Hurricane Matthew in North Carolina

Precipitation and Flood Analysis along the Neuse River

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Abstract

Many inland cities of North Carolina located along major rivers have historically been particularly vulnerable to flood events due to their low elevation and poor infrastructure. Record amounts of rainfall from Hurricane Matthew in October of this year caused one of the worst natural disasters in the history of the state. In order to better model storm effects in the future, it is important to find simple and effective methods to predict where soil saturation from single rainfall events can cause excessive runoff into stream systems and in turn, potential dam breach and flood inundation. In this project, the amount of potential runoff rainfall and groundwater buildup are calculated using SSURGO and NWS precipitation data then compared to alternative methods previously demonstrated during class exercises. It is also compared with streamflow data from the National Water Model and USGS stream gages to assess viability.

1. Background

1.1 Hurricane Matthew

In October of 2016, Hurricane Matthew became the first Atlantic Category 5 hurricane since 2007. Matthew swept through the Caribbean Islands with catastrophic force wreaking much destruction, especially in Haiti, where final death tolls from Matthew numbered into the thousands. The storm system landed along the North American coast in northern Florida before traveling upwards along the coast to Georgia and the Carolinas

Although massive evacuation efforts by state governments prevented much loss of life in these states, 49 deaths were attributed to Matthew in the US. Surprisingly, although Matthew had been downgraded to a tropical storm before it reached the North Carolina coast, 28 of these deaths occurred in the state North Carolina,[1] along with \$1.5 billion of damages.[2] Much of this occurred days after Matthew veered west and dissipated in the Atlantic Ocean in the inland communities of North Carolina, approximately 100 miles from the coast. Dangerously high levels of precipitation and heavy flooding along the Tar, Neuse, and Lumber Rivers were blamed.

These inland communities number among the most impoverished towns in the state. Many of them experienced 100-year flood events, surpassing the destruction caused by Hurricane Floyd in 1999, a hurricane which dumped similar amounts of rainfall in Mideast North Carolina. The severity of flooding was blamed on a flooded water table and oversaturation of soil, which caused massive amounts of runoff to drain into the streamflow network.[3]

1.2 Area of Analysis

The Neuse River was chosen for analysis due to its well-studied nature. A large amount of information about the area surrounding the river is readily available, and it is well monitored by the USGS and the NWS. The Upper Neuse River HUC 8 watershed drains almost directly at the location of the town of Goldsboro, where flooding in October was extremely destructive. Figure 1 illustrates the extent of the flooding caused by Matthew in Goldsboro. The “Research Triangle” of Raleigh, Durham, and Chapel Hill is located at the height of the basin, placing towns at the base of the basin downstream from one of the most developed areas in the state. Due to the impervious nature of surfaces in urban land cover, runoff coefficients and in turn runoff volume ratios are highest in these areas. Outside of the Research Triangle, the majority of land cover in the basin is forest and agricultural land, seen in Figure 2.

Figure 1. Aerial views of Goldsboro, NC before and after Hurricane Matthew flooding.

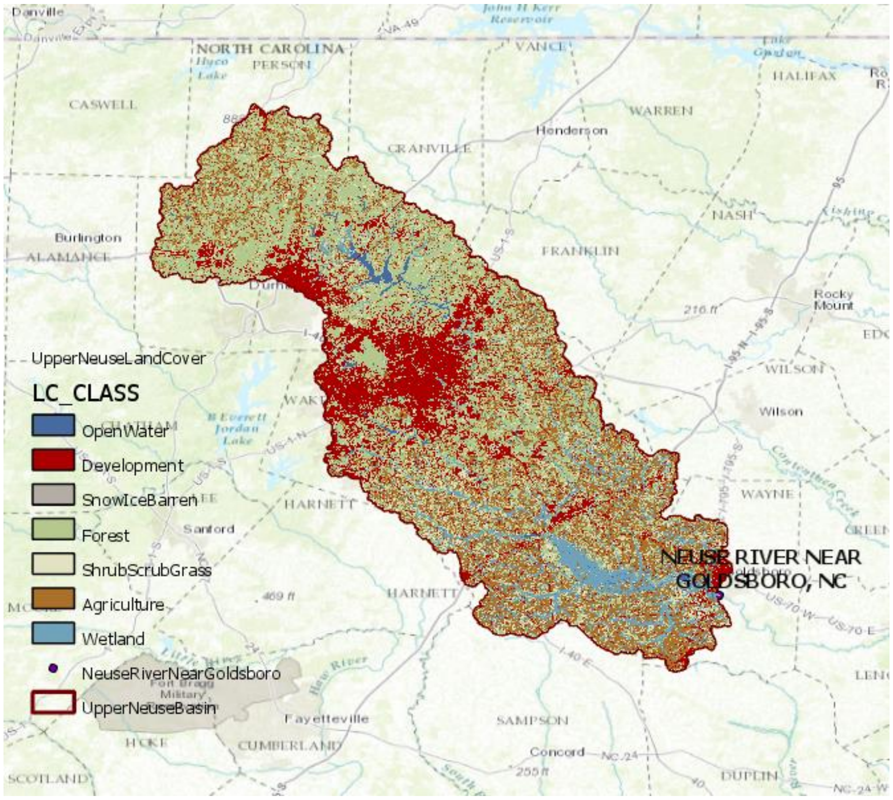

Figure 2. Land cover for the Upper Neuse Basin. The location of the Neuse River near Goldsboro gage is also shown

The Upper Neuse Basin also drains to USGS Gage 02089000, Neuse River near Goldsboro, NC. This gage peaked at a record height of 29.74 ft at 9:15 am EDT on October 12, 2016, just below its operating limit of 31 feet, another reason this basin was chosen for study.

2. Objective

The objective of this project is to assess the usage of NOAA's daily precipitation data in conjunction with SSURGO's soil available water storage data to create a map of where rainfall runoff will originate within the river basin. Primarily, the study will compare the effectiveness of this method to Thiessen polygons and spline interpolation of precipitation station data from Hurricane Matthew in the Upper Neuse Basin. Modeling of the sources of runoff due to specific precipitation event can help pinpoint and prevent sudden stream surges during future occurences.

