wetland retention depth. Conceptually this seepage can be considered a movement of water through the mucky bottom layer referred to as the wetland retention depth. Since this seepage flux persists, no matter the flow depth, it is included as a component of all three flow scenarios. When the flow depth rises and the vegetation is overtopped then the flow system has transitioned to one that is overland flow dominant. When this happens the vegetation is likely to be somewhat bent over (Figure 1-b) providing the basis for Manning's equation application. Figure 1-c illustrates a combination of the first two where the system has characteristics of both overland flow and a Darcy flux through the vegetation.

In total the user is expected to provide the following input parameters for each wetland: the lateral hydraulic conductivity through the wetland retention depth, K_{ret}, retention depth, h_r, average vegetation height, h_v, lateral hydraulic conductivity through the bottom of the vegetation, K_{veg}, and a fully submerged vegetation roughness coefficient, n_{veg}.

The wetland hydrodynamics described refer only to the overland flow hydrodynamics. Both infiltration and groundwater/surface water interaction occurs as described in Downer and Ogden, [in preparation] and are important source/sink terms for the wetland.



(a) (b) (c)

Figure 1. (a) Wetland system where the depth in adjacent computational cells (dotted lines) is less than the wetland retention depth and therefore flux is comprised entirely of a Darcian seepage. (b) Wetland system where the flow depth has overtopped the average vegetation height. Flux is comprised of both the seepage flux and a Manning's equation that conceptually considers bent over vegetation. (c) Wetland system in which the flow depth is greater than the retention depth, but less than the average vegetation height. In this instance the flow is comprised of seepage plus a weighted average of Manning's equation and a Darcy flux through the vegetation.

1. Flow depth is less than retention depth: If two adjacent grid cells are both less than the wetland retention depth the flow rate is calculated using Darcy's law to obtain a seepage flux:

$$q_{x\_darcy\_seepage} = h_{ij} \frac{dh}{dx} K_{ret} \tag{1a}$$

$$q_{y\_darcy\_seepage} = h_{ij} \frac{dh}{dy} K_{ret} \tag{1b}$$

where $q_{x\_darcy\_seepage}$ and $q_{y\_darcy\_seepage}$ (m^2 s^{-1}) are flow rates in either the *x* or *y* directions respectively, h_{ij} is the flow depth in the current grid cell with indices *i and j*, *dh/dx* and *dh/dy* is the head gradient between the two adjacent cells.

2. Flow depth is greater than vegetation height: The other extreme to consider is when the water surface depth has exceeded that of the vegetation height. In this case the flux is considered to be a combination of the Darcy seepage flux and modified form of Manning's equation for flow that conceptually has bent over the vegetation. Of course, the contribution from Manning's equation is expected to be much larger than the seepage component.

$$q_{x\_over\_veg} = q_{x\_darcy\_seepage} + \frac{1}{n_{veg}} h_{ij}^{5/3} S_{f_x}^{1/2} \tag{2a}$$

$$q_{y\_over\_veg} = q_{y\_darcy\_seepage} + \frac{1}{n_{veg}} h_{ij}^{5/3} S_{f_y}^{1/2} \tag{2b}$$

where $q_{x\_over\_veg}$ and $q_{y\_over\_veg}$ are the flow rates computed for overtopped vegetation, S_{f_x} and S_{f_y} is the friction slope in the *x* and *y* directions respectively. Friction slope calculations are described in detail in the GSSHA manual.

3. Flow depth is greater than retention depth but less than vegetation height: If the flow depth is less than the vegetation height but greater than the retention depth we have a situation where the flow has not fully bent over the vegetation. We compute three fluxes in this instance: seepage flux, Darcy flux through the vegetation, and a Manning's equation flux. The Darcy seepage flux is included as before to account for the seepage through the retention depth of the wetland. However we use a linear weighted average, based on the vegetation height, to describe the flow through the vegetation. The higher the depth of water, and thus the closer to overtopping the vegetation, the flow will more closely be described by Eqn 2. The lower the depth of water in a grid cell the flow will more adequately described by a Darcy flux through the vegetation.

$$q_{x\_in\_veg} = h_{ij} \frac{dh_{ij}}{dx} K_{veg} \tag{3a}$$

$$q_{y\_in\_veg} = h_{ij} \frac{dh_{ij}}{dy} K_{veg} \tag{3b}$$

This vegetative Darcy flux should not be confused with the seepage flux that is also contained in the formulation as they utilize different hydraulic conductivities and represent different mechanisms. Combining the seepage flux and a linear weight between the flow through and over the vegetation we arrive at:

$$q_x = q_{x\_darcy\_seepage} + \left(1.0 - \frac{h_{ij}}{h_{veg}}\right) q_{x\_in\_veg} + \left(\frac{h_{ij}}{h_{veg}}\right) q_{x\_over\_veg} \tag{4a}$$

$$q_y = q_{y\_darcy\_seepage} + \left(1.0 - \frac{h_{ij}}{h_{veg}}\right) q_{y\_in\_veg} + \left(\frac{h_{ij}}{h_{veg}}\right) q_{y\_over\_veg} \tag{4b}$$

