# Inundation Mapping Using Hydraulic Models and GIS: Case Studies of Steady and Unsteady Models on the Tar River, NC

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## ABSTRACT

The National Weather Service (NWS) recently began providing static inundation maps at selected river forecast points through the Advanced Hydrologic Prediction Service (AHPS) web pages. Positive feedback has motivated efforts to expand the forecast mapping program. In order to expand this mapping program efficiently and effectively, we need a more objective basis for determining where static forecast mapping is acceptable and where real-time, dynamic forecast mapping is required. With the current static forecast mapping approach, we do not have quantitative guidance specifying how far away from forecast points the maps are valid. This pre-print describes a methodology to develop this type of guidance and better understand sources of forecast mapping uncertainty. For this pre-print, we present limited results from an example case study on the Tar River, NC, comparing water surface profiles generated from steady and unsteady flow hydraulic models. Results that are more comprehensive will be presented at the conference.

## INTRODUCTION

The National Weather Service (NWS) recently began providing static inundation maps at selected river forecast points through the Advanced Hydrologic Prediction Service (AHPS) web pages. The static map libraries serve the public by providing information about the approximate extent of flooding associated with river stage forecasts at pre-defined stage increments. Positive feedback has motivated efforts to expand the forecast mapping program. In order to expand this mapping program efficiently while producing accurate maps, we need a more objective basis for determining where static mapping is acceptable and where real-time, dynamic forecast mapping is required. We also need improved verification methods to assure the accuracy of forecast maps and better understanding of the associated uncertainties. Specifically, the static inundation mapping techniques currently used may have limited validity as one moves away from the forecast point where they are calibrated. We expect dynamic forecast mapping techniques to be more accurate and applicable to longer river reaches. Here, we describe a methodology to quantify the errors associated with the static forecast mapping assumptions relative to a more robust dynamic forecast mapping approach. We also plan to look at the impacts of elevation data accuracy on mapping errors. Our first study area is the Tar River, NC, where we compare water surface profiles and inundation maps generated from steady and unsteady flow hydraulic models. Initial mapping verification efforts are focused on Hurricane Floyd, 1999, due to the availability of unique flood observations.

In this study, we use the US Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) -River Analysis System (HEC-RAS) and the HEC-GeoRAS pre- and post-processor. HEC-RAS was used to generate the existing static map libraries and the NWS is working with HEC to include HEC-RAS as an operational forecasting tool in the next generation NWS hydrologic software referred to as the Community Hydrologic Prediction System (CHPS).

## BACKGROUND

### What static inundation mapping services does the NWS currently provide?

The Advanced Hydrologic Prediction Service (AHPS) currently provides inundation maps for 33 of the 4257 NWS forecast points (http://www.weather.gov/ahps/inundation.php). The AHPS maps are often based on modeling done by Federal Emergency Management Agency (FEMA) mapping contractors. Under the "Inundation Mapping" tab on the web page for a given forecast point, three data type screens are available (Figures 1a-c) for each location.

