US Army Corps of Engineers
Hydrologic Engineering Center

# Susquehanna River Flood Warning and Response System

**July 2003**

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**14. ABSTRACT**
The Philadelphia District and the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers have developed a Flood Warning and Response System (FWRS) for 110 miles of the main stem of the Susquehanna River in northeast Pennsylvania. The objective of the flood warning system is to provide accurate and timely warnings in order to maximize response time for floodplain residents and emergency managers while also creating a floodplain management and planning tool for the region. The project incorporates aerial photography, terrain elevation data, channel geometry, demographic and structural data, transportation systems, and a hydraulic model to create an automated and interactive flood inundation mapping application using Geographic Information Systems technology.

The HEC developed an HEC-RAS hydraulic model for the complete project area. Geometric data for the model was developed using HEC-GeoRAS and a digital terrain model of the system. A database of structures within the floodplain, and their corresponding dollar values, was put together by the Philadelphia District office. The FWRS calculates damage to single or groups of structures, predefined impact areas, or counties for a given event. Additionally, users can bring up an Impact Response Table, which contains a listing of people to contact and actions to be taken given the forecasted water surface elevations. The HEC developed the FWRS software using ArcGIS 8.x. The functionality of the FWRS is based on the user entering river stages at any of the four stream gages located within the project area.

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# Susquehanna River Flood Warning and Response System

## July 2003

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This study was conducted by Gary W. Brunner, Mark R. Jensen, Cameron T. Ackerman, Jason Needham, and Chris N. Dunn of the Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers. Mr. Jason Miller of the Philadelphia District office provided valuable assistance in supplying information and assembling the data. Mr. Arlen Feldman was Chief of the Hydrology and Hydraulics Technology Division and Mr. Darryl Davis was the director of HEC during this study.

# Executive Summary

The Philadelphia District and the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers have developed a Flood Warning and Response System (FWRS) for 110 miles of the main stem of the Susquehanna River in northeast Pennsylvania. The objective of the flood warning system is to provide accurate and timely warnings in order to maximize response time for floodplain residents and emergency managers while also creating a floodplain management and planning tool for the region. The project incorporates aerial photography, terrain elevation data, channel geometry, demographic and structural data, transportation systems, and a hydraulic model to create an automated and interactive flood inundation mapping application using Geographic Information Systems technology.

The HEC developed an HEC-RAS hydraulic model for the complete project area. Geometric data for the model was developed using HEC-GeoRAS and a digital terrain model of the system. The model was calibrated to five historic events, and then further refined by calibrating to the rating curves at the four stream gages for the full range of frequency-based events (2 yr – 500 yr). Once the model was fully calibrated, a series of 35 flood events (ranging from less than a 2 yr event to greater than a 500 yr event) were run through the hydraulic model to compute a series of water surface profiles. The water surface profiles were then sent to HEC-GeoRAS and corresponding flood inundation maps and depth grids were generated for each of the 35 events.

A database of structures within the floodplain, and their corresponding dollar values, was put together by the Philadelphia District office. The FWRS calculates damage to single or groups of structures, predefined impact areas, or counties for a given event. Additionally, users can bring up an Impact Response Table, which contains a listing of people to contact and actions to be taken given the forecasted water surface elevations.

The HEC developed the FWRS software using ArcGIS 8.x. The functionality of the FWRS is based on the user entering river stages at any of the four stream gages located within the project area. A known or forecasted stage at one or more of the gage locations produces the appropriate flood inundation layer as a depth grid. Inundation depth grids, flood impact response tables, and flood damage tables are produced from the input stage. Using the depth grid and underlying base data, determination of extent and depth of flooding as it impacts buildings and transportation systems and expected damage to structures and contents are readily available through the user interface.

# Susquehanna River Flood Warning and Response System

## I. Introduction

The Susquehanna River Flood Warning and Response System was developed by the Hydrologic Engineering Center (HEC) in response to a request by the Corps' Philadelphia District. The district requested assistance in developing a flood warning and preparedness system for a portion of the Susquehanna River.

The main goal of the flood warning system is to provide accurate and timely warnings that maximize response time for emergency management officials and floodplain residents. The flood warning system is a piece of software that runs on top of ArcView GIS. After receiving stage forecasts from the National Weather Service (NWS), the local emergency managers can enter that information into the flood warning system. The software allows the response managers to view the extent of the flooding; the amount of potential damage to a given community associated with that forecasted stage; as well as a response table describing what actions should be taken. Managers can then implement the appropriate flood warning response activities and thus proactively prepare the community for the impending event.

The study area covers about 101 miles of the main stem, as well as about 5 miles of the West Branch of the Susquehanna River. The upstream end of the study is above the town of Wilkes-Barre, at the Luzerne County boundary. The downstream end of the study is below the town of Selinsgrove, at the Snyder and Northumberland County boundaries.

## II. Overview

HEC assisted the Philadelphia District in the development of a Flood Warning and Response System for the local communities of the Wyoming Valley area of the Susquehanna River system. The Hydrologic Engineering Center's (HEC) involvement in developing this system consisted of the following:

A. Performing the hydraulic analysis
B. Developing flood inundation maps
C. Calculating flood damages
D. Developing the Flood Warning System software
E. Writing documentation and performing training

## III. Hydraulic Analysis

### Flow Data Analysis

The hydrologic data for the hydraulics river model was developed in three sets: a historic calibration set, a frequency based calibration set, and a flood mapping set. The historic calibration set contains the 5 major floods with measured historic water surface elevations. The frequency-based set and the flood mapping set were developed from the flow frequency studies at the USGS gage locations and covers from low-flow conditions to beyond the 0.2% chance event (500 year). The calibration sets were used to adjust model parameters to reflect the real system. The flood mapping data set contained 35 profiles that were developed (from the frequency events) to cover the range of expected stages at about 1-foot intervals.

Flows were measured at five USGS gages, four locations along the main stem of the Susquehanna and one location in the West Branch. To get more accurate flow transitions along the ~100 miles of the study area, the changes in flow were distributed between the gages. Usually the frequency studies indicate that the flow increases going downstream, but there were several cases of the lower frequency events that indicated a decrease in flow downstream. Changes in flow were placed at tributaries that have more than 5 square miles of contributing area.

In the cases where flow increased, the flows increase from gage to gage was computed using the incremental addition in contributing area technique. With this method, tributaries with large contributing areas were recognized as the major source of flow between gages. In the few cases where flow decreased downstream, the decrease was linearly spread from gage to gage based on river mile. The tributaries that were used for flow changes are shown below in Table 1 with their contributing areas. Additionally, the total contributing area to that point on the river is shown.