In summary, the overland flow wetland hydrodynamics are represented as a Darcian flow through a peat layer, and a transitioning Darcian/Manning's flow through the upper vegetation layer. The water in the wetlands is allowed to infiltrate and the groundwater is allowed to exfiltrate into the wetland.

RIO GRANDE MODEL BACKGROUND

Albuquerque is an immerging city in the southwest desert environment. With its growth have come some adverse effects on the local environment. The Rio Grande River runs through Albuquerque below its headwaters in southern Colorado. The river is regulated by several dams but the two dams immediately affecting the flow through the Albuquerque reach are the Cochiti Dam and the Jemez Canyon Dam. Both dams were constructed for flood and sediment control purposes. There are also levees protecting the town from floodwaters. These safety structures have altered the ecology of the area and several rehabilitation programs have been started to restore indigenous plant and fish life to the area in between the levees. This area is known as the Bosque. One-dimensional hydraulic studies have been used to estimate the water surface elevation based on several different flow rates [Boberg, 2005].

GSSHA is two-dimensional finite difference hydrologic model. It has the ability to model 2-D surface runoff, 1-D infiltration, evapotranspiration, 2-D groundwater, 1-D channel hydraulic routing, interception, retention, snow accumulation, sediment transport, soil erosion and contaminant transport. The model was first developed under the name CASC2D by P. Y. Julien at Colorado State University. The model went through several revisions, each adding a new feature or changing the program language. In 1995, the model was revised and changed to accommodate the Watershed Modeling System (WMS) graphical user interface (GUI) developed by Brigham Young University. WMS was funded by the Department of Defense and developed by Environmental Modeling Research Laboraty (EMRL) at BYU. The model underwent further revisions and the name was changed to Gridded Surface Subsurface Hydrologic Analysis in order to better reflect these changes. The main differences between GSSHA and CASC2D are found in the types of processes modeled and the stability of the solution techniques. For example, GSSHA has a 2D groundwater model that allows accurate simulations of non-Hortonian catchments while CASC2D is limited to Hortonian (infiltration excess) catchments. [Downer and Ogden, in preparation]

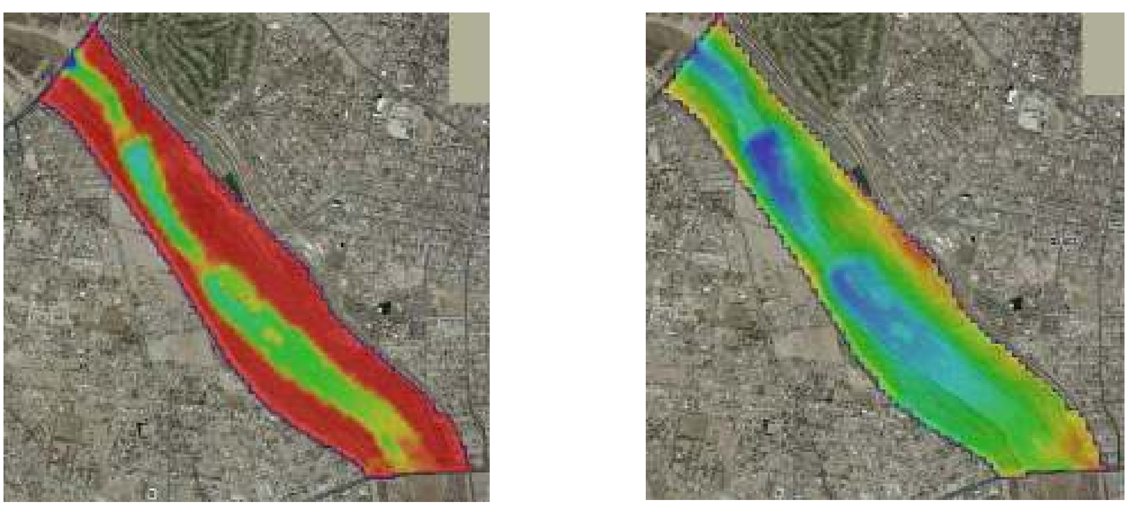
SIMULATION SETUP

The prototype simulation set up for this application utilized the two-dimensional overland flow model with wetland hydrodynamics, Green and Ampt with soil moisture redistribution infiltration model, the two-dimensional groundwater model, and the Deardorff evapotranspiration model. The grid cell size used for the domain was 35 m x 35 m. An interesting feature of this simulation is that it included overland flow boundary conditions rather than relying solely on precipitation as the primary driving function. The overland flow boundary conditions included no-flow, specified slope (at the downstream portion of the river,) and specified head (at the upstream boundary of the river.) Two simulations were run, one simulation of an as-is condition and the other of a wetland placed on the floodplain of the river.