3. Methodology

3.1 Data Sources

DATASET	SOURCE	TYPE	DESCRIPTION
WBD	USGS	VECTOR	The Watershed Boundary Dataset is a digital vector dataset from the United State Geologic Survey (USGS) that defines the drainage of surface water to a point. It divides water resources in the US into Hydrologic Unit Code (HUC) framework. 2-12 digits are used to define HUCs.
NHDVPLUS3	USGS	VECTOR	The National Hydrography Dataset is a digital vector dataset of surface water in the US. Hydrographic features such as rivers, streams, canals, lakes, coastline, dams, and stream gages, as well as flow velocities and length are represented in this dataset.
NLCD	MLRC	RASTER	The National Land Cover Database of 2011 from the Multi-Resolution Land Characteristics Consortium (MLRC) provides the most recent survey of land use in the US. 16 land cover classification is mapped in the Albers Conic Equal Area Projection at a spatial resolution of 30 m.
NED	USGS	RASTER	The National Elevation Dataset provides the best available seamless raster elevation data for the US. Elevation is given in meters at a resolution of 1 arc-second (with higher resolution in some areas) and referenced in the North American Datum of 1983 geographic system.
NHC TRACK	NOAA	POINT, LINE	The National Hurricane Center (NHC) Track Forecast Cone provides twice-daily forecasts for past and current tropical storms and hurricanes approaching the US. Forecasts can be predicted for up to 5 days from present. Historical storm track data can also be downloaded in form of point, line, and polygon shapefiles that represent the location of the center of the storm, path of storm, and cone of the weather system, respectively.
DAILY PRECIPITATION	NOAA	POINT	Daily precipitation data from the National Weather Service (NWS) River Forecast Centers (RFCs) gives a precipitation estimate for the entire US. Data is obtained from both radar imagery and real time precipitation gage readings for the best quality daily precipitation data available in inches. The data is projected as point shapefiles in the Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system. Historical data is available by day at the Advanced Hydrologic Prediction Service website.
SSURGO	NRCS	RASTER	The Soil Survey Geographic Database contains a large array of information about US soil. Collected by the National Cooperative Soil Survey and the Natural Resources Conservation Service (NRCS), SSURGO classifies soil in an incredible number of categories at different resolutions. The dataset that was primarily used in this project is the Available Water Storage (AWS) dataset, which gives the amount of water storage available to a depth of 150 cm at a spatial resolution of 30 m.
PRECIPITATION STATION	USGS	POINT	Precipitation data from the USGS South Atlantic Water Science Center (NC office) provided daily rain gage totals from all precipitation stations in the state of North Carolina. Gage data is collected hourly and can be viewed at real-time at the NC USGS website. Historical data can be downloaded in both graph and table form at an hourly breakdown from NWISWeb.
NWM	NOAA	HYDROSHARE OUTPUT	The National Water Model from the NWS via a partnership with the National Water Center simulates observed and forecasted streamflow in the US using a multi-sensor system. Forecasts for streamflow can be viewed for up to 30 days from present using the NWM Image Viewer and the Hydroshare NWM application. Analysis for historical streamflow is also available. Although NWM does assimilate data from the WRF-Hydro IOC system, historical land surface model outputs and precipitation data for single events are not available for download.

3.2 Data Processing

Watershed, subwatershed, and catchment data for the Upper Neuse Basin HUC 03020301 were downloaded from USGS, as well as flowlines and NHD data for the Upper Neuse River and surrounding streams. Hurricane Matthew's path was also downloaded from the National Hurricane Center. Figure 3 shows the path of the storm never breached the shore of North Carolina. Rather, it was the residual precipitation from the system in the days following its route along the NC shore that caused the massive amounts of flooding in the state.

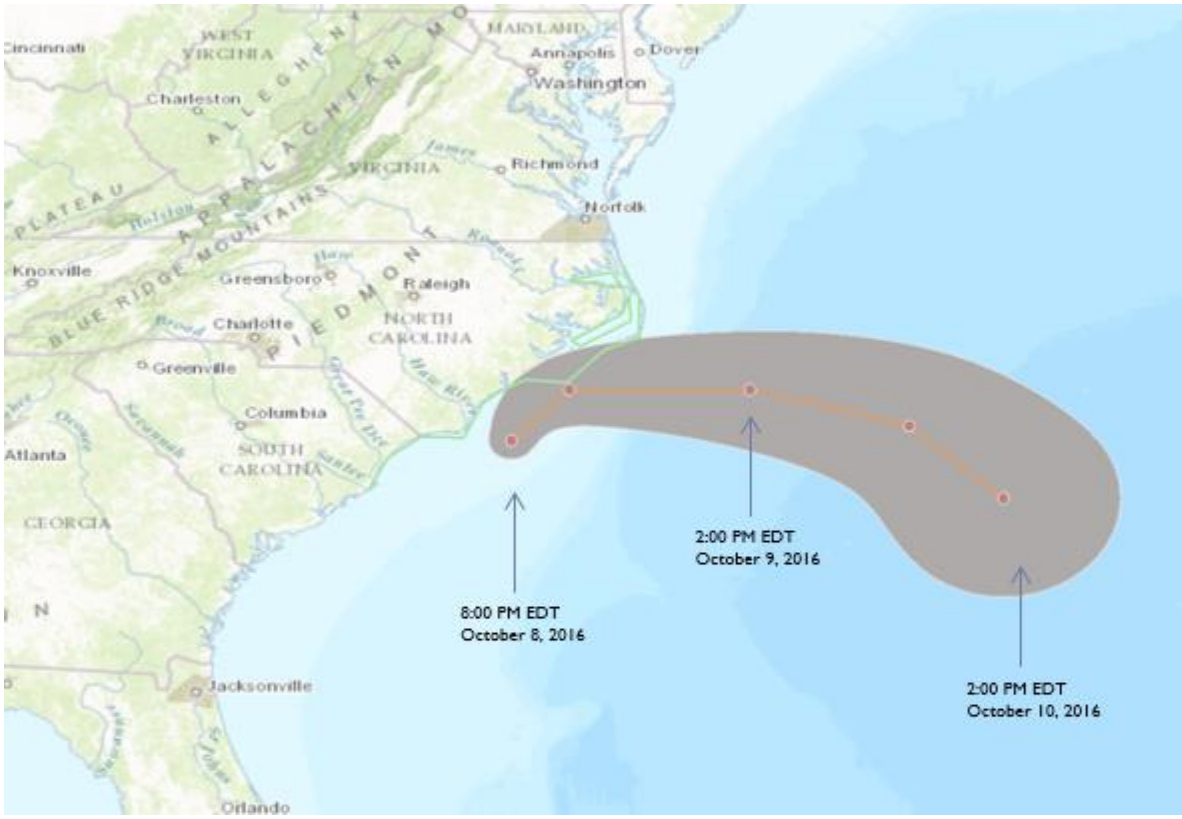

Figure 3..Path of Hurricane Matthew along North Carolina coast.