**Table 1.**
**Flow Change Locations and Contributing Area**

| Tributary | Side Facing D.S. | River Mile | Incremental Drainage (sq mi) | Total Contributing Area (sq mi) |
|---|---|---|---|---|
| **West Branch of Susquehanna** | | | | |
| Buffalo Creek | R | 7.73 | 134.00 | 6856.49 |
| **Lewisburg Stream Gage** ~.2 mi downstream Buffalo Creek | | **7.53** | | 6856.49 |
| Limestone Run | R | 6.88 | 8.43 | 6864.92 |
| Chillisquaque Creek | L | 5.01 | 112.00 | 6976.92 |
| Turtle Creek | R | 4.60 | 12.70 | 6989.62 |
| Winfield Creek | R | 3.54 | 5.38 | 6995.00 |
| West Branch of Susquehanna | | 0.00 | | 6995.00 |

| | | | | |
|---|---|---|---|---|
| **Main Branch of Susquehanna** | | | | |
| Sutton Creek | R | 203.30 | 11.50 | 9548.48 |
| Gardener Creek | L | 202.66 | 18.10 | 9566.58 |
| Lackawanna River | L | 198.30 | 348.00 | 9914.58 |
| Abrahams Creek | R | 192.14 | 17.40 | 9931.98 |
| Mill Creek | L | 190.38 | 36.60 | 9968.58 |
| **Wilkes-Barre Stream Gage** downstream of Mill Creek | ~.86 miles | **189.52** | | 9968.58 |
| Toby Creek | R | 187.79 | 36.50 | 10005.08 |
| Solomon Creek | L | 184.62 | 18.20 | 10023.28 |
| Naticoke Creek | L | 183.04 | 7.57 | 10030.85 |
| Newport Creek | L | 181.54 | 14.00 | 10044.85 |
| Harvey Creek | R | 181.02 | 46.30 | 10091.15 |
| Hunlock Creek | R | 178.21 | 32.50 | 10123.65 |
| Shickshinny Creek | R | 172.34 | 35.00 | 10158.65 |
| Little Wapwallopen Creek | L | 168.16 | 39.50 | 10198.15 |
| Wapwallopen Creek | L | 166.64 | 53.20 | 10251.35 |
| Nescopeck Creek | L | 161.14 | 174.00 | 10425.35 |
| Briar Creek | R | 157.92 | 33.00 | 10458.35 |
| Tenmile Run | L | 155.53 | 8.24 | 10466.59 |
| **Bloomsburg Stream Gage** upstream of Neals Run | ~.6 miles | **150.38** | | 10466.59 |
| Fishing Creek | R | 147.45 | 385.00 | 10851.59 |
| Catawissa Creek | L | 145.80 | 153.00 | 11004.59 |
| Roaring Creek | L | 142.36 | 87.30 | 11091.89 |
| Little Roaring Creek | L | 140.88 | 5.98 | 11097.87 |
| Logan Run | L | 138.96 | 8.70 | 11106.57 |
| Sechler Run | R | 136.95 | 7.76 | 11114.33 |
| **Danville Stream Gage** above Mahoning Creek | ~.81 mi | **137.07** | | 11114.33 |
| Mahoning Creek | R | 136.26 | 32.00 | 11146.33 |
| Kipps Run | L | 134.14 | 6.38 | 11152.71 |
| Gravel Run | L | 130.58 | 6.33 | 11159.04 |
| Lithia Springs Creek | R | 127.82 | 8.96 | 11168.00 |
| West Branch Suquehanna River | R | 125.52 | 6995.00 | 18163.00 |
| Shamokin Creek | L | 122.90 | 137.00 | 18300.00 |
| **Sunbury Stream Gage** below Shamokin Creek | ~.82 mi | **122.08** | | 18300.00 |
| Sealholtz Run | L | 120.24 | 7.71 | 18307.71 |
| Hollowing Run | L | 117.22 | 7.71 | 18315.42 |
| Boile Run | L | 116.32 | 5.97 | 18321.39 |
| Penns Creek - Below Selinsgrove | R | 115.79 | 306.00 | 18627.39 |

## HEC-GeoRAS Pre-Processing

Before the water surface profiles could be generated, the terrain data had to be processed. The HEC-GeoRAS software, a pre and post processor for the HEC-RAS hydraulic/water surface profile program, was used to extract cross-section data from the terrain model supplied by the district. The terrain model provided by the district office was updated to include the new levee modifications. Plan view lines were created to match the centerlines of the levees from the AutoCAD design drawings and the elevations were added to make three-dimensional shape files. These shapes where then added to the ground surface TIN originally produced by the Philadelphia District.

The hydraulics model started with the creation of the stream network system. In the 101 miles of the Susquehanna River modeled, long islands braided numerous sections. In high flows, many of the islands are totally submerged, so it was decided to model most of these sections with normal cross sections that span both "channels" around the islands. Cross section cut lines were laid out on about a 400 foot spacing, extending to the possible flooding limits on either side of the river. Preliminary bank stations were estimated from contour lines and the orthophotos. Land use regions were developed from the photos and converted by a look-up table to Manning's n values (see Table 2). The vertical elevations for the cross section were retrieved from the terrain model and all the data was exported into the hydraulics model.

## Hydraulic Model Development

<u>Geometric Data</u>

The GIS data, developed in HEC-GeoRAS, were imported into HEC-RAS, the bridges were added, and various flow events were tested with preliminary Manning's n values. For low flows, 10 % chance events and smaller, it was not possible to match any of the stages at the gages, even with very low Manning's n values. The profiles suggested that the problems in calibration were due to errors in the channel geometry.

The terrain model was developed from two data sources: an aerial survey that covered the overbank areas, and a hydrographic survey of the submerged channel. The hydrographic survey recorded cross sections approximately at one mile intervals. The channel between the surveyed cross-sections was interpolated using the "Channel" program developed by the Philadelphia District's GIS section. Some problems were encountered with the resulting channel in the transitions around the numerous islands in the main branch of the Susquehanna River. The Channel program was not developed to handle islands and more research needs to be directed at this problem.

To gain insight into the problem, a polygon of the dry land as depicted at the time of the aerial survey was developed in the GIS using the orthophotos of the system. The polygon was developed by using the ineffective area layer within HEC-GeoRAS to simulate the bounds of the wetted cross section. The polygons were then imported into the HEC-RAS model. The vertical lines, marking the simulated ineffective flow regions, bound the wetted channel as portrayed in the aerial pictures. Theses lines also represent the limit of the two data sources: outside the simulated ineffective lines, the data is from the aerial survey; and between the lines, the data is from the channel interpolation.

Many cross sections did not have a channel between the simulated ineffective areas, indicating that the channel interpolation was deficient in these sections. An example of a cross section with poor channel data is shown in Figure 1.

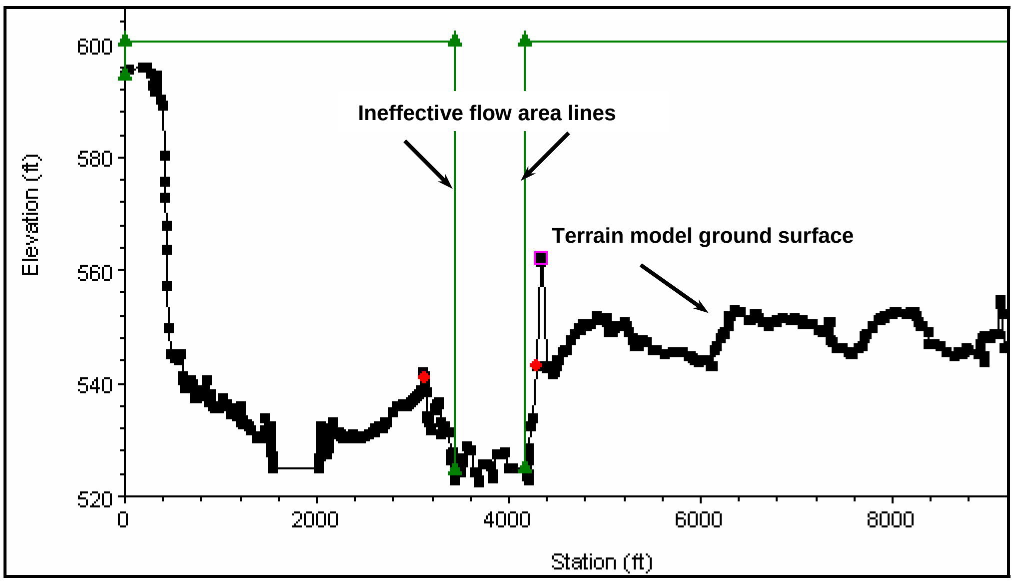



**Figure 1. Cross section with ineffective flow area lines indicating low flow channel. NOTE: The ineffective flow area lines were only used as markers between dry land and the channel surface at the time of the aerial survey.**

This problem generally occurred in the island sections, but it was also present between some of the hydrographic survey sections where the thalweg moved from one side of the channel to the other. Using the edge of the water surface at a section as a marker, the cross sections were graphically edited in HEC-RAS to have a channel that transitioned from an acceptable cross section upstream to an acceptable cross section downstream. Figure 2 shows the same cross section as Figure 1, with the modified channel. This procedure obviously required a lot of engineering judgment.

