SCS-CN HYDROLOGIC MODELING OF THE GREAT DISMAL SWAMP WITH HEC-HMS

by

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A Thesis
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DEDICATION

This is dedicated to my family and friends whose support got me to this point.

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I would like to thank Fred Wurster of the Great Dismal Swamp National Wildlife Refuge, U.S. Fish and Wildlife Service, for critical data and direction. I also wish to thank the U.S. Geological Survey Climate and Land Use Change Division, Reston, VA, for data and technical support.

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LIST OF ABBREVIATIONS AND/OR SYMBOLS

cubic meter .... m^3
Digital Elevation Model .... DEM
Geographic Information System .... GIS
Hydrologic Engineering Center Hydrologic Modeling System .... HEC-HMS
meter .... m
Modeling Efficiency .... EF
Normalized Objective Function .... NOF
Soil Conservation Service Curve Number .... SCS-CN
square kilometer .... km^2
Watershed Modeling System .... WMS

ABSTRACT

SCS-CN HYDROLOGIC MODELING OF THE GREAT DISMAL SWAMP WITH HEC-HMS

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George Mason University, 2015

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The simulation of surface runoff at the Great Dismal Swamp National Wildlife Refuge, located in southeast Virginia and northeast North Carolina, is modeled on a digital elevation model (DEM) with 2 meter post spacing. An application of the Soil Conservation Service Curve Number (SCS-CN) hydrological model as implemented through the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) is used to predict how the basin might respond to rainfall events, including measures of the quantity of surface runoff, detention, and peak runoff. Validation of the model is conducted by comparing results to streamgage readings at the swamp. Accuracy is greatly limited by an unknown configuration of water control structures at the swamp and programmed outflow through a lock and dam system. But a detailed configuration of streams and watershed units is achieved.

INTRODUCTION

The Great Dismal Swamp National Wildlife Refuge (GDSNWR) is a freshwater wetland encompassing over 500 km^2 in southeast Virginia and over 50 km^2 in North Carolina. The swamp developed over shallow, poorly drained basins. According to Lichtler (1974), in these basins peatland ecosystems developed filling in the basins with woody debris and accelerating the formation of peat over thousands of years. The submerged woody debris further inhibited the surface drainage and contributed to the continued growth of peat layer, which is still increasing in many parts of the swamp (Lichtler, 1974). The GDSNWR hydrology was further changed by the introduction of ditches designed to lower the water table in an unsuccessful attempt to develop agriculture in the swamp. The ditches accelerated the drainage of the swamp after rainfall. Today the ditches remain, but the drainage is managed through water control structures. Several hydrologic and geologic studies of the swamp have been conducted to understand the complexity of swamp hydrology and the relationship of hydrology to other processes. The depth to water table is thought to influence critical components of restoration, including cedar regeneration, cedar growth, and carbon storage. (Hogan, 2015)

This study attempts to develop a rainfall-runoff model of the swamp based on swamp topography. The model will predict, for a particular rainfall event, where the water goes and how much water reaches the outflow stream for the period during and after the rainfall event. The result defines the watershed basins and the height of the water level at the outflow point. This information may provide useful insight for management decisions related to hydrological engineering at the swamp, to restore habitats, and prevent fires.

LITERATURE REVIEW

There are many types of hydrologic models. Loftin (2001) applied a soil moisture accounting model at the Okefenokee Swamp in GA. This was a continuous model that tried to synthesize wet and dry conditions over a long time period. In contrast are event models such as TOPMODEL (Beven, 1979). The TOPMODEL creates a topographic index of catchment wetness based on topography that accounts for variability in the hydrological response of different areas. The USDA Soil Conservation Service Curve Number (SCS-CN) is also an event model that provides runoff as a function of cumulative precipitation, land cover, soil type, and antecedent moisture (USACE-HEC, 2000). The SCS-CN method has wide use for estimating rainfall-generated surface runoff in watersheds (Chu, 2009). Chu (2009) modeled the Mona Lake watershed in west Michigan with SCS-CN achieving good agreement with observed flow.