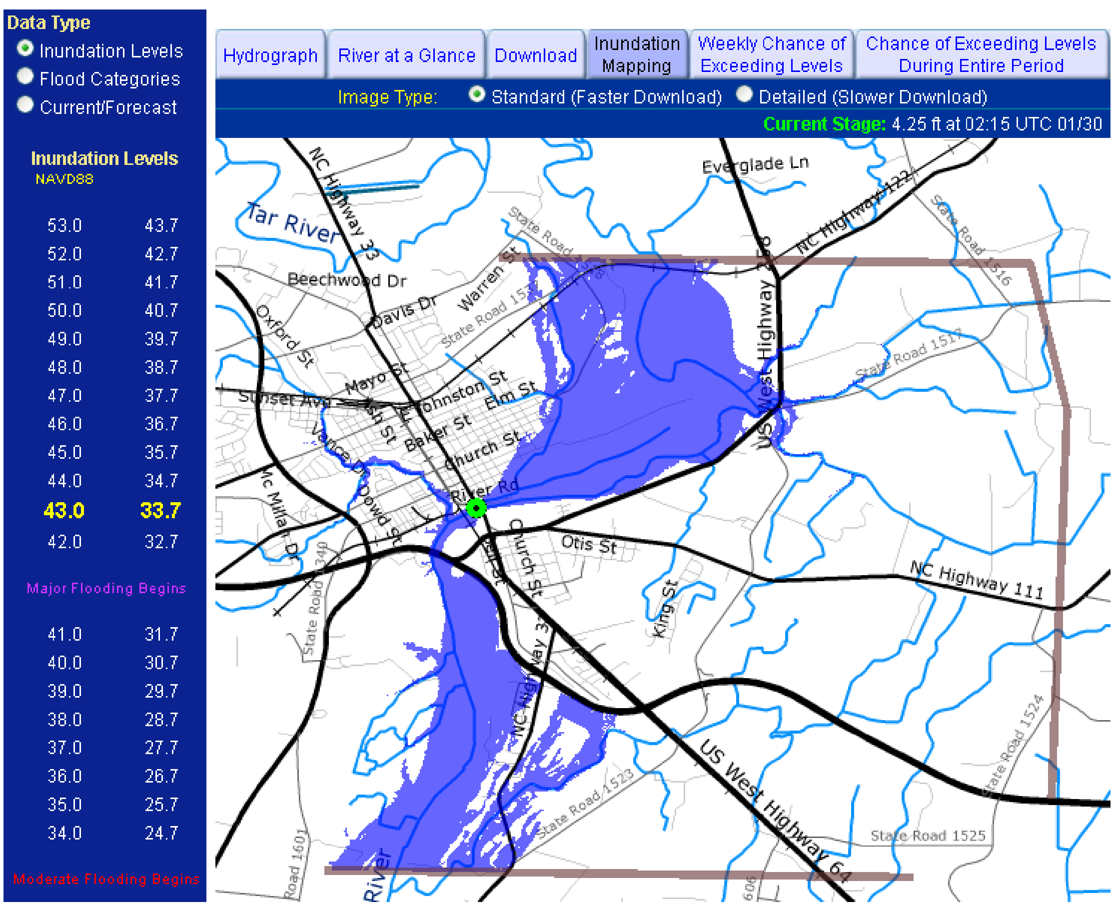

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Figure 1a: Inundation levels for the Tar River at Tarboro, NC (TARN7)

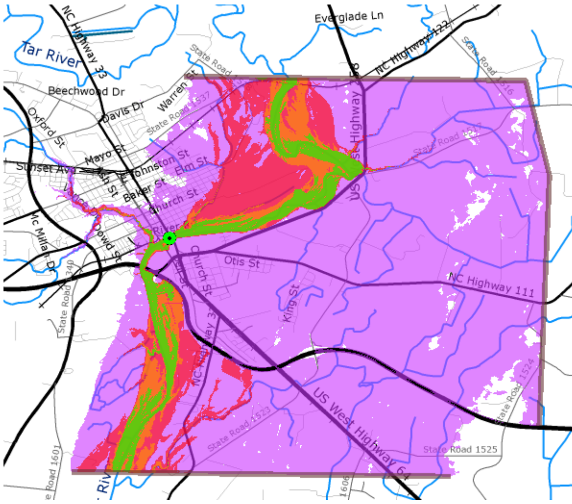

Figure 1b: Flood categories for TARN7

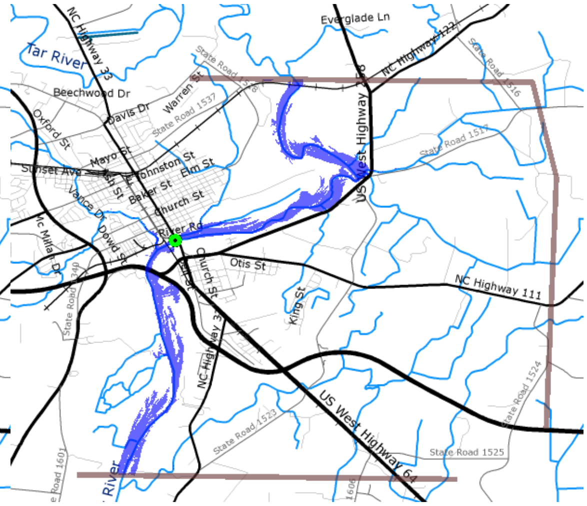

Figure 1c: Current/Forecast for TARN7

Figure 1. (a) The user can mouse-over different stages to see the corresponding inundation levels. (b) The NWS defines the five flood categories “Below Flood Stage” (green), “Action or Near Flood Stage” (yellow), “Minor Flood Stage” (orange), “Moderate Flood Stage” (red) and “Major Flood Stage” (purple) for each river forecast point location. “Action or Near Flood Stage” may coincide with “Minor Flood Stage” depending on each location. (c) Inundation map associated with the most recent forecast stage.