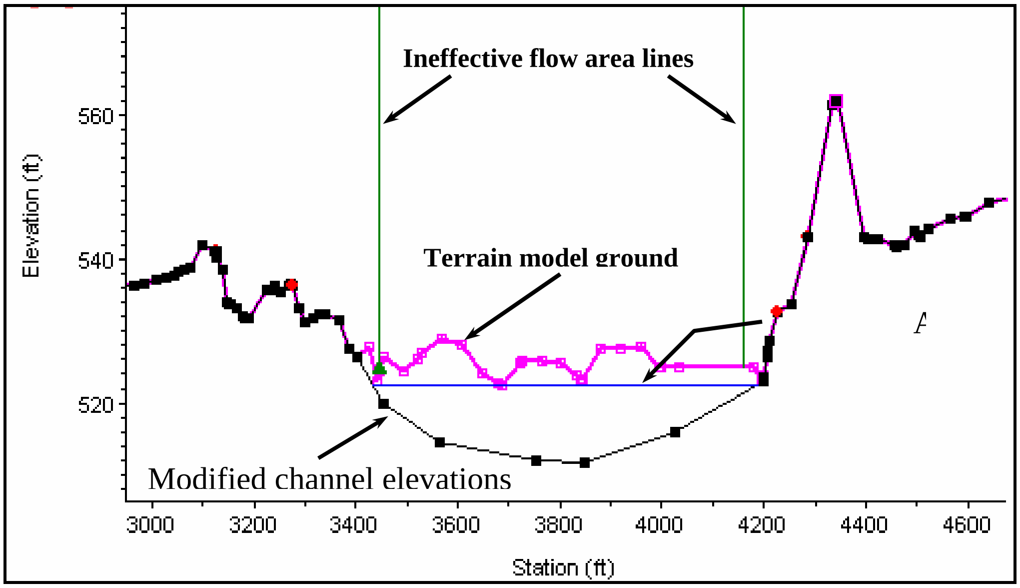



**Figure 2. Cross section with modified channel.**

After the cross sections were modified using HEC-RAS, the channel forming (2.5 year discharge) water surface profile was computed. This profile was used as a reference for setting the main channel bank stations.

Manning's n Values

The initial Manning's n data was set from within the GIS using land use coverage and a lookup table in HEC-GeoRAS. With this capability HEC-GeoRAS reads the land use coverage and then automatically associates a Manning's n value with a land use along the cross section. In fact one cross-section can cross multiple land uses and thus have multiple Manning's n values. Later, these values were imported into the HEC-RAS model. The following table shows the initial estimated Manning's n values for the various types of land use in the study area. The Manning's n values were selected from past modeling experience and from the USGS Water Supply Paper 1849, Roughness Characteristics of Natural Channels.

**Table 2.**
**Manning's n Values for Different Land Use**

| Land Use | Manning's n Value |
|---|---|
| River Channel | 0.030 |
| City Area | 0.120 |
| Open and Farmed Fields | 0.050 |
| Forests | 0.065 |
| Ponds | 0.030 |

The sample of the land use coverage shown in Figure 3 is the confluence of the main stem of the Susquehanna and its West Branch.

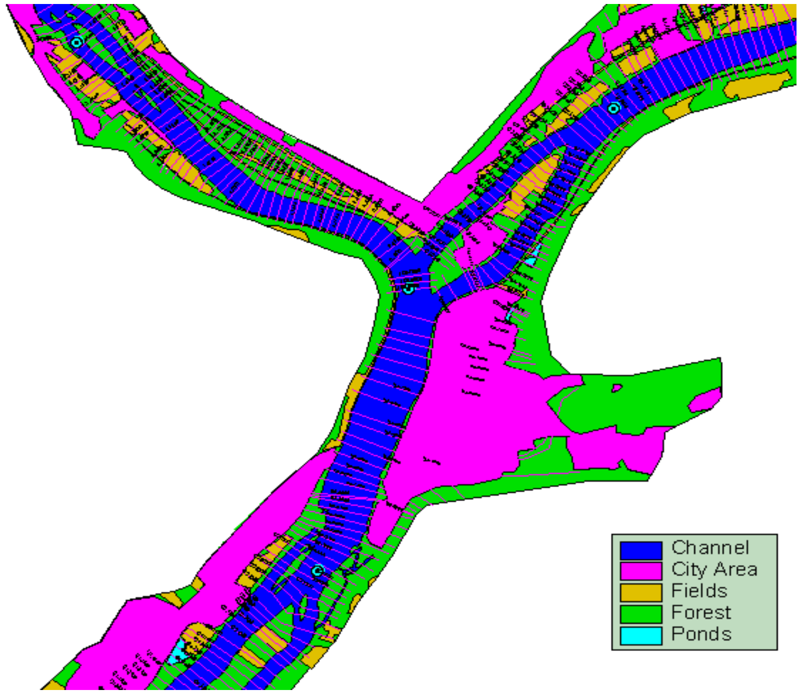



**Figure 3. Sample Land Use Coverage**

The imported Manning's n values were adjusted in the calibration process to match observed stages at gages and high water marks.

In addition to the horizontal variation, the flow roughness was further adjusted by flow, with the "Flow Roughness Change" option in HEC-RAS. For example, the cross sections on the main stem of the Susquehanna from river mile 205.877 to 198.887 were adjusted as shown in Table 3 below. Table 3 is not complete, but shows the transition where Manning's n (roughness) were reduced by 7% for flows below 175000 cfs and then transition to a 10% increase over the base values for larger flows.

**Table 3.**
**Example of Manning's n Versus Flow**

| Flow | Roughness Factor |
|---|---|
| 150000 | 0.93 |
| 175000 | 0.93 |
| 200000 | 0.98 |
| 225000 | 1.00 |
| 250000 | 1.02 |
| 275000 | 1.02 |
| 300000 | 1.02 |
| 325000 | 1.10 |
| 350000 | 1.10 |

Ineffective Areas

Ineffective areas in the HEC-RAS model are regions that fill with water but do not actively convey it downstream. Typical locations for an ineffective region are at the contraction and expansion of flow through a bridge. The ineffective flow regions were primarily developed from within HEC-GeoRAS and then imported into HEC-RAS. The contraction typically happens at a ratio of 1:1, meaning the flow narrows at about a 45$^{o}$ angle to the opening. The expansion happens over a longer distance, typically around a ratio of 2:1, or two steps downstream for each side step. Ineffective polygon regions were created in the HEC-GeoRAS software. The intersection of the cross sections with these polygons determined the ineffective area positions in the hydraulics model. An example of the polygon layout from the HEC-GeoRAS software is shown in Figure 4.