Available Water Storage data for up to 150 cm in data was downloaded from SSURGO using the ESRI online server and then extracted for the study area. Figure 4 demonstrates the completeness of the dataset in the Upper Neuse Basin.

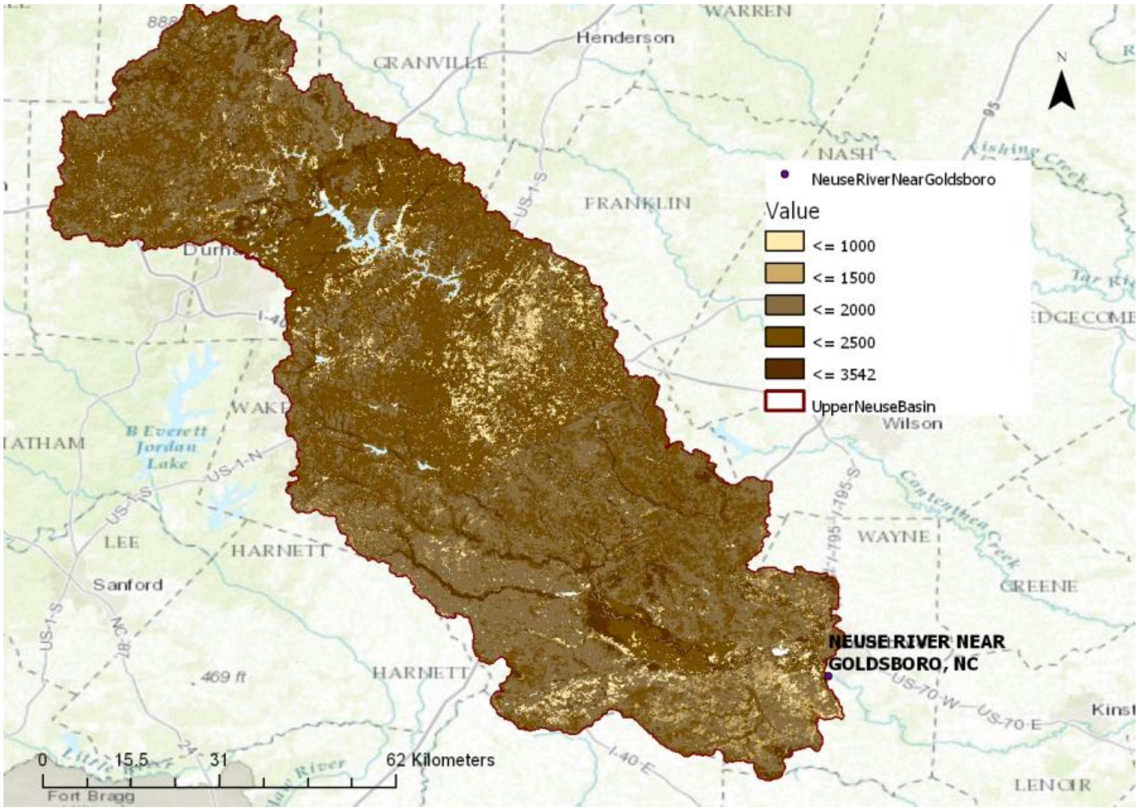

Figure 4. AWS soil data for the Upper Neuse Basin. Numbers are show as 100x the available water storage depth in cm.

Daily precipitation data was downloaded as individual precipitation point shapefiles from the the National Weather Service for the dates of October 5 through October 11, when rainfall from Matthew in North Carolina occurred. All attribute tables were joined in order to produce cumulative daily precipitation data. Because some individual points were not represented in each daily precipitation shapefile, when joined, these double numberical values were stored as <null>. If then statements were used to convert these values to 0, and columns of daily values were added to produce cumulative precipitation 2-6 days (ending October 11). The shapefiles produced for cumulative rainfall was then converted into a raster file. To shorten processing, these rasters were then clipped to the state of North Carolina and then projected onto the map. Figure 6 shows the 6 day cumulative precipitation map in comparison to a estimated rainfall value map. While spatial resolution of the model is not as high, it does match up almost exactly with reported values.