Spatial and time scales are very important in the understanding of parameters and the modeling method chosen. Hydrologic modeling is typically done by dividing catchments into smaller geographical units, assigning parameters to the individual units and assessing their hydrologic properties; they represent a drainage basin as an interconnected system of hydrologic components and simulate the surface runoff response of the basin to precipitation. Modeling attempts to simplify the physics of each unit so that the runoff can be predicted. The precipitation that falls on the surface is accounted for through soil infiltration, evapotranspiration, and finally surface runoff, depending on the model. The surface runoff then moves into stream channels and out the outflow points.

In order to choose an event model that accounts for variable surface landcover and soil type, the SCS-CN model implemented through the Hydrological Engineering Center Hydrologic Modeling System (HEC-HMS) was selected for this study. The latest version of HEC-HMS (USACE-HEC, 2006) is used along with ArcHydro tools (ESRI, 2011). These tools provide a comprehensive modeling environment facilitating the processing of various geographic information system (GIS) data, and simplify many tasks including basin delineation and computation of hydrologic parameters. It is important to note that the model does not consider several important processes including surface/groundwater interactions other than infiltration; no considerations are made for groundwater upwelling despite the possibility of its existence mentioned in Lichtler (1974). Also not accounted for is surface water that may infiltrate the peat surface and then move laterally towards the ditches, reappearing as surface water. The model also does not analyze sediment transfer or account for any process resulting in change to the soil surface.

DATA

The DEM used in this study was created from a lidar survey collected by Woolpert and Associates in March 2010 and August 2012. The DEM covers the extent of the refuge including the adjacent state park in North Carolina. The ground class lidar returns were used to create a terrain model under the vegetation canopy at 2 meter post spacing. After the 2010 collection, two large fires burned from August to November 2011, and over 6,500 acres of burn scar changed the topography of the swamp necessitating an updated DEM. A new collection in August 2012 collected just the burn scar area, and this DEM was merged with the 2010 DEM to create the most current surface. The lidar shows that the swamp surface begins at the base of a steep-sloped escarpment along the western edge, then slopes gently eastward with a very small slope. Existing USDA Watershed Boundary units describe the Great Dismal Swamp as split into two watersheds, with northern regions draining towards the north into the James River and the southern regions draining toward the south. (USDA, 2015) Flow monitoring of ditches done by GDSNWR staff generally corroborate this delineation.

The DEM required hydrological conditioning in order to be used for modeling. Large areas of open water like Lake Drummond were represented with null values. For hydrologic modeling the DEM must be continuous, therefore the lakebed needed to be incorporated as a surface into the DEM. The null values in were manually changed to 3.2 meters, an elevation consistent with an average lake elevation from Lichtler (1974) and with survey information provided by Fred Wurster of the GDSNWR staff. One additional gap (less than 100 m^2) found in the data was interpolated to create a continuous surface.

The ditch beds also did not appear in the raw DEM. Standing water in the ditches would result in no lidar returns to the laser sensor, and such gaps found during the DEM creation might be left as null (as in the case of Lake Drummond.) But in some cases the null values were interpolated; the ditches are an example. The result was that the true depth of the ditches are not represented in the data. Since the locations of the ditches are known, they were manually "burned" into the DEM using the AGREE method as implemented in the ArcHydro tools (Hellweger, 1997). The ditch polylines were provided by the GDSNWR staff. The ditches were burned to depth of 2 meters below surface and a sloped buffer of 10 meters. See Figure 1. Burning ditches also negated any effects of culverts and bridges appearing in the DEM. Once burned into the hydroDEM, these features would be eliminated as potential dam structures.

The landcover data was provided by GDSNWR staff with high spatial resolution. These data are current as of 2015. The landcover was resampled into four basic classes per the model requirements: open water, agriculture, forest, and urban. For the study area, 92% was classified as forest, 3 % agriculture, 4% open water, and less than 1% were classified as urban cover. The soil data were collected from U.S. Department of Agriculture Gridded Soil Survey Geographic Database (SSURGO 2014). The hydrologic soil group attribute was extracted for this application and applied to the model. Precipitation data were obtained from a precipitation gauge in the swamp, with data served through the NOAA Hydro meteorological Automated Data System.