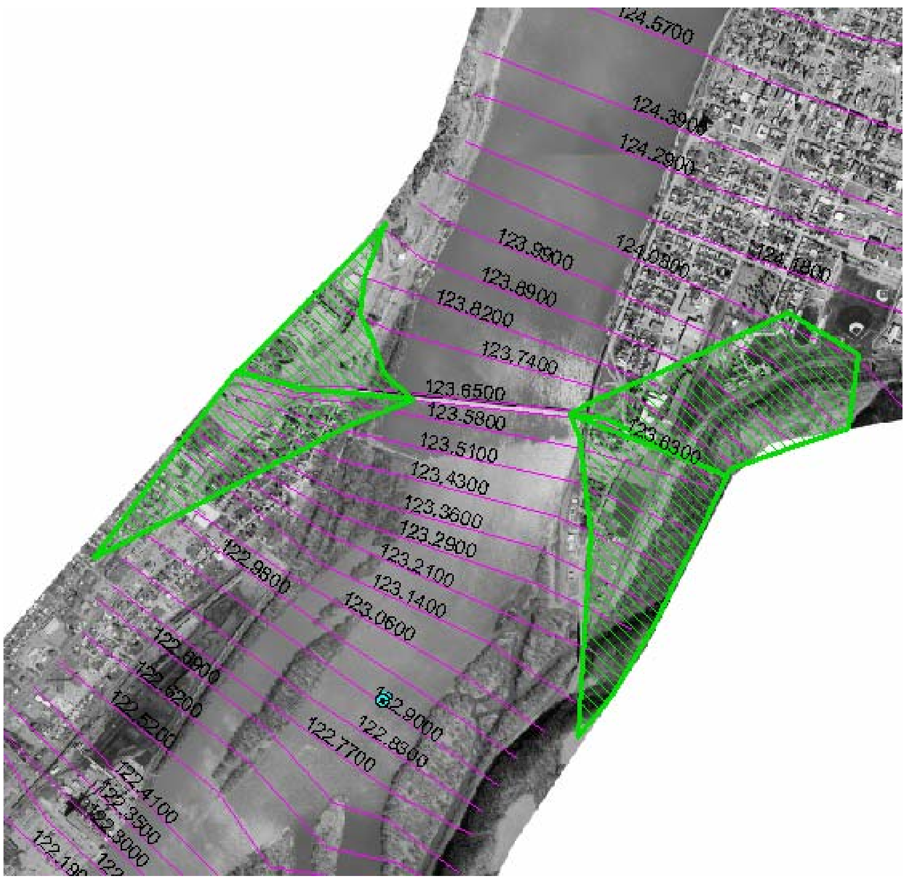



**Figure 4. Ineffective Area Polygon Layout in HEC-GeoRAS**

Levees

Locations and elevations of levees were determined from several data sources. CAD files developed by the Baltimore District for the levee improvement projects were used to create a modified TIN surface model of the system. These levee data layers were used with HEC-GeoRAS to position the levee markers for the hydraulics model. In addition to the CAD files, aerial photography and information from the site visit was used to position the rest of the levees. This information was then imported into the HEC-RAS model.

Bridge Data

Thirty one highway and railroad bridges were modeled. The HEC-RAS hydraulic computation methodology used for all of these structures was the energy method. The energy method accounts for losses with two components, friction losses (bed roughness/Manning's n) and contraction/expansion losses. The area of the bridge deck, roadway, and piers are subtracted out from the active flow area, and additional wetted perimeter is accounted for due to the edges of these features. In general, because the bridges are not a tremendous blockage of area to the flow, the energy method is the best selection for calculating the hydraulics through the bridges.

*Highway Bridges*
Detailed construction plans, or as-built plans received from the Philadelphia District, were used to develop the model representation of these structures. The required information for the bridge energy method is the top-of-road profile, the low chord of the bridge opening, bridge abutments, and pier widths and stationing.

*Railroad Bridges*
Most of the railroad bridges did not have detailed survey or construction information. The geometry for these structures was estimated from the few railroad bridges that had available plans. The elevations for the start and end were determined from the terrain model and the location and size of piers was determined from aerial photography and pictures taken during the site visit. The main concern with the approximate geometry of the railroad bridges is elevation of the low chord. When water starts impacting the low cord of a bridge, there is a significant increase in the head loss through the structure. The model was successfully calibrated to several observed events and to the expected stage at the USGS gages for the mapping events. The calibration gave us confidence in our estimated geometry for these railroad bridges.

**Calibration of HEC-RAS to Historic Events**

The HEC-RAS model was calibrated to five historic events and eight frequency based events. Once the model was calibrated, it was tested on a few of the events that were not used in the calibration process in order to evaluate its accuracy. The principal high flow event used for calibration was the 1972 event, Hurricane Agnes. The Agnes event was the flood of record with a return period of 200-500 years depending on the location of the river. This event caused widespread flooding. Various county and federal agencies recorded water depths and flooding extents. Since 1972, the geometry of the system has changed by the recent levee improvements, the addition of a few automobile bridges, and the removal of a few derelict train bridges. The calibration of the model to the Agnes event was done using the geometry with the bridges and levees based on the 1972 data. While the best observed data was for the 1972 event, the model was also calibrated for the 1975, 1993, 1994, and 1995 peaks.

Further calibration was performed with eight frequency-based events that covered the range from the 2 year (50 % chance) to the 500 year (0.2 % Chance) event. The models were refined to match the rating curves at the gages for the frequency-based events. The model adjustments were made by using the flow versus roughness factors option within HEC-RAS. This option allows the user to specify a range of cross sections in which a set of factors are used to change the roughness based on the flow rate.

The geometry with the calibrated parameters was used to make a current geometry with improved levees, new highway bridges, and a few less train bridges. The current geometry was used to generate the flood warning system profiles and inundation maps.

A comparison of gaged or measured stages verses the computed stage are shown in the next two tables. The “Gaged” stages for the frequency based events are based on extracting the stage from the gaged rating for the frequency based flow.

## Table 4. Historic Events Calibration

| Gage | Historic Event | Flow (cfs) (cfs) | Observed WS (ft) | Computed WS (ft) |
|---|---|---|---|---|
| | 1972 Agnes | 345000 | 552.5 | 552.8 |
| | 1975 | 227000 | 545.9 | 545.7 |
| **Wilkes-Barre Gage** | 1993 | 185000 | 541.0 | 541.1 |
| | 1994 | 148000 | 537.0 | 537.4 |
| | 1996 | 221000 | 545.0 | 544.8 |
| | 1972 Agnes | 352824 | 485.0 | 485.7 |
| | 1975 | 240000 | 479.0 | 479.4 |
| **Bloomsburg Gage** | 1993 | 186000 | 474.0 | 474.8 |
| | 1994 | 142000 | 471.0 | 471.2 |
| | 1996 | 213000 | 477.0 | 476.7 |
| | 1972 Agnes | 363000 | 466.0 | 465.7 |
| | 1975 | 258000 | 460.0 | 459.7 |
| **Danville Gage** | 1993 | 188000 | 455.0 | 455.1 |
| | 1994 | 139000 | 451.0 | 451.6 |
| | 1996 | 210000 | 457.0 | 456.9 |
| | 1972 Agnes | 620000 | 445.0 | 445.1 |
| | 1975 | 439000 | 439.5 | 439.5 |
| **Sunbury Gage** | 1993 | 333000 | 436.0 | 435.9 |
| | 1994 | 257000 | 433.0 | 432.9 |
| | 1996 | 424000 | 439.0 | 439.0 |

**Table Notes:**

1972 Event uses "old geometry"
Other Events use "current geometry"

All observed water surfaces from rating curve and rounded to nearest ft, except Observed WS to 1 decimal place taken from recorded values.