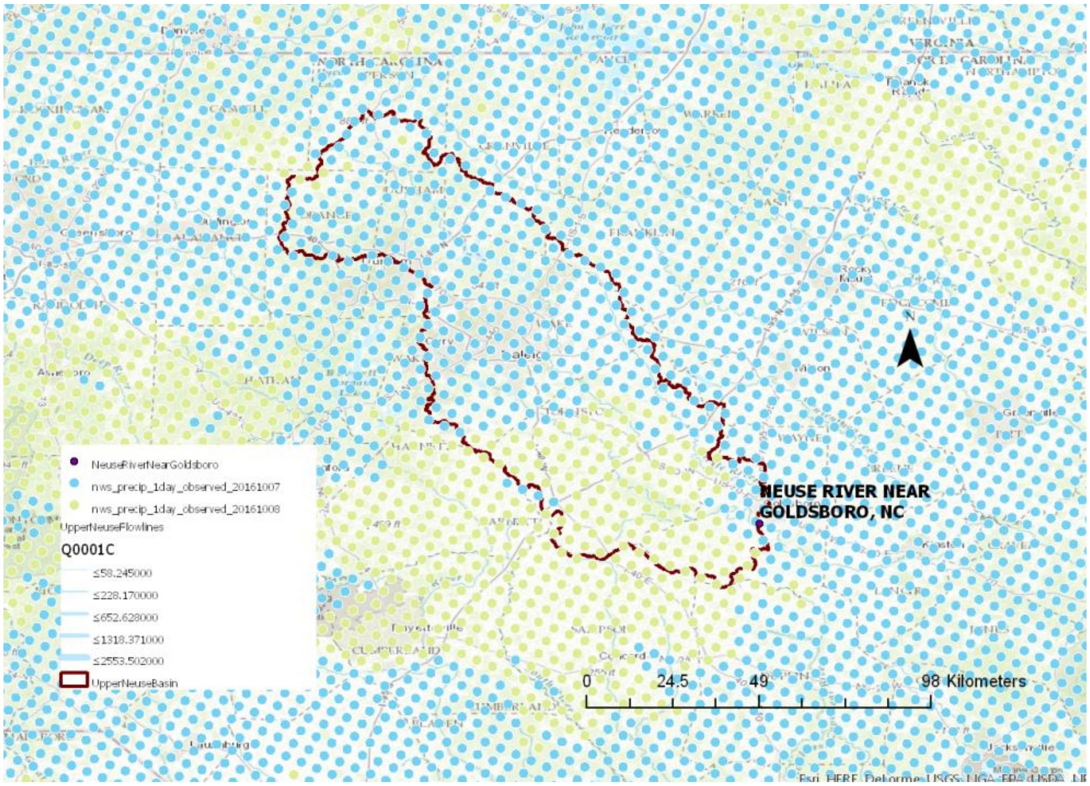

Figure 5. Sample point dataset for daily precipitation downloaded from the NWS.

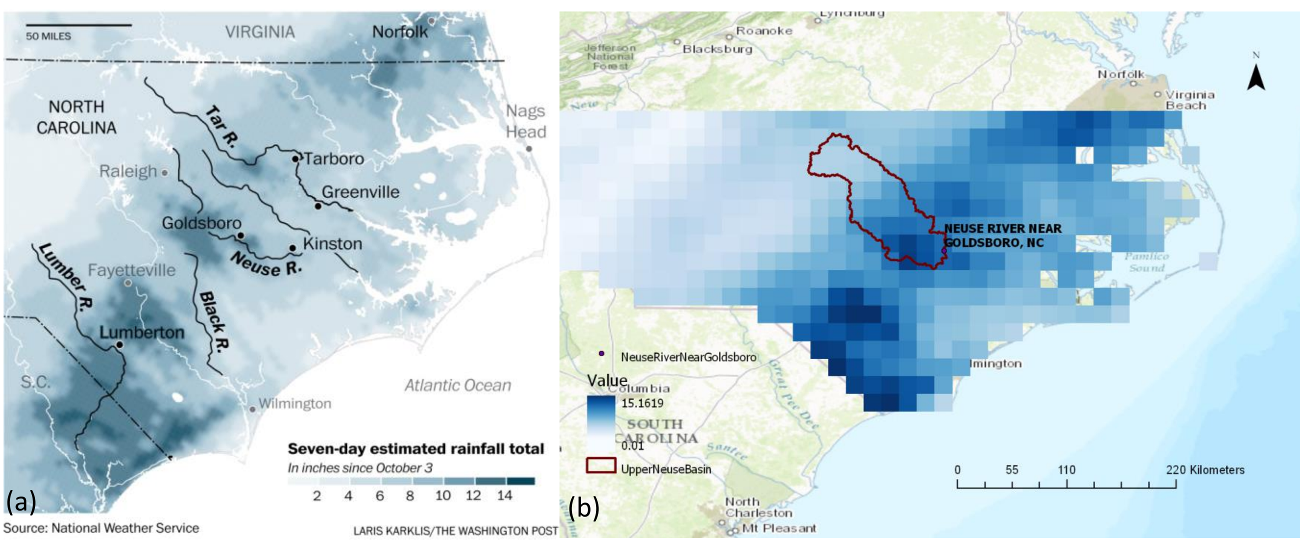

Figure 6. (a) 7-day estimation of rainfall from the NWS as of October 9 as published by the Washington Post. (b) 7-day raster projection of cumulative rainfall from October 5 through October 11 clipped to the state of North Carolina.

Then, the difference between the cumulative precipitation and the AWS was taken to get a prediction of where runoff would originate. In order to subtract the AWS value from the projected map, unit conversions were made and differences in cell size were corrected. In order to automate this tedious process, a simple tool was made using ModelBuilder.