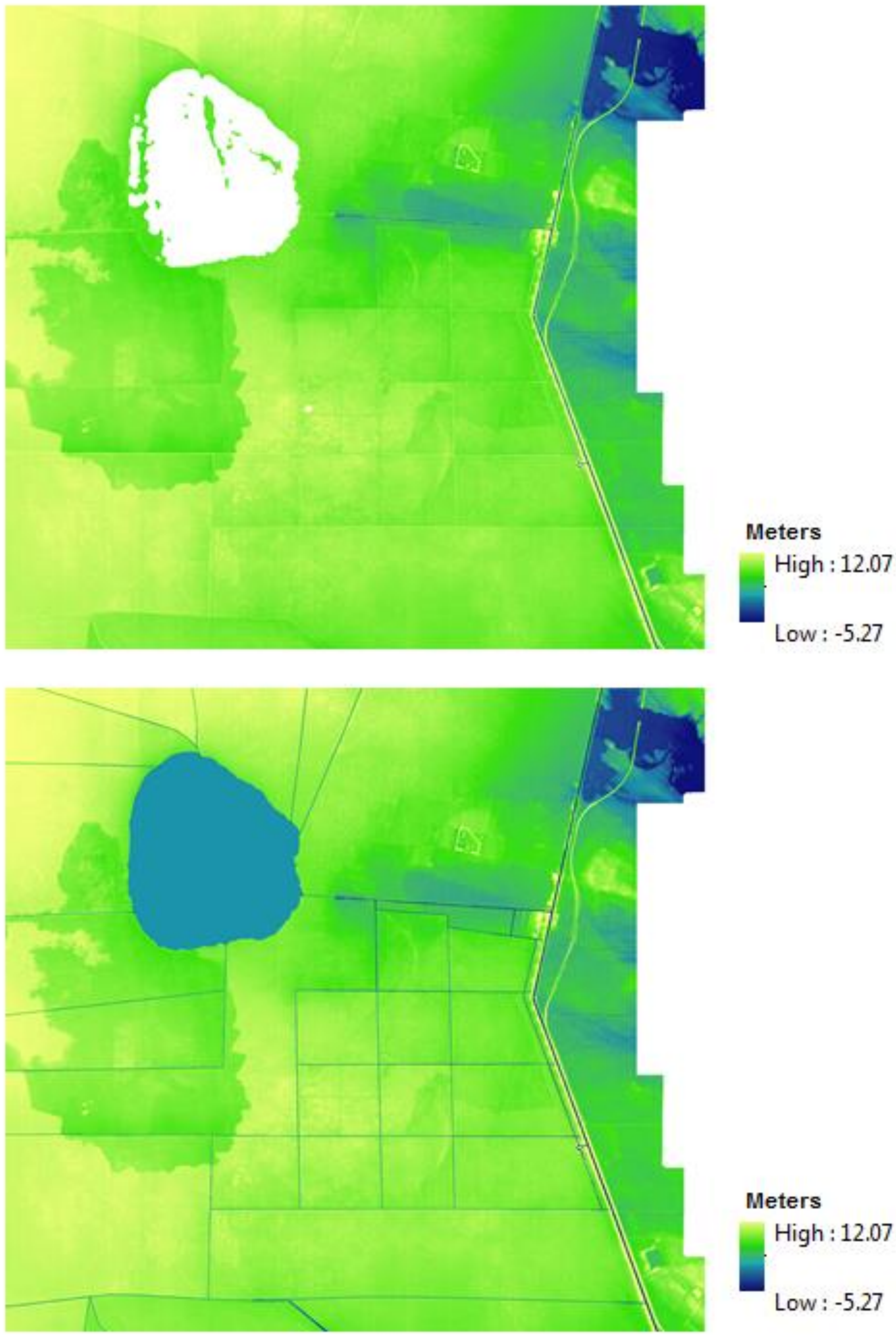

Figure 1 Subset of raw DEM without hydrologic conditioning (top) and hydroDEM after conditioning (bottom)

METHODS AND MODEL DEVELOPMENT

The basis of the hydrologic model is an analysis of the topography. The process used here was the Fast Watershed Delineation method; this process can be generalized with the following steps (Djokic, 1997): 1. fill sinks 2. determine flow direction 3. determine flow accumulation 4. identify streams 5. segmentation of streams 6. define watersheds 7. vectorize watersheds and stream segments. During flow direction and flow accumulation processing, each cell can drain to just one of the eight neighboring cells with the steepest slope. In this way, one cell will accumulate the down-flow from all upstream cells. Cells that have accumulated flow above a certain threshold (in this case, 1% of the maximum accumulation for the grid) are then identified as streams. The dendritic stream network is linked and classified to create a catchment where subbasins and outflow points are identified.