Bloomsburg gage is suspect beyond 200,000 cfs

**Table 5.  Frequency Based Events Calibration**

| Gage | Frequency Event | Flow (cfs) (cfs) | Gage Reading (ft) | Computed WS (ft) |
|---|---|---|---|---|
| Wilkes-Barre Gage | 2 Year | 110000 | 533.4 | 533.4 |
| | 5 Year | 142000 | 536.0 | 537.1 |
| | 10 Year | 167000 | 539.0 | 539.4 |
| | 25 Year | 200000 | 543.0 | 543.1 |
| | 50 Year | 226000 | 545.8 | 545.9 |
| | 100 Year | 256000 | 549.0 | 548.8 |
| | 200 Year | 282000 | 551.2 | 551.4 |
| | 500 Year | 333000 | 555.9 | 555.9 |
| Bloomsburg Gage | 2 Year | 112471 | 468.4 | 468.7 |
| | 5 Year | 154200 | 471.6 | 472.4 |
| | 10 Year | 176300 | 473.5 | 474.3 |
| | 25 Year | 209900 | 476.5 | 476.9 |
| | 50 Year | 246300 | 479.4 | 479.5 |
| | 100 Year | 277800 | 481.4 | 481.5 |
| | 200 Year | 330400 | 484.4 | 484.8 |
| | 500 Year | 378000 | 487.4 | 487.7 |
| Danville Gage | 2 Year | 115644 | 449.9 | 449.5 |
| | 5 Year | 158000 | 452.5 | 453.0 |
| | 10 Year | 185000 | 454.6 | 454.9 |
| | 25 Year | 220000 | 457.2 | 457.3 |
| | 50 Year | 255000 | 459.7 | 459.7 |
| | 100 Year | 285000 | 461.6 | 461.8 |
| | 200 Year | 345400 | 465.0 | 465.1 |
| | 500 Year | 394000 | 468.3 | 468.5 |
| Sunbury Gage | 2 Year | 192280 | 430.4 | 429.6 |
| | 5 Year | 255000 | 432.4 | 432.8 |
| | 10 Year | 305000 | 434.5 | 434.8 |
| | 25 Year | 375000 | 437.2 | 437.4 |
| | 50 Year | 435000 | 439.3 | 439.4 |
| | 100 Year | 505000 | 441.7 | 441.8 |
| | 200 Year | 585300 | 444.2 | 444.1 |
| | 500 Year | 701000 | 447.7 | 447.5 |

Plots of the historic calibration profiles for the Wilkes-Barre area are show in Figures 5 and 6.  Note that there are high water mark elevations for the Agnes event, and that these were scattered.  The final calibration was a balance of matching at the gage points and the observed high water marks for the Agnes event, with more weight being given to the gage locations.