Where available, the 100-year flood, the 500-year flood and the floodway data layers from the Federal Emergency Management Agency (FEMA) can be turned on for reference. The inundation levels stored in the static map library begin at “Action or Near Flood Stage” with one foot increments and end at the historic recorded crest level. The transparency of each layer can be adjusted and basic zooming or panning features exist.

The Current/Forecast Data Type screen (Figure 1c) automatically displays the static map layer that corresponds to the current, maximum forecast stage at a gauge location. Because all of the map layers representing different inundation levels were pre-calculated and are being stored in the map library, computational requirements are minimal and the flood forecast map display changes immediately when a new stage forecast is available.

**What techniques are used to create these maps**?

One dimensional hydraulic models are used to create water surface profiles and GIS-based post-processors are used with digital terrain data to create inundation maps. Most of the static map libraries are created using steady-state models. Using this approach, modelers will adjust the flow until a profile with the desired stage at the forecast point of interest is reached. This ties a forecast stage to a map layer.

An alternative approach was used to create static maps for the Lower Colorado River in Texas. For the Lower Colorado, profiles corresponding to stages of interest at NWS forecast points were interpolated from profiles developed for FEMA's National Flood Insurance Program (NFIP). The input FEMA profiles correspond to design floods (e.g. 2, 5, 10, 25, 50, 100, and 500 year floods) generated using design storms, hydrologic models, and unsteady HEC-RAS models. Both steady and unsteady approaches to generate static libraries are relatively simple and can leverage data and models from FEMA's National Flood Insurance Program (NFIP).

The hydraulic models generate water surface profiles extending upstream and downstream from forecast points of interest; however, the validity of steady flow modeling diminishes with distance from a forecast point. In the case of the Lower Colorado, the pre-defined profiles generated from unsteady models may also differ from dynamically generated profiles if the real-time conditions do not match the assumed conditions in generating the profiles. The distances upstream and downstream for which these static maps are valid will vary from site to site and have not been rigorously quantified. NWS (2007) suggests only a general guideline to apply models for no more than one to two miles upstream or downstream from the forecast point.

Another limitation of static forecast mapping is that static maps will not be available for stages that exceed the historic flood.

**What is dynamic inundation mapping?**

Dynamic forecast mapping addresses limitations of static forecast mapping. Dynamic forecast mapping involves re-computing maps based on real-time conditions that may be different from the conditions assumed when creating the static maps. If a NWS River Forecast Center (RFC) runs an unsteady hydraulic model for forecasting, dynamically generated water surface profiles from this model can be used to generate forecast maps that are valid all along a river.

Unsteady hydraulic models, as opposed to hydrologic models, are required to create accurate stage forecasts at locations with looped rating curves (a single stage may correspond to two different flows). Channels with large flood plains and mild slopes often have looped rating curves. For points that have single valued rating curves, hydrologic models can predict flows and a rating curve can convert flows to stages. In both cases, the static maps are tied to a stage rather than a flow and therefore are valid at the forecast point. However, at locations away from the forecast point, deviations between the true water surface profile and the statically mapped profile may occur in either case due to differences in the actual flood wave from the conditions assumed when creating the static maps.

Two drawbacks of dynamic forecast mapping are an increase in the computational requirements and that more human resources are required to quality control model outputs.

## METHODOLOGY

### Static versus Dynamic Forecast Mapping

In this study, we compare flood maps from a static forecast mapping approach to those from a dynamic forecast mapping approach. To generate example static maps, we run a steady flow model, generate a water surface profile and create a map. We then run an unsteady model for the same reach. From the unsteady model and for the forecast point of interest, we can identify times when the simulated stage matches the stage predicted by the steady model. We output instantaneous profiles at these times, generate maps and compare these maps to those from the steady model.