After processing the hydroDEM, the data was found to consist of 11 separate watersheds, each with their own outlet point at the edge of the DEM. 74% of the area, however, drains to a single outlet. This single watershed was chosen as the primary study area for this research; the others were not included in the analysis. The catchment extends up to the edge of the hydroDEM, and because of possible inflows described in Lichtler (1974) it’s likely that this catchment receives inflow from an area upstream to the west for many miles. But because of lack of availability of data, this inflow is not included in the model. It is believed that the swamp is wetted primarily from precipitation, up to 50in per year (Lichtler, 1974) and the contribution from upstream may be minimal. This will be discussed further in the error analysis.

Figure 2 shows the watershed schematic of the derived subbasins in the study area. The flow direction among watershed components is modeled by links between the subbasin centroids. The swamp has very little relief and sits close to sea level, with all elevation falling within a range of 1m to 7m up to the base of the escarpment on the western edge. There some lack of agreement with existing USDA hydrological units and observed flow by the GDSNWR staff. Based on the DEM, many of the basins in the northwest will flow south, then join with the Swamp Canal to flow back to the north. Also much of the area to the south of Lake Drummond also flows to the north. This contradicts in-situ observations that indicate the ditches south of Drummond generally flowing south.

The Swamp Canal is the waterway which makes the east edge of the swamp and bifurcates the two watersheds covered by the lidar, creating a bridge between the two. The Swamp Canal flows north in the study area, but for the remaining catchments found on the original DEM it flows south. (Actually the Swamp Canal is controlled at both ends by canal locks which maintain a water level above sea level.)

The SCS-CN model estimates excess precipitation available for surface runoff through a function of soil type, land cover, antecedent moisture, and maximum retention (USACE-HEC, 2000). The equation for the excess precipitation is given as:

Equation 1 SCS-CN Model Equation

$$R = \frac{(P - I_a)^2}{P - I_a + S}$$

where R is the accumulated precipitation excess for the time interval; P is the accumulated precipitation, I_a is the initial loss; and S is the potential maximum retention. The relationship between I_a and S is provided in the literature as $I_a = 0.2\,S$. The cumulative excess runoff can then be restated as:

Equation 2 Cumulative excess runoff

$$R = \frac{(P - 0.2\,S)^2}{P + 0.8\,S}$$

S is related to the curve number parameter through the following relationship:

Equation 3 Curve number

$$S = \frac{25400 - 254\,CN}{CN}$$

The Curve Number ranges from 30 for highly permeable soils to 100 for open water (USACE-HEC, 2000). The curve number is a dimensionless value based off two physical parameters: land cover and soil type. For the study area, the curve number was computed from the soil and landcover parameters previously described. Figure 3 shows the curve number result for the study area.