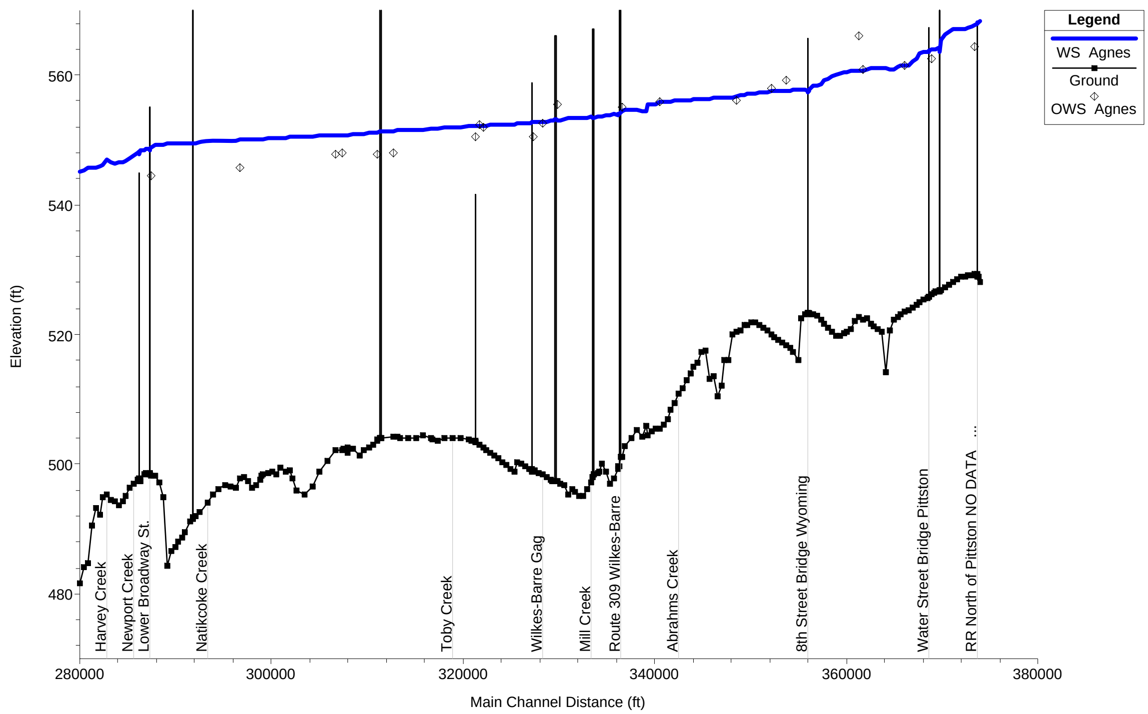



**Figure 5. Profile plot of the Agnes (1972) flood in Wilkes-Barre**

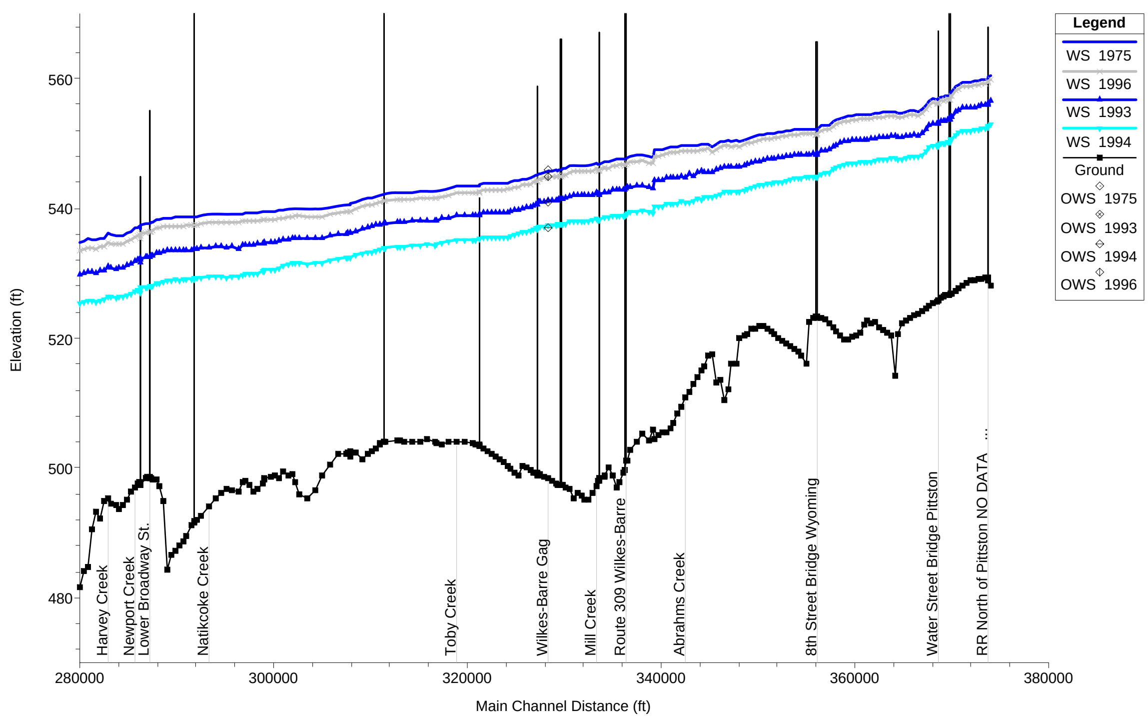



**Figure 6. Profile plot of the 1975, 1993, 1994 and 1996 events in Wilkes-Barre**

### Computing Multiple Profiles for Floodplain Mapping

Once the HEC-RAS model was calibrated and tested, 35 profiles from low flow to beyond the 500 year (0.2 % chance) event were run (the profiles above the 500 year event were computed as 110% and 120% of the 500 year flow). The flows for this set were developed so that the difference in stage would be approximately one foot. The resulting profiles were evaluated closely to ensure that the water surfaces were reasonable and hydraulically accurate. The results from these profiles were exported from HEC-RAS through the HEC GIS file format for use in the HEC-GeoRAS program.

### Evaluation of Ice and Ice-Jam effects

The original proposal called for an analysis of potential ice jam effects on the water surface profiles. In order to perform such an analysis, detailed information about historic ice jams was needed to make a reasonable engineering estimate of potential ice effects. The Philadelphia District provided us with information gathered on historic ice jams. The information consisted of the date and location of the ice jam, and occasionally a comment about increases in the water surface due to the ice jam. However, the information did not include the extent of the ice jam upstream from the blockage, or any information as to the thickness of the ice jams. In order to make a reasonable estimate of the effects of ice on increased stages in the river, the HEC-RAS model requires the user to enter ice thicknesses and extents. Unfortunately, without this information, we were not able to include the effects of ice on the water profiles.

## IV. Developing Flood Inundation Maps

The HEC-RAS computed water surface profiles for 35 equally spaced events were imported into HEC-GeoRAS and processed to create flood inundation maps. The water surface profiles were processed using HEC-GeoRAS to generate an atlas of floodplain boundary maps and depth grids.

### Process HEC-RAS Results

Initial floodplain boundary maps were developed in HEC-GeoRAS and visually compared with floodplain geometry. Obvious errors in floodplain delineation due to incorrectly modeled geometry were corrected in HEC-RAS. Profiles were then recalculated, exported, and processed by HEC-GeoRAS. After completing the geometric modifications in HEC-RAS to produce appropriate delineations (such as adjusting levees to overtop together or changing the cross-sectional layout), the final results were exported back to HEC-GeoRAS.

The final results were imported to the GIS and then processed using HEC-GeoRAS. A few improper floodplain delineations were still apparent. The final flood inundation results were developed by modifying the bounding polygon to properly account for the appropriate amount of inundation. The greatest uncertainty in floodplain delineation lies with the extreme flood events that overtop levees where small channels, ridges, culverts, curbs, and gutters usually control flow. Figure 7 shows an example flood depth grid computed for one of the larger events.

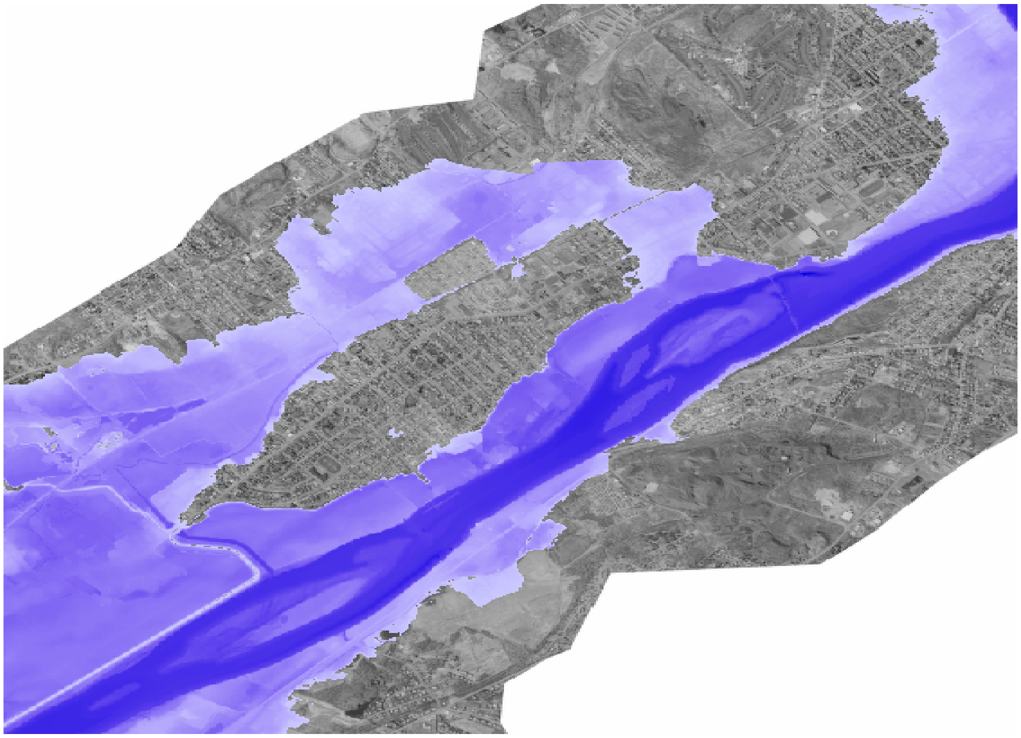


**Figure 7. Example Flood Depth Grid for an Extreme Flood Event.**

**Creating Final Flood Inundation Maps**

Final depth grids and floodplain boundary maps were developed. A few isolated pockets of inundation and suspect areas were found, but not removed from the final inundation results. These edits were not performed due to the inability to account for the intricate floodplain micro-topography. Further, these areas will give forecast personnel a conservative forecast where local floodplain knowledge may be applied in real time.

Delineation of floodplain boundaries along tributaries was done in a conservative manner. The tributaries to the main river were not modeled within the hydraulic model, only their contributing flows were accounted for. The inundation that occurs at small tributaries due to backwater conditions from the main stem Susquehanna River was not calculated for the floodplain delineation. Instead, water surface elevations calculated from cross sections spanning the main stem and tributary were used.

## V. Flood Damage Calculations

The objective of this portion of the project was for HEC to develop an urban flood damage calculation system that could be accessed through the flood warning software. The flood damage calculation system computes damages to single or groups of structures, predefined impact areas, or counties for a given event. This section describes how the damage calculation data were originally developed, and then how the process was revised to enable easier updates to the damage values.

### Initial Flood Damage Computation Procedure

As originally stated in the scope of work, HEC used two programs to develop damage information along the Susquehanna River. First, using individual structure data, the HEC Flood Damage Analysis program (HEC-FDA) was used to develop stage vs. damage functions for impact areas (damage reaches) along the river. Then, the HEC Flood Impact Analysis program (HEC-FIA) was used to compute damage in those impact areas for each of the inundation maps in the set of inundation maps that were developed in the previous section.