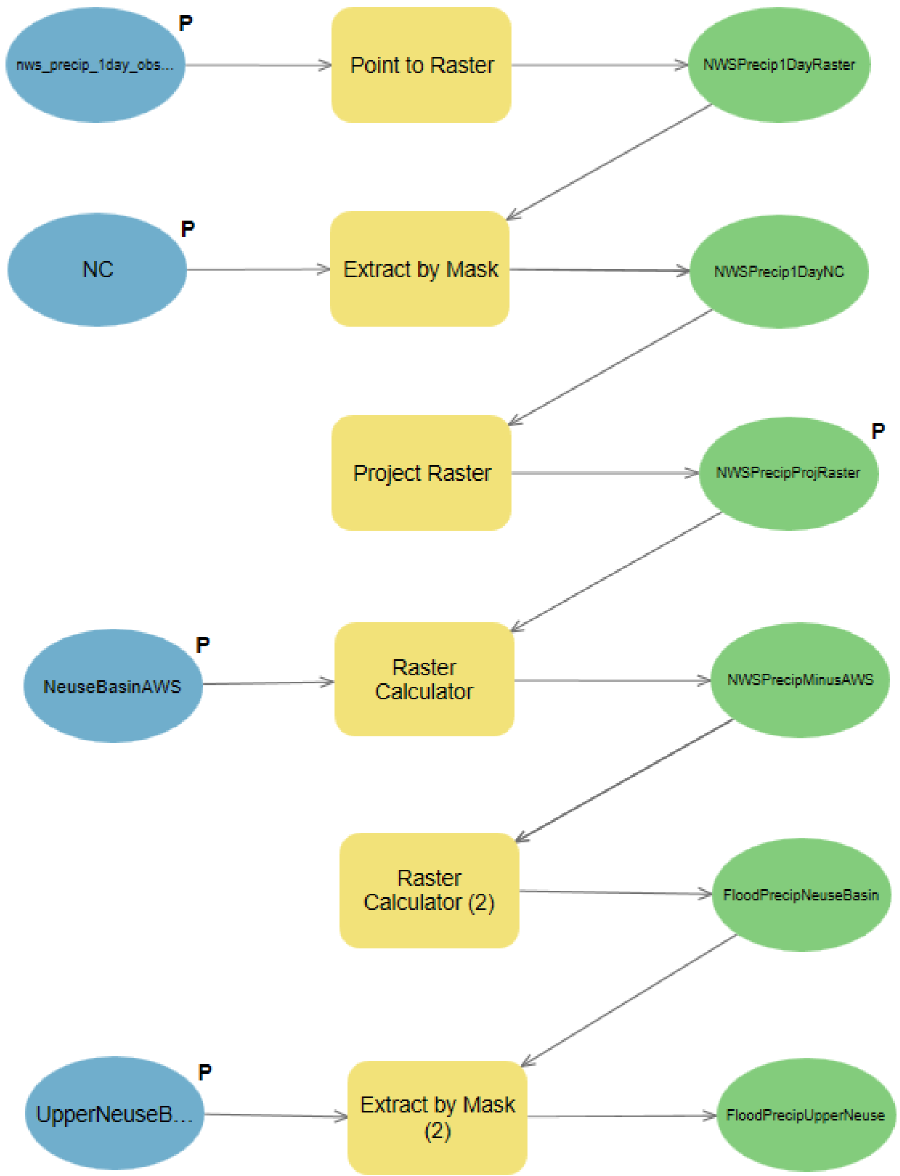

Figure 7. ModelBuilder representation of automated tool constructed for the transformation of NWS precipitation point datasets to rasters, then substraction of the AWS dataset.

Precipitation station locations for North Carolina as well as daily precipitation data for October 5-11 were downloaded from NWISWeb. As shown in Figure 8, the location of precipitation stations is heavily uneven in its distribution. In the Upper Neuse Basin, majority of the rain gages are located in and around Raleigh. Only a 7 day cumulative precipitation total was calculated for the stations. Figure 9 shows the amount of rainfall at each station location by graduated symbols overlaid on a digital elevation model (DEM) of the Upper Neuse Basin. These values match up well with the previously projected map. The elevation of the basin also shows a maximum elevation height in the basin of ~270 m.

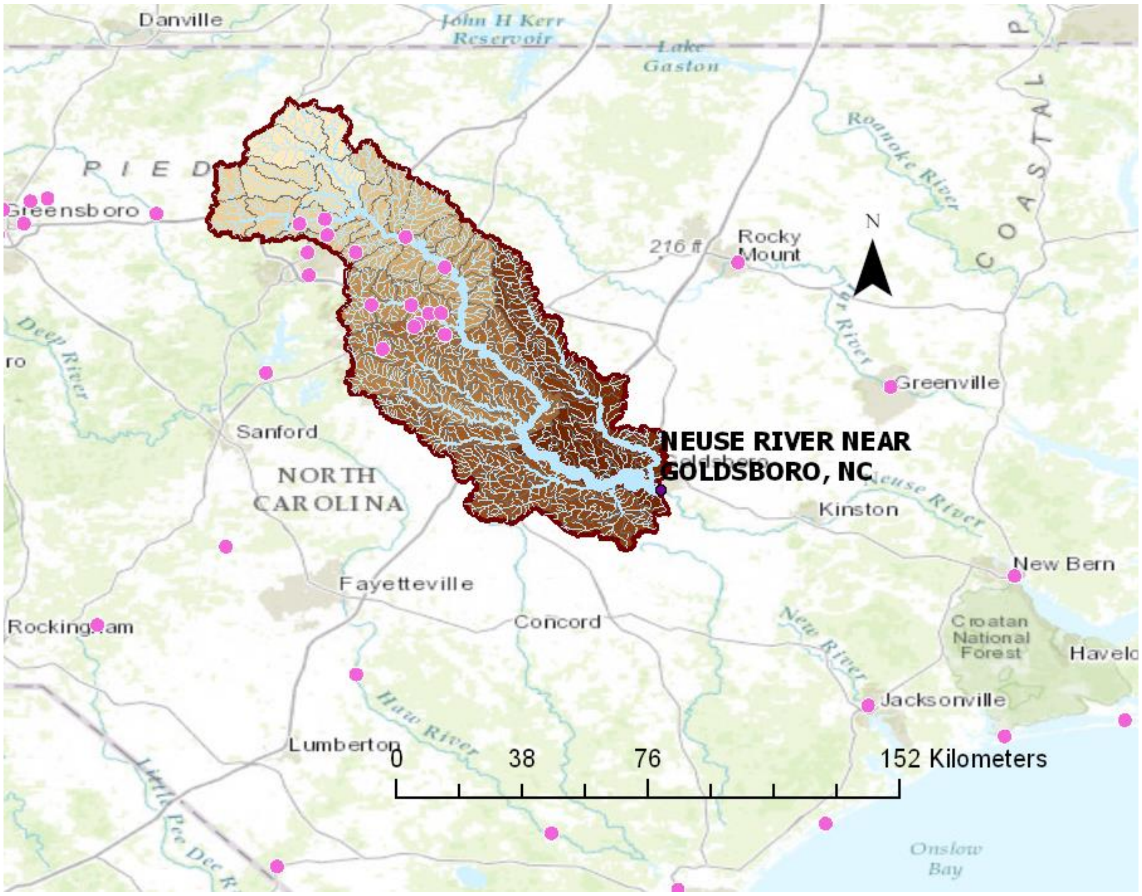

Figure 8. Location of rain gages operated by the USGS in Eastern North Carolina.