We used HEC-RAS to generate water surface profiles and HEC-GeoRAS to map the extent of the flooding. HEC-GeoRAS intersects the modeled water surface with digital terrain data to determine the inundated area. HEC-RAS includes both Steady Flow and Unsteady Flow modules. The Steady Flow module computes profiles using the standard-step approach based on the Energy equation and the Unsteady Flow module solves the Saint-Venant Continuity and Momentum equations. The HEC-RAS Steady Flow module uses empirical contraction and expansion coefficients to compute energy losses at contracting and expanding sections. The Unsteady Flow module accounts for expansions and contractions only through changes in cross-sectional flow area through the Momentum equation. This approach cannot account for all the forces caused by large scale eddies that occur with expansions and contractions. Because of this, HEC-RAS Steady Flow elevations will generally be higher than Unsteady Flow results even if the same flows, model geometry, and roughness parameters are being used (Brunner, personal communication).

Here, we wish to isolate the differences between static and dynamic forecast mapping approaches. Therefore, we wish to eliminate any differences in unsteady and steady flow computational techniques. To do this, we generate steady flow results in this study by inputting constant flow time series into the HEC-RAS Unsteady module. Identical channel geometry and roughness parameters are used for both steady and unsteady runs. For the same reason, we do not use the existing maps on the AHPS web site as examples for our steady state runs. Although we are using the same underlying cross-section data, other parameters in our HEC-RAS model are different from those used to create the AHPS maps and, in the case of the North Carolina points, we are using different software to convert the water surface profiles into maps. It will be useful to compare the overall accuracy of the AHPS maps to those we create from our unsteady model but that is not our purpose here.

### Study Area

We plan to study several forecast points in North Carolina where static inundation mapping services are already available. Figure 2 shows the NWS forecast locations where static maps are available. Figure 2 also shows the locations of high water marks that were collected by the US Army Corps of Engineers after Hurricane Floyd (USACE, 1999). These data will help in evaluating the quality of our mapping results. To the extent possible, we will also use post-event aerial photography obtained from the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center for qualitative verification.

For this pre-print, we present example results near Greenville, North Carolina. To do this, we use an unsteady HEC-RAS model developed for approximately 48 river miles of the Tar River from Tarboro, NC to Washington, NC (area highlighted in red on Figure 2). To build this model, we obtained the cross-section data in HEC-RAS format from the North Carolina USGS via the North Carolina Floodplain Mapping Program. The cross-sections were originally produced from a combination of Light Detection and Ranging (LIDAR) data and USGS field surveys. Moreda et al. (2009, this proceedings) describe this model in more detail, including how the unsteady flow model was calibrated. The calibration period spanned several years, July 1 1999 through August 31 2005. Observed stage data at four observation stations were used in calibration. In the example presented here, we focus on the USGS Station near Greenville, NC and on the flood peak generated during Hurricane Floyd (September, 1999).

The initial HEC-RAS model we obtained was not geo-referenced. To correct this, we imported a geo-referenced river centerline into HEC-RAS to replace the existing straight centerline. In this process, HEC-RAS geo-references all cross sections starting from the upstream boundary following the new river centerline downstream and assuming that all cross sections were originally cut at 90 degree angles. The distance between the cross sections is based on the distances (river miles) entered in the hydraulic model.

**NED versus LIDAR Data**

Two sources of digital terrain data are available for the Tar River study area. The USGS National Elevation Dataset (NED) is readily available for the whole country and relatively easy to process on a personal computer; however, the data accuracy may be inadequate for flood mapping in some areas (http://ned.usgs.gov/). LIDAR data are more accurate and more precise than the NED data but are not available for the whole country. LIDAR data used in this study are available from the North Carolina Floodplain Mapping Program. We will create inundation maps using both sources of elevation data in this study and compare the results. This will give us some idea as to the importance of collecting more accurate elevation data relative to developing a dynamic forecast mapping capability with the existing lower accuracy data. Another factor to consider is that with the HEC-GeoRAS software, the processing of each map is much more computationally expensive when the LIDAR data are used. This may be alleviated with more efficient mapping algorithms or conversion of the raster LIDAR data into a Triangulated Irregular Network (TIN) format.