As called for in the scope of work, the Philadelphia District provided the following information to HEC:

- The percent damage vs. stage curves for the structure occupancy types to be used.

    The District provided the FEMA percent damage vs. depth relationships shown in Appendix A.

- Impact response tables from the local communities.

    The District did not provide impact response tables. They intend to use the flood inundation maps developed from this study to help create the impact response tables at a later date. These tables may then be entered into the flood warning and response system.

- Demographics:

    While it was originally thought that the entire structure inventory would be used in this study, only a limited number of the structures provided by the district had enough data associated with them to be useful.

    The district provided an inventory of structures that are in the floodplain. This inventory included 4845 habitable and non-habitable structures. This inventory contained elevation information for each structure as well as a structure damage type and content damage type that matched the damage categories listed in the FEMA percent damage vs. stage curves described above.

The district also provided tax assessor records from Luzerne, Northumberland, Columbia, and Snyder counties. These records described a total of 1330 individual structures. The records cross-reference the structure inventory that the District provided. Since structure values were not available for the other 3515 structures contained in the structure inventory, all damage computations are based on the 1330 structures identified in the county tax assessor records. The information in the tax assessor records that was used to develop input to HEC-FDA included:

Structure value
State plane coordinates
Owner name
Structure address

## HEC Data Acquisitions and Development

HEC worked with the Philadelphia District and the local sponsor to identify 56 impact areas (damage reaches) in the study area. An impact area is a distinct portion of a watershed that is affected by the rising stage in a stream, river, lake, or reservoir. The impact area delineations are based on a list of areas that the district wanted to use, and a shapefile that the district provided containing boundaries for local municipalities in the area. Using ArcView capabilities, HEC overlaid the boundary shapefile on top of a USGS map of the area and edited the boundary shapefile so that all the desired areas were included with proper boundaries.

Table 6 lists the names of the impact areas used in this study and shows the maximum potential damage in that impact area (this damage is based on calculation using an event equal to 1.2 * 500-yr event, which is the largest event modeled for this project). Structure information was incomplete or not provided for the impact areas that show zero potential damage. A map of the impact areas is contained in Appendix B.

**Table 6.**

**Susquehanna River Impact Areas**

| Impact Area | Potential damage* | Impact Area | Potential damage* |
|---|---|---|---|
| Berwick Borough | $18,387 | Nanticoke City | |
| Bloomsburg Town | $6,724,538 | Newport Township | |
| Briar Creek Borough | | Northumberland Borough | $38,756 |
| Catawissa Borough | $340,648 | Penn Township | $47,596 |
| Catawissa Township | | Plains Township | $273,933 |
| Chapman Township | | Plymouth Borough | $22,111 |
| City of Sunbury | | Plymouth Township | $643,768 |
| Conyngham Township | $443,730 | Point Township | |
| Cooper Township | | Pringle Borough | |
| Danville Borough | | Ransom Township | |
| Duryea Borough | | Riverside Borough | |
| Edwardsville Borough | | Rush Township | |
| Exeter Borough | $1,681,863 | Salem Township | $103,511 |
| Exeter Township | | Scott Township | $3,374,530 |
| Forty Fort Borough | $262,486 | Selinsgrove Borough | $1,297,360 |
| Franklin Township | | Shamokin Dam Borough | $176,725 |
| Hanover Township | | Shickshinny Borough | $1,130,926 |
| Hunlock Township | $62,183 | South Centre Township | $6,555,497 |
| Jenkins Township | $1,140,381 | Swoyersville | |
| Kingston Borough | | Union Twp (Luzerne) | |
| Larksville Borough | | Union Twp (Snyder) | |
| Lower Mahanoy Twnsp | | Union Twp (Union) | |
| Luzerne Borough | | Upper Augusta Township | $631,784 |
| Mahoning Township | | West Pittston Borough | $4,692,196 |
| Mayberry Township | | West Wyoming Borough | $397 |
| Mifflin Township | | Wilkes-Barre City | $13,105 |
| Monroe Township | $503,312 | Wyoming Borough | $5,999 |
| Montour Township | $576,651 | Nanticoke City | |

***** Maximum damage potential based on an estimate using 1.2 times the 500 yr event.

Table 7 lists the data required by HEC-FDA for each individual structure in order to compute stage vs. damage relationships for a damage reach. Also shown in Table 7 is a description of where that data came from for this study.

**Table 7.**

**HEC-FDA Data Requirements**

| Data | Description |
|---|---|
| Structure name | Individual structure ID. A unique numerical ID for each structure was in the structure inventory provided by the district. The tax assessor records contained matching ID's so the information was easily cross-referenced. |
| Category name | The damage category for the structure. There were only two damage categories for structures in this study: residential and commercial. All structures were assumed to be residential unless their content type was listed as commercial in the structure inventory provided by the district. |
| Stream name | All structures that we obtained complete data for were along the Susquehanna River. |
| Occupancy name | Occupancy code. This code signifies the type of structure. All the structures in this study were either one story without basement, one or two story with basement, split level with basement, or split level without basement. The occupancy code information was provided by the district in the structure inventory. |
| Station | The station along the river that specifies the location of the structure. Stream stations were computed for each structure using a structure polygon coverage provided by the district and the stream stationing coverage developed at HEC. |
| Bank | The bank of the river (looking down stream) on which the structure is located. This was manually input by looking at the structure inventory coverage overlaid on the stream coverage. |
| Structure value | The depreciated replacement value of a structure. This value represents the actual cost of replacing the structure. The tax assessor records provided by the district contained data that we used to develop these values. |
| Content value | The value of the contents contained in each structure. No information was provided. Content value was set to 50% of structure value. |
| Ground elevation | The elevation of the ground at each structure. This information was in the structure inventory provided by the District. |
| Foundation height | The distance from the ground to the first floor. This information was in the structure inventory provided by the District. HEC-FDA uses this along with ground elevation to compute first floor elevations. |
| Owner | The name of the owner of each structure. This information was in the county tax assessor records provided by the district. |
| Address | The address of each structure. This information was in the county tax assessor records provided by the district. |
| State plane coordinates | The state plane coordinates of each structure. This information was in the county tax assessor records provided by the district. |

HEC-FDA Model

HEC-FDA was used to compute stage versus damage functions throughout the study area. Using the output tables from HEC-RAS, eight water surface profiles were imported into HEC-FDA. The profiles included a range of frequencies from the 0.999 to the .002 exceedence probability event. The demographic data supplied by the District were also imported into HEC-FDA. HEC-FDA was run and results consisted of separate stage vs. damage functions by category (residential and commercial) for each of the impact areas.

HEC-FDA computes stage vs. damage functions for an impact area by stepping through each structure and computing the damage to that structure for each frequency event. Then aggregating the damage over the range of frequency events for all structures in an impact area. Damage to a structure for an event is computed by first finding the water elevation from the nearest cross-section for that event, then using that and the first floor elevation of the structure to compute depth of flooding at the structure. Next, the % damage to the structure and contents is picked off the depth vs. percent damage function for the structure type (FEMA depth vs. % damage in this case). The % damage to structure and content is then multiplied by the structure value and content value to give the total damage to that structure for that event.

HEC-FIA Model

An HEC-FIA model was setup and populated for the Susquehanna River study area. HEC-FIA computes event damage based on a hydrograph at a given location. In this study, each of the 35 HEC-RAS water surface profiles were converted into a peak stage hydrograph. The peak stages are then compared to the stage vs. damage functions to compute the damage in an impact area for the given event.