RESULTS

The model results show that GSSHA is able to simulate a transient two-dimensional shallow water riverine environment including full groundwater – surface water interaction and evapotranspiration effects. The simulation is able to reasonably simulate the overbank flooding of a stream. The inclusion of a wetland demonstrated the interaction of a wetland on both the groundwater and the surface water.

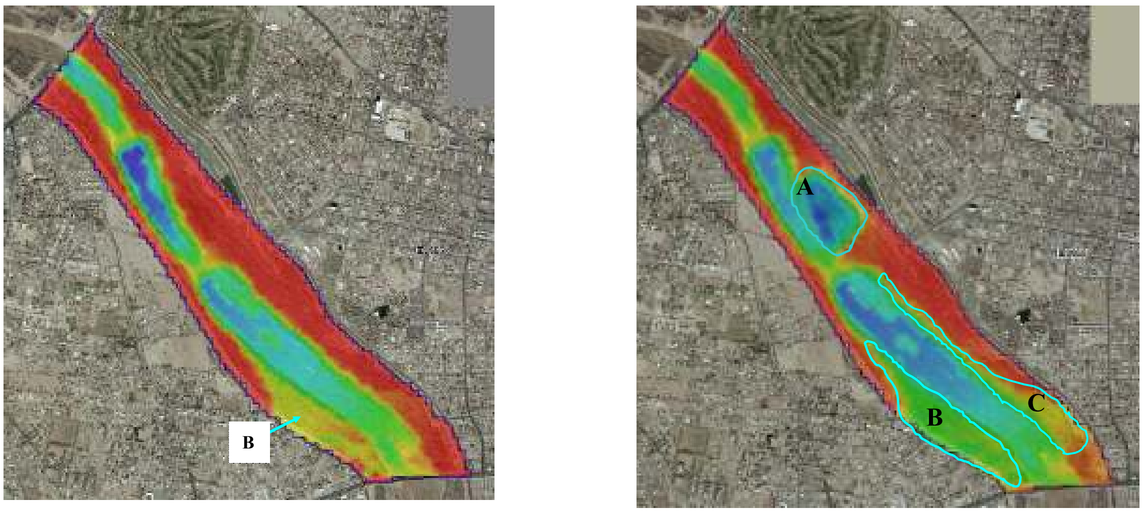
Figure 2 shows a hypothetical flooding scenario on the river that lasted approximately two days. The water started from a low flow condition and the upstream overland head boundary was raised to represent the change in stage due to a flooding event. The peak of the flood depth was



(a) (b)

Figure 2. River depths at low flow (a, 300cfs) and high flow (b, 10,000cfs); Red to Blue = 0 to 2.7m. This is from a simulation run without the wetlands.

set to 2.1 meters and is representative of significant flooding events as computed by a HEC-RAS model provided to the authors by Steve Boberg of the U.S. Army Corps of Engineers. GSSHA was able to simulate the flooding sequence by changing the specified head on the upstream boundary.