**RESULTS AND DISCUSSION**

Figure 3 shows a simulated rating curve from the unsteady HEC-RAS model at Greenville, NC. This curve was built from hourly simulations spanning July 1, 1999 to

August 31, 2001. The looped section of the curve is comprised of data from the Hurricane Floyd event. At a river stage of 20 ft, the flow can be approximately 36,400 cfs while the flood is rising but 8,000 cfs lower when the flood is falling. Clearly, the flood profile is dynamically changing during the event at moderate to high flood levels. At Greenville, flooding begins at 12 ft, moderate flooding begins at 16 ft, and major flooding begins at 18ft.

During Hurricane Floyd, our calibrated unsteady model simulates the peak stage at Greenville to be 25.9 ft (on September 22, 1999 at 0500z) while the observed stage is 25.8 ft. At this time, the simulated flow from the unsteady model is 65,809 cfs. To emulate the static forecast mapping approach, we used trial and error to identify a constant flow input so that the steady flow model predicts the same stage as the unsteady model. The flow required to produce a matching stage was 64,108 cfs.

We repeated this procedure for a smaller flood peak that occurred on October 25, 1999 at 0900z. For this event, the unsteady model simulated peak was 12.8 ft and the observed stage was 13.1 ft. The simulated flow from the unsteady model was 16,816 cfs at this time. A constant flow of 18,329 cfs was applied in the steady state model to generate a matching stage.

For both of these events, we are interested in the difference between the steady and unsteady water surface profiles as one moves away from the Greenville gauge. Figure 4 shows the water surface profiles predicted for approximately a six mile stretch of river centered on Greenville for the September (3a) and October (3b) events. Note that the unsteady profiles are instantaneous profiles predicted at the peak of the flood. Figure 4a shows that the water surface profiles corresponding to the September peak stage are very similar. This may be because the flood was so large that storage areas that would normally be filled with a steady model but not with an unsteady model are filled up in the unsteady model. The fact that the rating curve (Figure 3) is not looped for the highest stages supports this hypothesis. We would expect greater differences in the profiles if these instantaneous profiles were selected during the rising or falling limbs of the hydrograph.

Figure 4b shows that steady and unsteady water surface profiles differ more for the smaller October event. Here, the unsteady result is also the instantaneous profile at the event peak. In this case, the static forecast mapping approach produces errors up to 0.33 ft for distances within 3 miles of the forecast point and up to 0.25 ft for distances within 2 miles.

Due to last minute changes in our methodology, we were unable to create and compare the inundation maps corresponding to the profiles in Figure 4 for this paper. For this reason, we also do not present our verification results using the high water mark data and aerial photography data at this time. These maps and more results will be presented at the conference. To develop a robust set of results, we plan to create and quantitatively compare similar maps at several forecast points and for several stages.