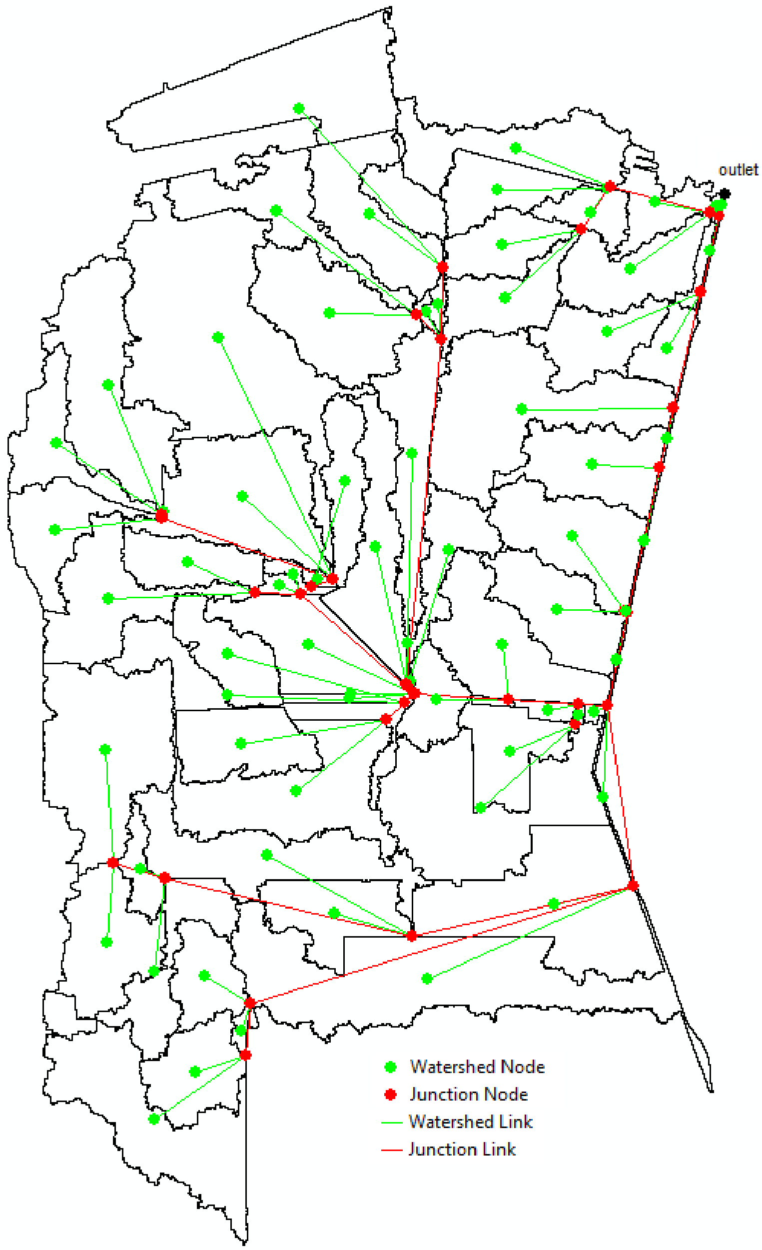

Figure 2 GDSNWR Watershed schematic

Muskingum routing method was chosen as the channel routing model and the parameters were determined for K (travel time) and X(weighting coefficient) in the HEC-HMS software. The model was run with hourly intervals from 15 April 2015 to 30 April