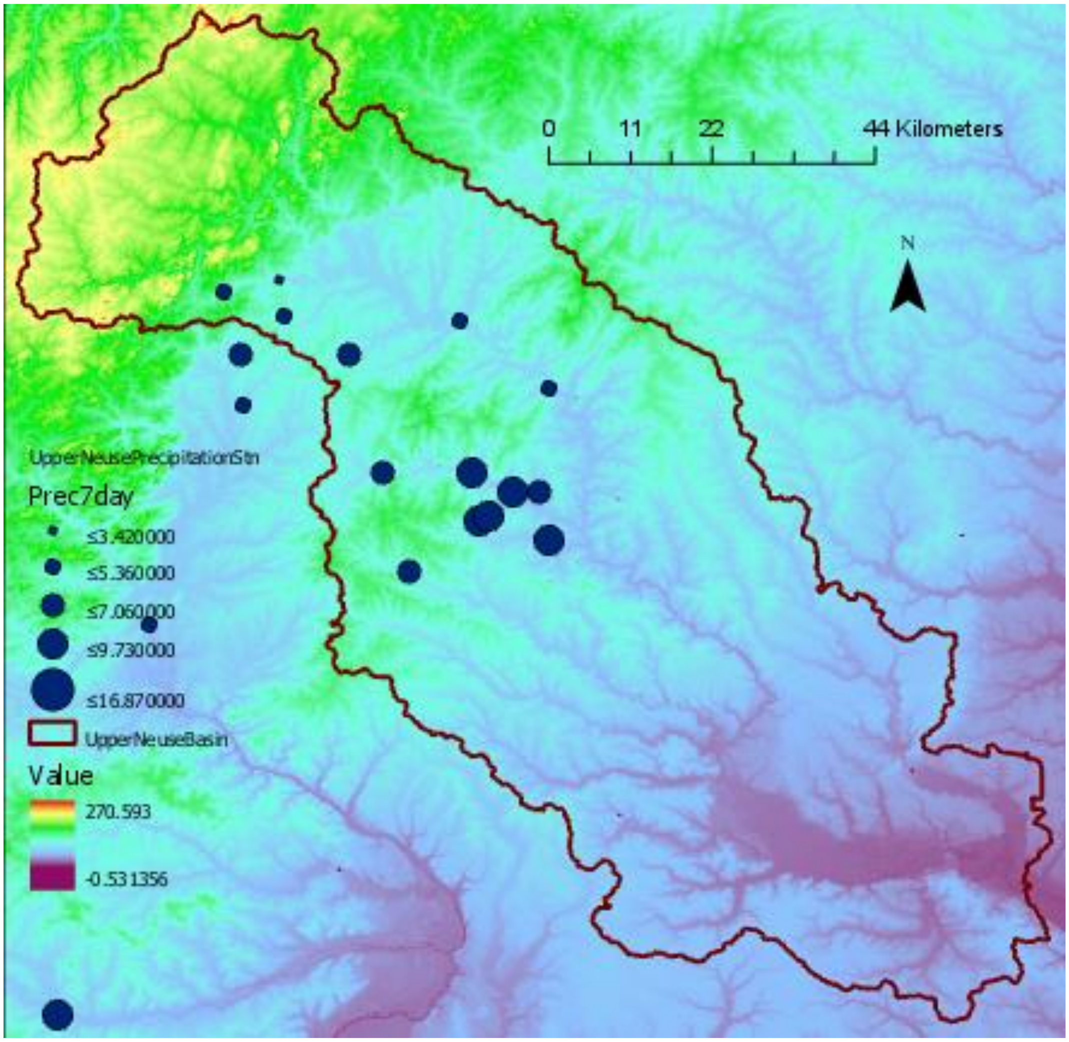

Figure 8. Graduation precipitation symbols representing 7-day cumulative precipitation from October 5 to October 12 collected at rain gages around the Upper Neuse Basin. Under this layer, the NED projection of the basin and surrounding area can be seen.

Interpolation of gage data was completed using both Thiessen Polygon and spline methods, and total amount of runoff water for the watershed was calculated using Theissen Polygons.

4. Results and Discussion

4.1 Project Map Analysis

Figure 9 show the runoff precipitation height for the Upper Neuse Basin for accumulated rainfalls for 5, 6, and 7, days. It can be seen there is a drastic increase of runoff precipitation near Goldsboro at the base of the basin between the end of day of October 9 and October 11. This resulted in the rapid jump in streamflow and height between the October 8 and October 11 at the Neuse River near Goldsboro Station.