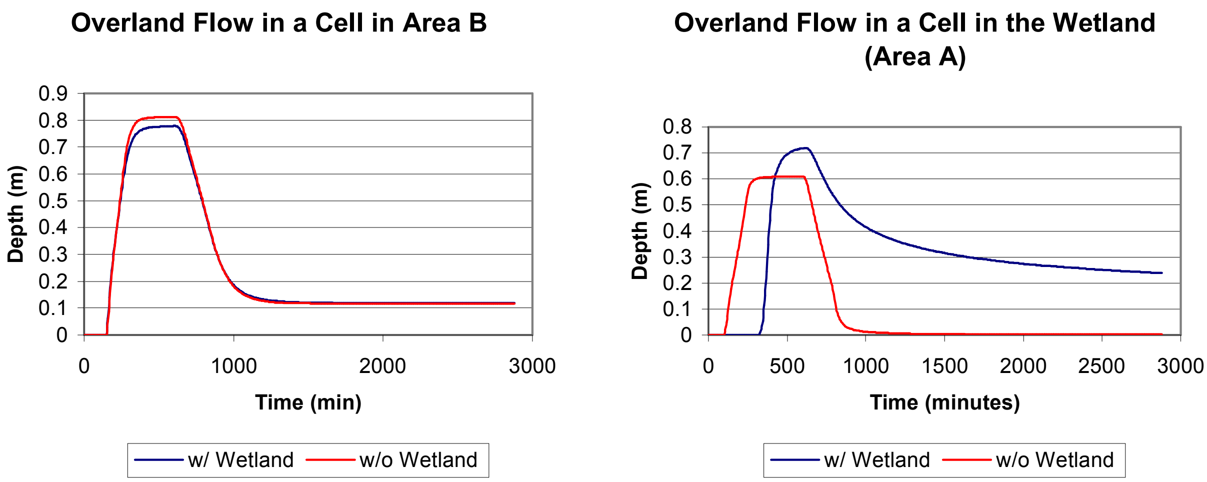


(a) (b)

Figure 3. (a) Surface water depths after the above flooding event. The upstream head boundary has the same head as before the flooding event. Note the extra water produced by exfiltration of the groundwater, especially that marked B. (b) River depths at low flow (1000cfs) after a flooding event. A wetland area is included (area marked A). The wetland area shows a depth comparable with the channel; Red to Blue = 0 to 0.46m. The areas marked B show considerable groundwater discharge to the channel and also should be considered when deciding where to place the wetland.

Figure 3 shows the surface water depths at the end of the flooding event for the two scenarios, with and without the wetland. A comparison of Figures 3a and 2a reveals that groundwater discharge is feeding the stream after the event, which would be expected. This groundwater discharge would be able to help sustain a wetlands habitat. Large areas where groundwater is discharging after a flooding event indicate that the groundwater and the surface water are closely coupled, just as a wetlands environment would need.

Figure 3b shows the results of the same flooding event after the addition of the wetland. Area A is the wetland and shows considerable retention of the flood waters. Areas B and C appear at first glance to have more water in Figure 3b than in Figure 3a. This is actually due, however, to a skewed contour range. The following plots (Figure 4) are of water depth in a cell in both the A and B areas in Figure 3.



(a) (b)

Figure 4. (a) A plot of surface water depth over time in a cell in the B area. Note the decreased peak value due to the effects of the wetland. Also note that the two simulations yield a similar value after a day. (b) A plot of depth of water in a cell in the wetland area. Note the delayed onset of flooding due to the buffering effect of neighboring cells. While the peak value of the wetland is higher, the base elevation (ground surface) is lower (by 1.0 m) than with no wetland scenario. Also note that the cell retains water much longer than the cell without the wetland.

DISCUSSION OF RESULTS

The results of the prototype model demonstrate several key points. The first point is that GSSHA is able to model two-dimensional shallow stream flows in a riverine environment and have fully coupled interaction with the groundwater. Typical stream models include a simplified base flow volume or loss whereas GSSHA uses more detailed equations to simulate the two-dimensional groundwater-surface water interaction for shallow streams such as the Rio Grande. Whether or not a stream is a gaining or losing stream changes both across the stream cross-section as well as with time, so being able to simulate the full groundwater-surface water interaction is key to fully understanding the water budget of the stream.

The second point that the prototype model demonstrated is that GSSHA is able to include the effect of a wetlands model on the stream. These effects included modifying the local flow regime as well as influencing the groundwater levels. The conceptual wetlands model employed in GSSHA is a reasonable approximation to the physical dynamics of a wetlands system but observed data is needed to validate the numerical wetlands model in GSSHA.

The third point is that, because GSSHA can model both the groundwater and the surface water of a shallow stream system, GSSHA can identify areas of the stream where the groundwater is close to the surface which in turn is where engineered wetlands are more likely to be successful. Thus

GSSHA can be a useful tool in determining suitable hydrologic conditions for wetland restoration.

CONCLUSION

The GSSHA model has a new wetland hydrodynamics model that simulates lateral flows through and over peat and vegetation layers. The wetland model is fully interactive with the groundwater model and the overland flow model. A prototype simulation of a portion of the Middle Rio Grande River through Albuquerque was set up. The prototype simulation successfully showed that GSSHA can model two-dimensional shallow stream flow with full groundwater and wetland hydrodynamics. The prototype model also showed areas where the groundwater is close to the surface water. These areas would be considered more suitable for engineered wetlands placement.

ADDITIONAL INFORMATION

The study was conducted as an activity of the Regional Watershed Modeling and Management work unit of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.swwrp.army.mil/ or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@erdc.usace.army.mil.

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