2015. Precipitation data collected at a rain gauge in the swamp were applied uniformly to all basins in the model.

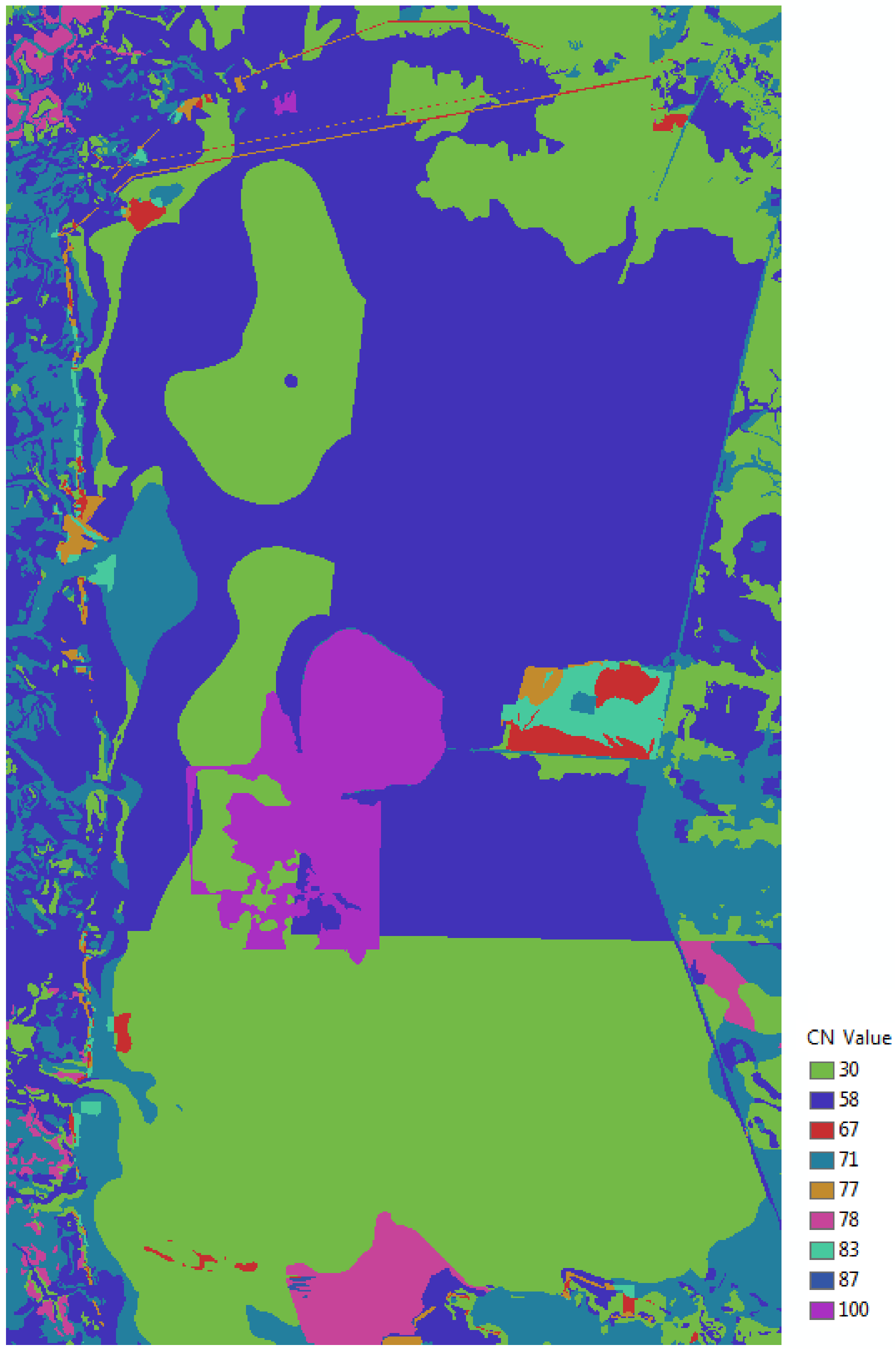

Figure 3 Curve number result

RESULTS ANALYSIS

Hydrographs were modeled in three locations: the catchment outlet, and two junction points. The resulting hydrographs are seen in Figure 4. These graphs show the total outflow as well as the component of outflow form the basins directly upstream from that element. On April 20, peak outflow from the J300 junction and the J254 junctions combined raise the gauge over 20cm at the outlet point with a lag time of approximately 6 hours.