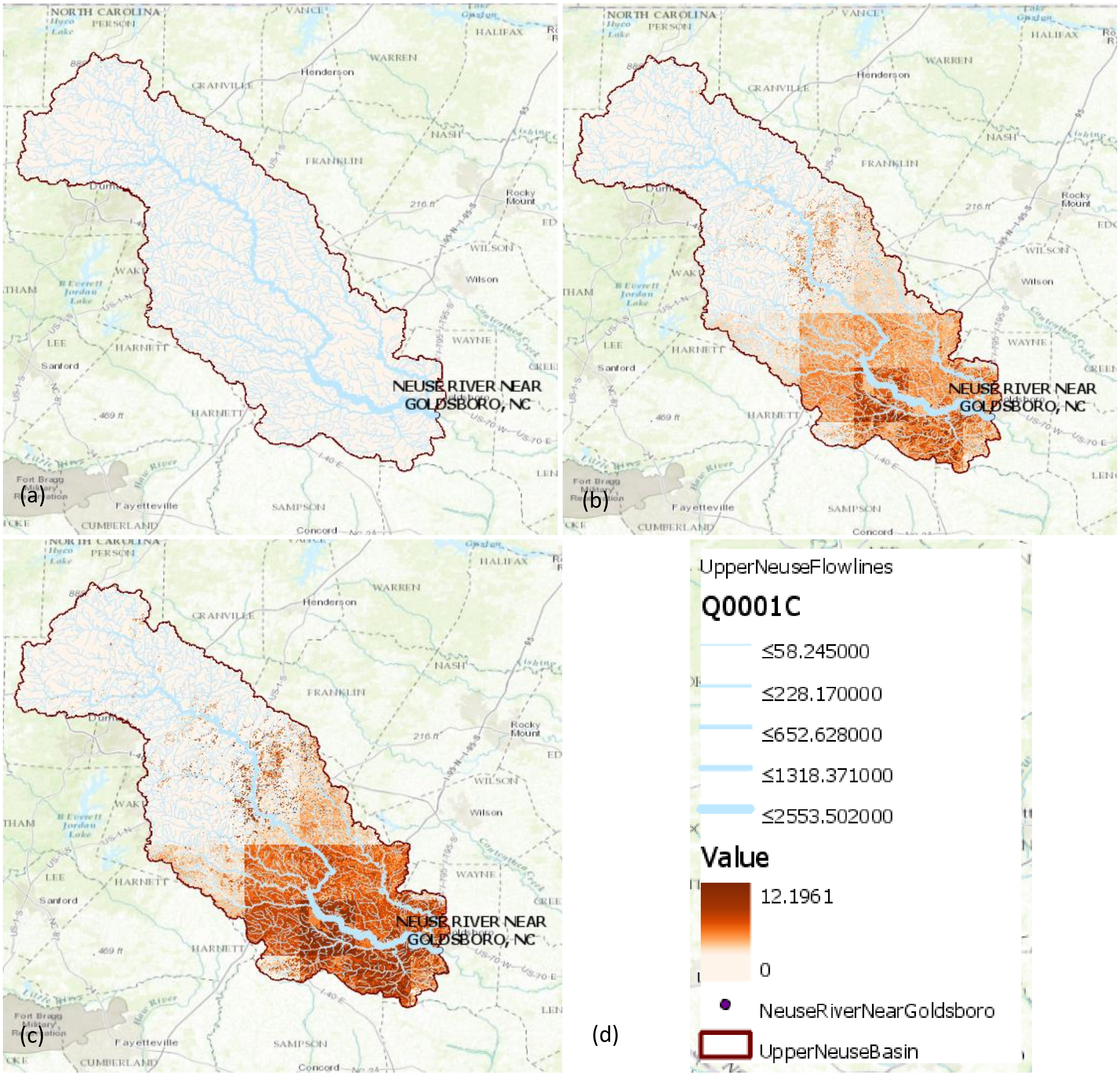

Figure 9. Runoff rainfall data inches using NWS daily precipitation data and AWS for cumulative (a) 5-day precipitation (b) 6-day precipitation (c) 7-day precipitation with (d) legend.

The resolution of these maps is limited by the large cell size of the precipitation data projected from the HRAP point files. The result is a stilted map with distinct grid lines. However, some information regarding the largest sources of runoff rainfall can be gleaned. The areas southwest of Goldsboro are of particular interest, showing over 12 in of runoff precipitation in some areas.

Zonal statistics was used to calculate the mean runoff precipitation of the basin and total runoff volume that would drain to the Neuse River near Goldsboro stream gage.

4.2 Interpolation Analysis

Maps using Thiessen polygon and spline interpolations of 7-day cumulative precipitation station data is shown in Figure 10. Resolution of the results using the Spline tool are good; however, the interpolation breaks up near the boundary of the state at the North end of the basin, creating a large portion of unavailable data. Because of this reason, total runoff was not calculated from this method.

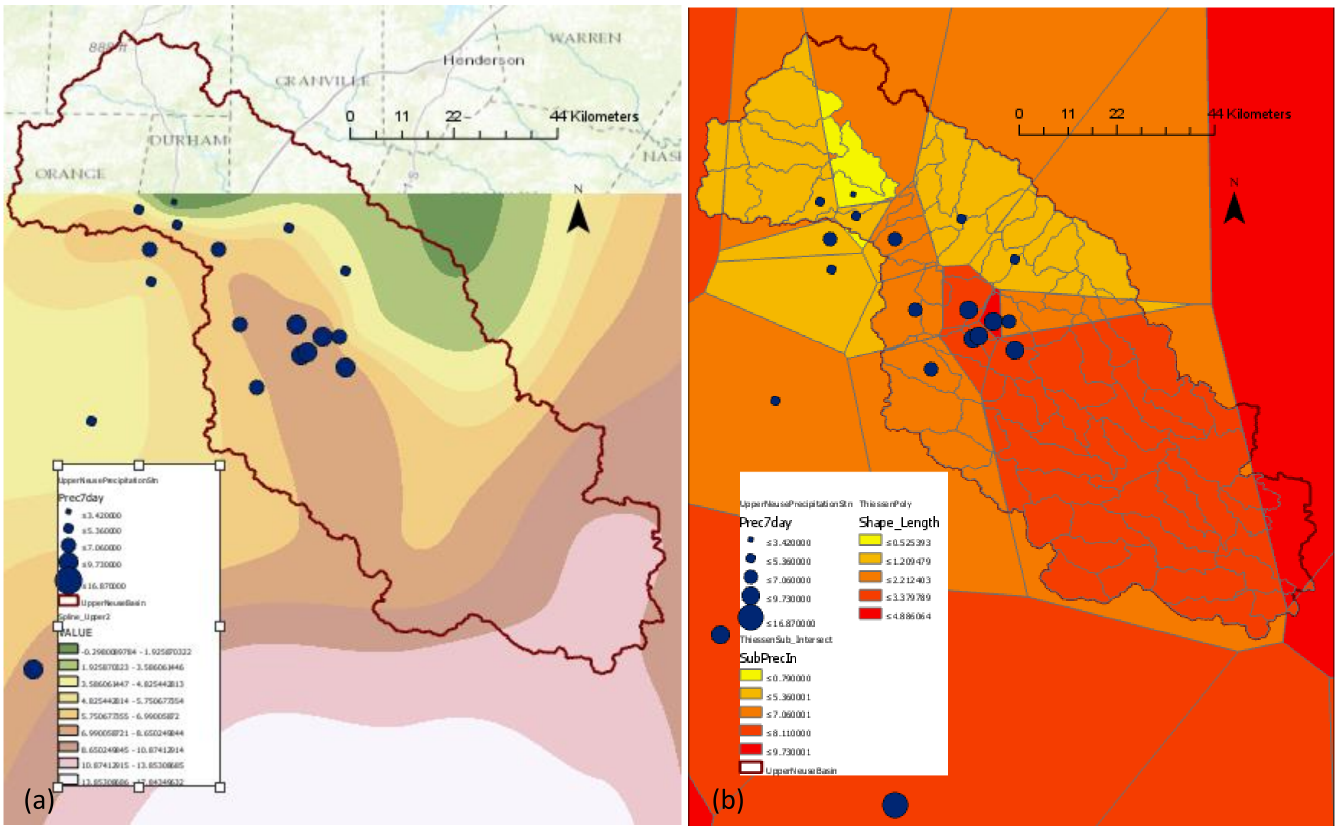

Figure 10. Interpolation of 7-day cumulative rainfall data from (a) Spline method and (b) Thiessen Polygons method.