## REFERENCES

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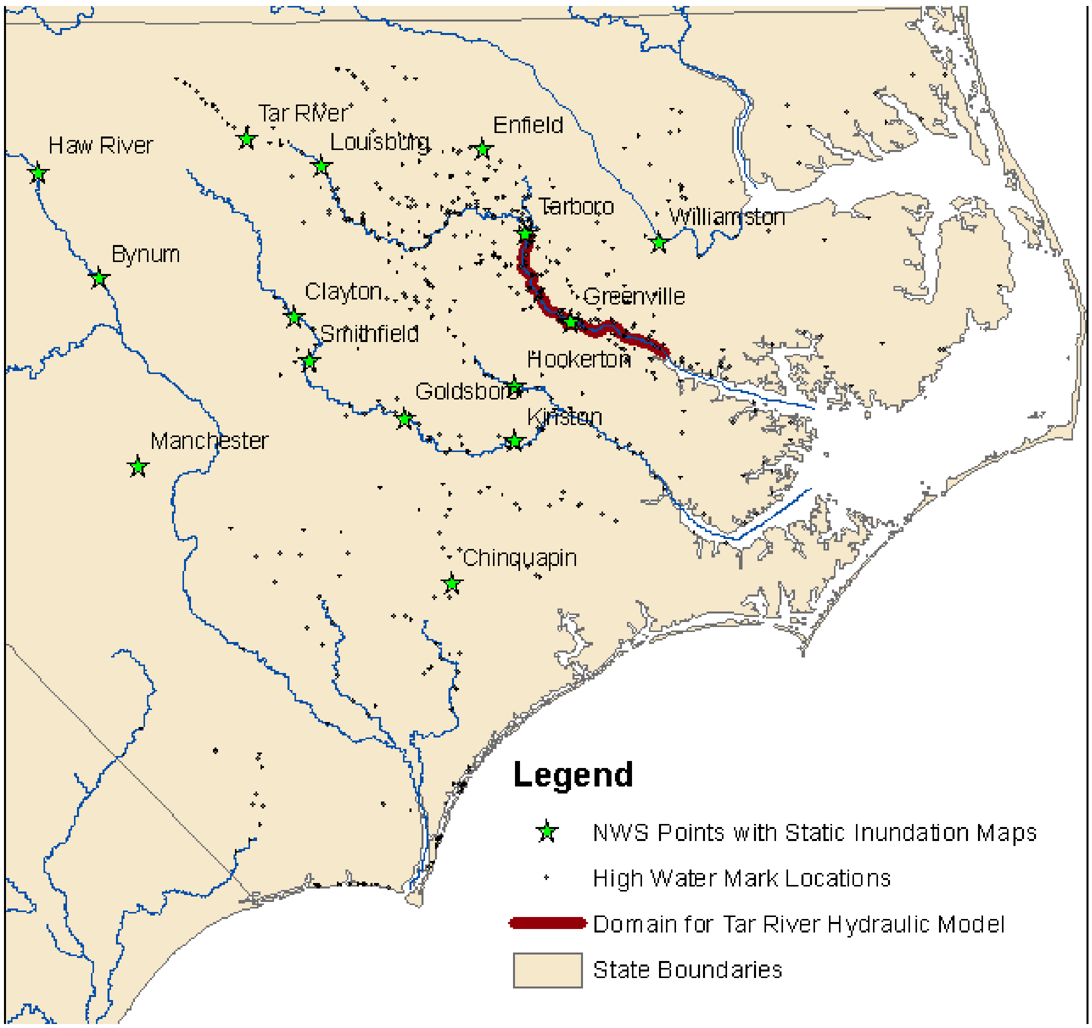


Figure 2. Locations of NWS forecast points with static inundation mapping services in North Carolina. Static forecast maps are available at 15 of the 109 NWS forecast points in North Carolina: Chinquapin (CHIN7), Hookerton (HOKN7), Kinston (KINN7), Greenville (PGVN7), Williamston (WLLN7), Bynum (BYNN7), Clayton (CLYN7), Enfield (EFDN7), Goldsboro (GLDN7), Haw River (HAWN7), Louisburg (LOUN7), Manchester (MANN7), Smithfield (SMFN7), Tarboro (TARN7), and Tar River

(TRVN7). Our initial HEC-RAS model is set up for the Tar River (highlighted in red). High water mark locations from Hurricane Floyd are also shown.