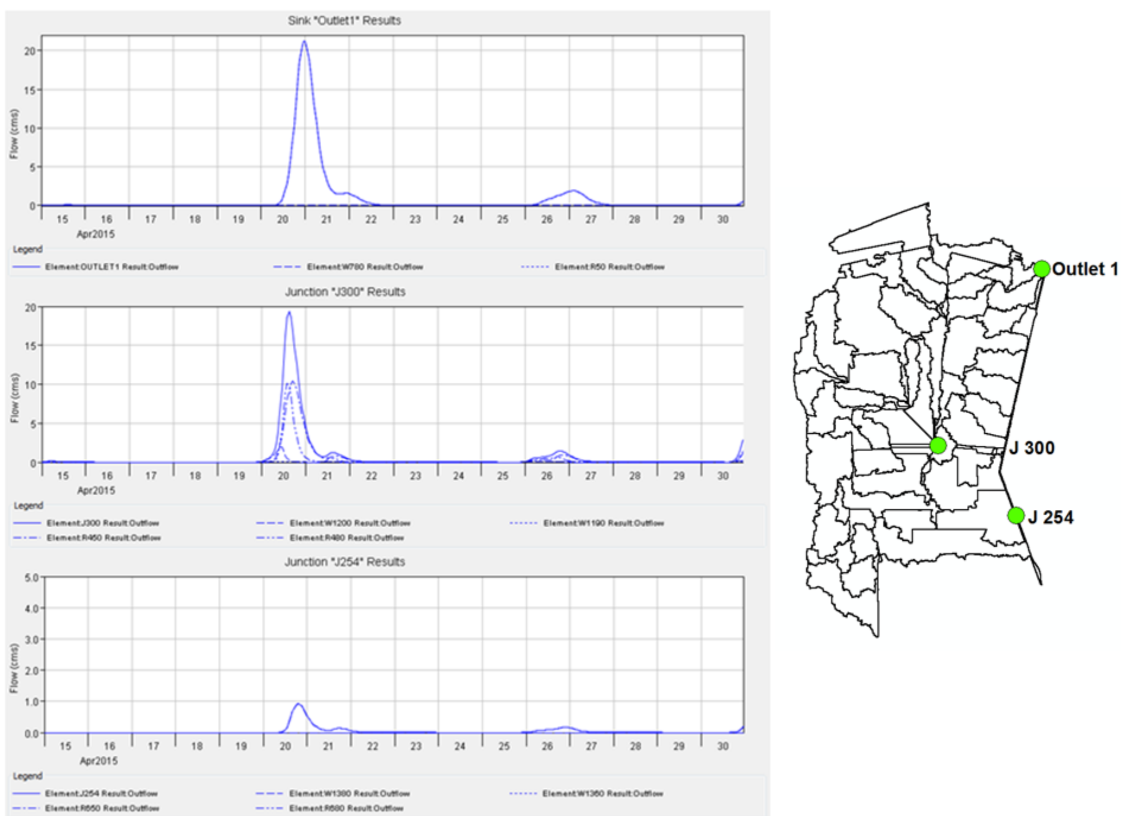

Figure 4 Model output hydrographs

Measured streamgage data was available at the J300 junction. This data is graphed in Figure 5. Daily variability of the gage height is believed to be due to scheduled outflow on a daily basis the lock and dam on the Dismal Swamp Canal. While the precipitation event on April 20 appears to have a measurable effect on the streamgage, the peak is less than ten percent of the magnitude of the modeled hydrograph. Any attempt to use the measured hydrograph to validate the model would not produce useful result since the amount of outflow through the locks is unknown.