Interpolation using the Thiessen Polygon tool, although the most simplistic approach to interpolation, did provide a complete map for the basin. The produced polygons were intersected with all subwatersheds in the basin. The precipitation gage data was then spatially averaged for each subwatershed. Figure _ shows that these intersections are large and bulky in the base of the basin, due to the lack of precipitation stations in the area. The area weighted precipitation was calculated by spatially averaging the data using the equation provided in class Exercise 3:

$$P_i = \frac{\sum_k A_{ik} P_k}{\sum_k A_{ik}}$$

Mean precipitation data for each subwatershed was used to calculate total runoff precipitation to the Neuse River near Goldsboro stream gage.

4.3 Total Runoff Calculations

Table 1 shows the calculated runoff volume calculated for the 7 days of precipitation studied. Figure 2 shows the stream flow data for the days of October 7 to October 17 for the Neuse River near Goldsboro, NC station. This flow data was crossed referenced with NWM channel flow data for the segment of stream that flows right into the study gage to confirm accuracy. Although it is difficult to related the cfs rate flow from the runoff volume, the estimates made are reasonable given the sustained flow volume following October 9.

METHOD	MEAN PRECIPITATION (IN)	AREA (MI^2)	7 DAY RUNOFF VOLUME (FT^2)
PROJECT	3.895	3662.68	9.983 E +08
THIESSEN POLYGONS	2.1092	3584.89	2.868 E +08

Table 1. Total runoff volume for the entire Upper Neuse Basin calculated using demonstrated method and Thiessen Polygons interpolation in cubic feet.

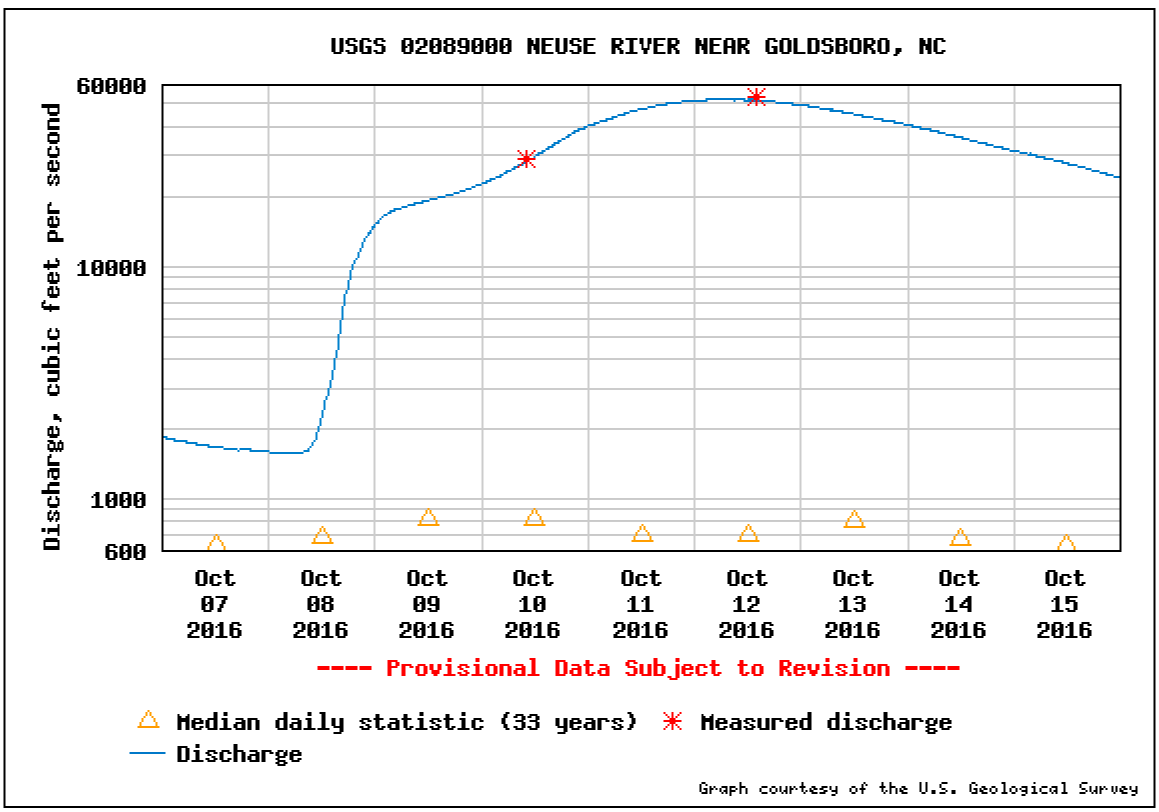

Figure 10. Streamflow data for USGS 02089000 gage Neuse River near Goldsboro, NC.

5. Conclusions

5.1 Validity

While the method demonstrated in this project is a simplistic modeling of runoff precipitation sources, the results did demonstrate its effectiveness in targeting the location of these sources. There is a loss of resolution with the conversion of NWS precipitation data to a projected raster. However, there is no other simple method of getting accurate, full-coverage, historical time-series precipitation data for single events. As these data sources improve, the resolution product from this method can be improved as well.

5.2 Assumptions

Many simplifying assumptions were made in using both the project method and the interpolation methods. The total runoff volume accumulated precipitation does not take into account the evaporation of any water from the soil bed. It also does not take into account absorption of water by areas of soils not totally saturated on its path to the nearest drainage point. Further calculations of runoff flow path, as well as velocity of runoff flow and runoff flow coefficients will be needed to build a more complex model than the one demonstrated here.

Interpolation methods did not take into account the available water storage and possible absorption into soil in the calculation of total runoff volume. This may account for the high runoff volume calculated using interpolation as compared to the project method.

5.3 Future Work

For future storm events, this analysis could be done based on precipitation forecasts. Precipitation forecast data from the NWM could result in higher resolution and more precise findings. Ideally, a basin scale modeling program similar to SWAT could be used as a tool to simply and accurately predict areas where sudden runoff rainfall volume may originate due to soil table saturation. Preventative measures could be taken to either divert or mitigate runoff flow, which may reduce the occurrence of sudden flood surges in vulnerable areas.

References

[1] "In North Carolina, some flood waters crest while other remain on the rise." Harlan, Fritz. *The Washington Post.* 13 October 2016

[2] "North Carolina estimates $1.5 billion in hurricane damage to buildings." Maler. *Reuters*. 16 October 2016

[3] "Why has the flooding in North Carolina been so bad?" Miller. *CNN*. 13 October 2016