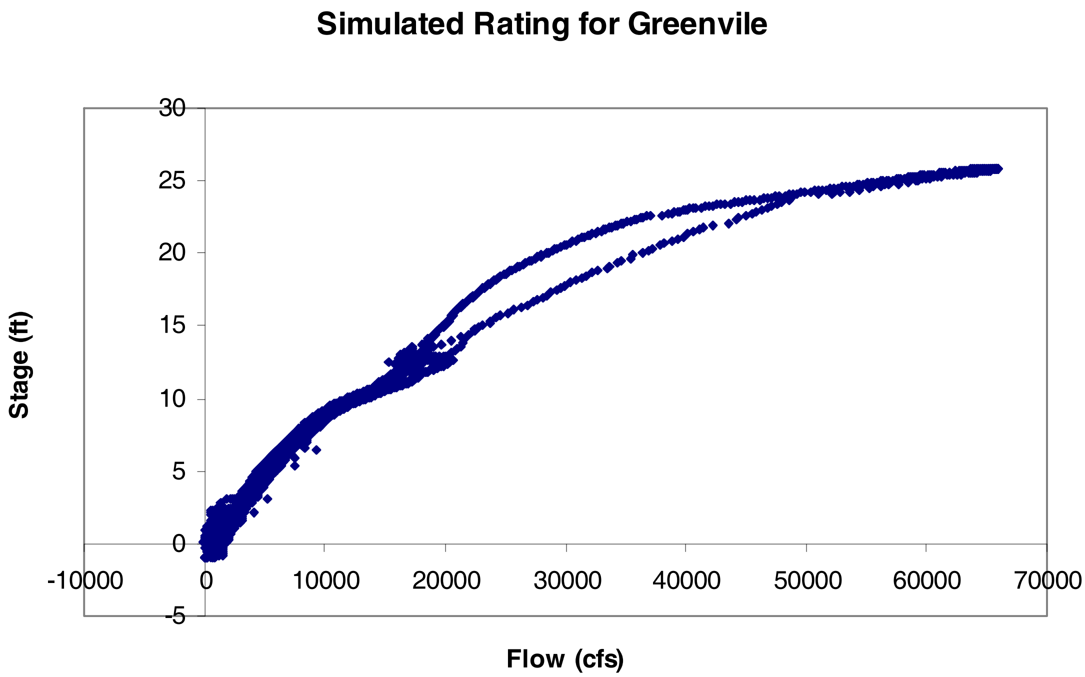


Figure 3. Simulated rating curve for Greenville, NC.

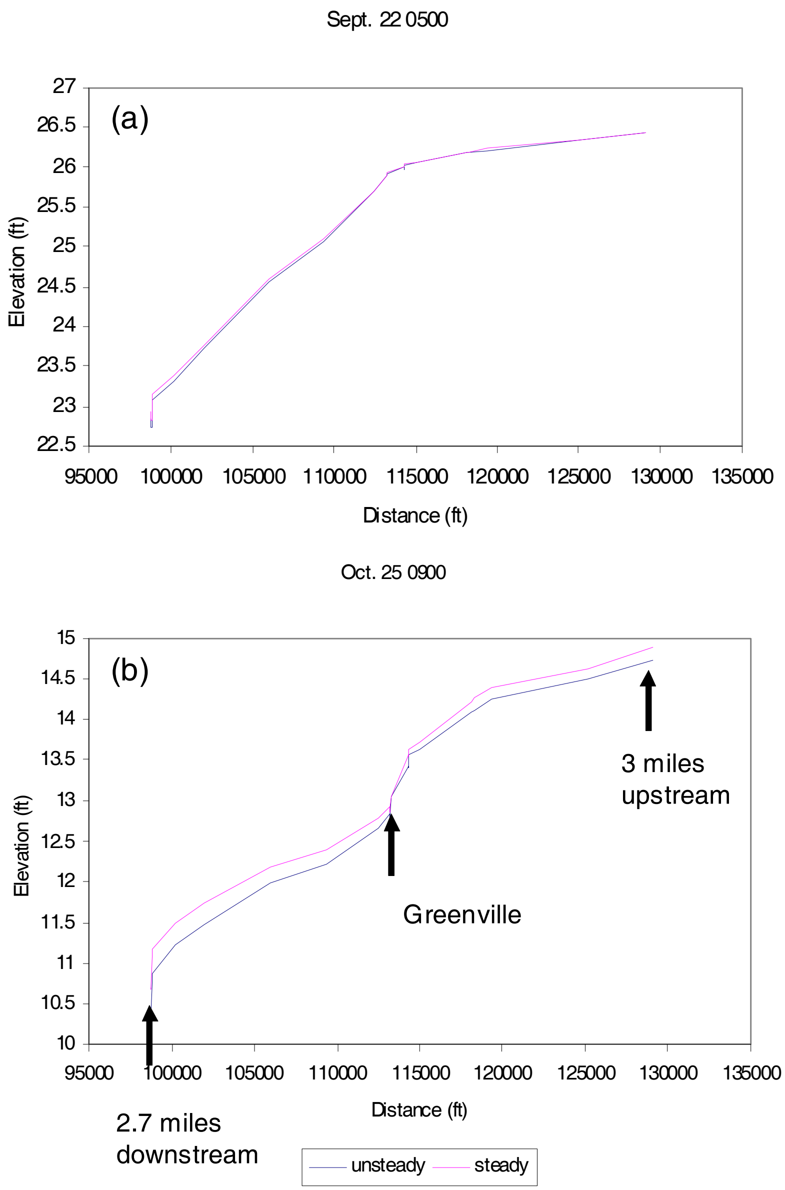


Figure 4. Two sets of water surface profiles generated so that the steady and unsteady model stages at Greenville match. (a) Water surface profiles simulated during the peak of flooding caused by Hurricane Floyd. (b) Water surface profiles for a less severe event during a subsequent month.