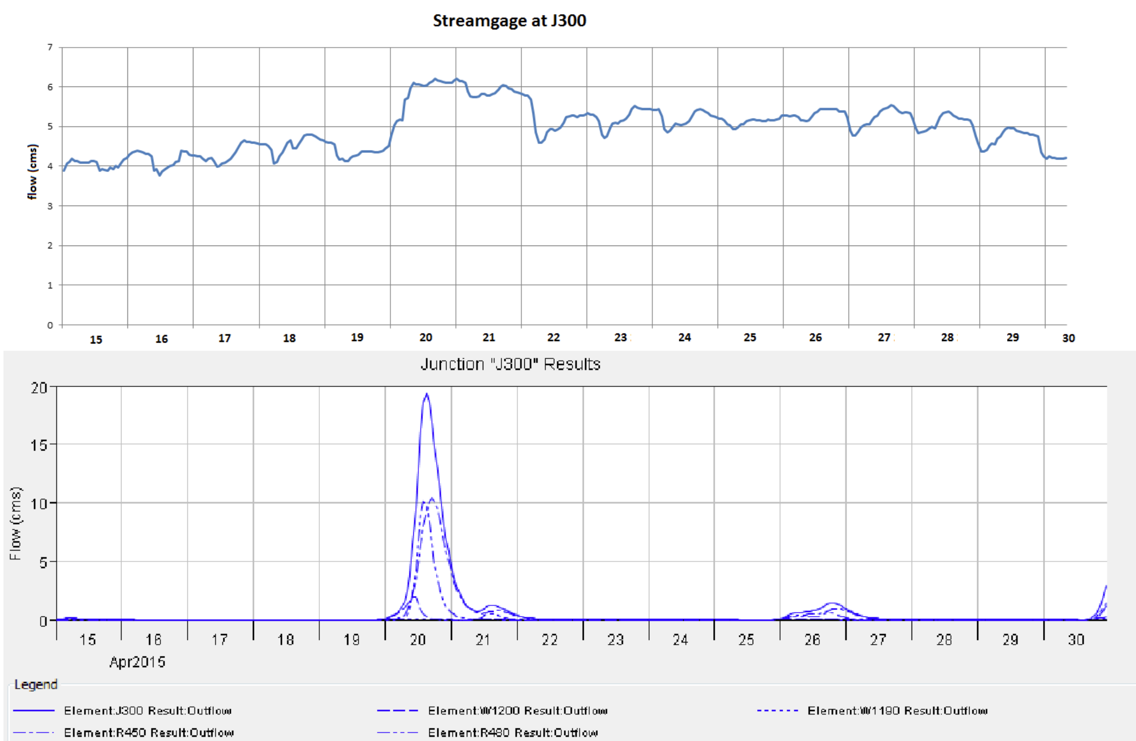

Figure 5 Streamgage hydrograph and model hydrograph comparison at J300

Other problems that inhibit the validation of the model with in-situ data include complex surface and groundwater interactions. No considerations are made in the model for groundwater upwelling despite the possibility of its existence as noted by Lichtler (1974). There may be other mechanisms in the generation of surface runoff. Lateral movement of water through the peat surface may reappear as surface water in the ditches. Evapotranspiration is not directly accounted for in the model. Also antecedent moisture conditions are not used as initial conditions for the model – since runoff occurs when precipitation falls onto saturated surfaces, current moisture conditions are necessary to initialize the model.

SUMMARY AND CONCLUSIONS

This study was able to produce fine-resolution watershed delineation for use in modeling runoff in the Great Dismal Swamp National Wildlife Refuge. The delineation can be applied to other runoff models and increases understanding about flow direction and the relationships between hydrological units within the swamp. However the runoff model produced outputs that could not be directly validated with in-situ data. A large number of system complexities contributed to the lack of validation including unknown inflows and managed unknown outflows through lock and dam system, complex surface/groundwater interaction, and lack of initialization with antecedent conditions. The watershed should be expanded to include all upstream contribution areas, although high resolution data for these areas are not currently available; whether inflows contribute more water to the swamp than precipitation needs to be determined. The response of the peat to precipitation should also be studied to account for any spatial variation due to the effects of dried peat on the swamp hydrology. Another runoff model may be more suitable for the complex hydrology of the swamp and should be tested.

REFERENCES

Beven, K.J., & Kirkby, M. (1979). A physically-based variable contributing area model of basing hydrology. *Hydrol. Sci, J.*, 24(1), pp. 43-69.

Chu, X., & Steinman, A. (2009). Event And Continuous Hydrologic Modeling With HEC-HMS. *Journal Of Irrigation & Drainage Engineering* 135(1): pp. 119-124.

Djokic, D., & Ye, Z. (1997). Efficient Watershed Delineation Using ArcView and Spatial Analyst, *Proc. 17th Annual Esri User Conference,* San Diego, CA.

Environmental Systems Research Institute (ESRI). (2011). Arc Hydro Geoprocessing Tools. *ESRI,* Redlands, CA.

Hellweger, F. (2015). AGREE DEM Surface Reconditioning System. Retrieved from <http:// www.ce.utexas.edu/prof/maidment/GISHydro/ferdi/research/agree/agree.html>.

Hogan, D. (2015, April 21). The Great Dismal Swamp Project. Lecture conducted from USGS.

Lichtler, W., & Walker, P. (1974). Hydrology of the Dismal Swamp, Virginia-North Carolina. *U.S. Geological Survey, Open File Report 74-39.* Richmond, Virginia. 57p.

Loftin, C. (2001). Development and Application of a Spatial Hydrology Model of Okefenokee Swamp, Georgia. *Journal of the American Water Resources Association*, 37(4), pp. 935-956

Survey Staff. The Gridded Soil Survey Geographic (SSURGO) Database for Virginia. United States Department of Agriculture, Natural Resources Conservation Service. Available online at http://datagateway.nrcs.usda.gov/. January 15, 2014 (FY2014 official release).

United States Army Corps of Engineers, Hydrologic Engineering Center (USACE-HEC). (2006). *Hydrologic modeling system HEC-HMS user's manual*, Davis, Calif.

United States Army Corps of Engineers, Hydrologic Engineering Center (USACE-HEC). (2000). *HEC-HMS hydrologic modeling system. Technical reference manual*, Davis, Calif.

United States Department of Agriculture. (2015). Hydrologic Units and the Watershed Boundary Dataset. Web. <http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/watersheds>. Accessed July 20, 2015

BIOGRAPHY

Timothy R. Larson received his Bachelor of Arts from Bethel University in 2004. He has been employed in industry as a GIS specialist and in government as a research associate in physical science for the USGS. He is studying for a Master of Science in Geoinformatics and Geospatial Intelligence from George Mason University to be completed in 2015.