The impact area shapefile and aggregated stage vs. damage functions developed by HEC-FDA for each impact area were imported into HEC-FIA. Using these functions and peak stage hydrographs for each of the HEC-RAS profiles, the damage for each of the profiles was computed. Given that agricultural damages are not going to be computed, the duration and seasonal aspects of the events were not critical to the calculations.

### Modified Flood Damage Computation and Reporting within the GIS

While the damage computations described above fulfill the original requirement of the project, the District and HEC agreed to modify the procedure. Under the new method, all damage computations are coded directly into the flood warning system software. This modification was made mainly because District staff planned to not only complete the original structure inventory they provided to HEC, but also to update it regularly as well. Under the original method for computing flood damage, District staff would be required to run HEC-FDA and HEC-FIA every time the structure inventory in the study area was modified. The new method removes the HEC-FDA and HEC-FIA programs from the process, which makes it easier to update damage computation.

The new method for computing flood damage that is programmed into the flood warning system software computes damage for a forecasted stage by:

1. Determining all the structures that are inundated.
2. Finding the inundation depth at each structure from the depth grid computed by HEC-RAS for that forecasted stage.
3. Finding the % damage to each structure and to their contents from the depth - % damage functions provided by the District and shown in Appendix A.
4. Computing the damage to each structure and its contents by multiplying the % damage to structure by the structure value and the % damage to contents by the content value.

The total damage to each structure is then saved for that event. The user can choose to view those individually or have the software group them by impact area or county.

### Response Activities

The District did not provide response activities information that could be used to develop flood response summary tables. The flood warning system interface was developed to allow for integration of these tables once they are available.

## VI. Flood Warning System Software

The flood warning and response system (FWRS) software is a tool bar that runs in ArcMap (ESRI, 2002). The interface allows the user to enter an observed or forecasted stage or elevation at one or many of the gages along the Susquehanna River. Inundation depth grids, flood impact response tables, and flood damage tables are then produced from the input stage. The user is then able to interactively identify depth and structural damage at specific locations, once a forecast has been made.

## Software Design

The FWRS software was designed at HEC and initially implemented on the ArcView 3.x platform. Because ArcGIS 8.x has become the future standard for GIS software, the final graphical user interface was re-designed for ArcMap 8.x. The final FWRS tools were developed based on the initial scope of tools requested and comments provided to HEC by the Philadelphia District.

The graphical user interface designed in ArcMap was designed to allow a user with limited GIS experience to generate flood forecasts. However, the interface was designed to compliment the GIS by using consistent methods and using existing ArcGIS tools. This design combination results in the most efficient and effective use of the GIS for visualization and query of the geospatial data.

In addition to the GIS tools, a data management structure and methods for delivering the data to the end user was developed. The FWRS relies on practical, efficient, and flexible methods for storing data, allowing user access, and publishing data.

## Development of Software

The FWRS was programmed in Visual Basic as a dynamic link library (DLL). Because the FWRS is a self-contained library of routines, it may be added to any ArcMap project document as the customized tool bar shown in Figure 8. The tool bar then allows access to the FWRS buttons and tools. In addition to the FWRS requiring ArcMap, the user must have Microsoft Excel.

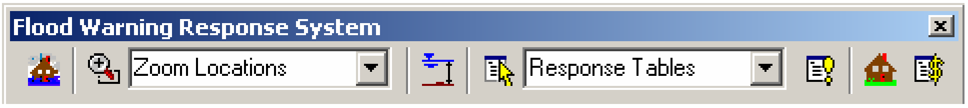



**Figure 8. Flood Warning and Response System Toolbar.**

The main purpose of the FWRS tool bar is to provide forecasters the ability to enter a forecasted river stage at one or more gage locations. Forecasted values are entered in the Flood Warning Response System main dialog shown in Figure 9. Once a forecast is entered the flood inundation boundary maps are automatically plotted. The user has access to flood depths, impact response tables, and flood damage calculations.

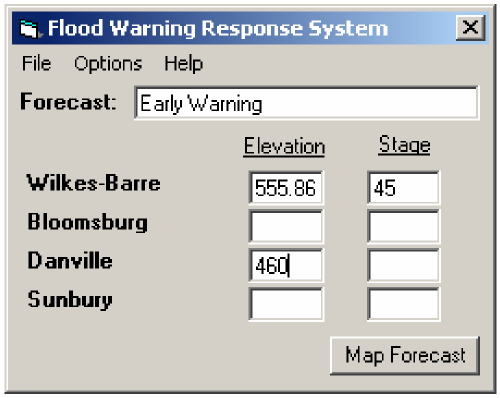



**Figure 9. Flood Warning and Response System Forecast Dialog**.

The FWRS forecast dialog requires several data files to implement the flood warning and response system. These data include: a setup file, GIS data layers, depth grids, and flood impact response tables. A discussion of data required for using the FWRS and the resultant output follows.

Setup File

The initialization file, FWS.xml, is used to set up the parameters for the flood warning and response system. This file establishes user-defined preferences such as the gage names, zoom locations, and constants such as gage datum, river mileage location, and gage abbreviation.

The FWS.xml setup file is written in the extensible markup language (XML) format and is sensitive to structure and case. It may be viewed in a tree structure through an HTML reader that supports XML parsing.

GIS Data Layers

Background GIS will automatically be displayed when a flood is forecasted. The default background data displayed includes an aerial photograph of the system and the location of cities, roads, bridges, and counties boundaries. Users may define additional data sets and the symbols for display by adding the data to the forecast. The settings for these layers may be modified and saved for future forecasts as a ArcGIS layer file.

Depth Grids

Depth grids were developed for the entire Susquehanna River study area. Each large grid spanning the entire area was then broken into four individual grids specific to each gage area. This allows the user to view only the depth grid of interest in their gage-specific area. Further, this allows for increased flexibility in forecasting various stages along the river.

The depth grids are used to query floodplain inundation depths and calculate individual structure damage. Query results are displayed in the dialog shown in

Figure 10. Results show the flood depth, gage used for the depth grid, actual reference flood elevation calculated by HEC-RAS, and elevation forecasted.

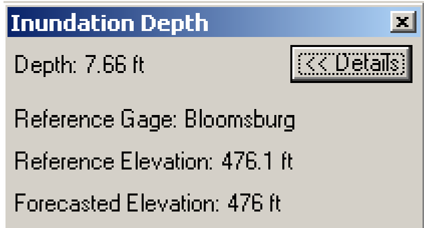



**Figure 10. Flood Depth Identification Dialog.**

Flood Impact Response Tables

Flood impact response tables are stored in an Excel spreadsheet. Each site-specific response table is entered on one Excel worksheet with the flood impact response table workbook. This allows for customization of impact response tables and will be required for each community prior to using the flood warning system. For each flood impact response table there must be the corresponding name and river mile location in the water surface profile table.

In addition to customizing the impact tables for stage and response, the tables may also be customized for font properties. Therefore, actions may be colored by severity for easy recognition to forecasters. When viewing the response table, the forecasted elevation is highlighted for quick reference. An example flood impact response table is shown in Figure 11.

Flood Impact Response Tables

Print ... Copy ...

| | Elevation | Stage | Impact | Response |
|---|---|---|---|---|
| Exeter Borough | 554 | 32 | Main St. Shickshinny Inundated | County Installs Barrier Erie-Lackawanna RR Tracks, Swoyersville |
| | 555 | 33 | Inundation: Mocanaqua | Kingston Installs Stop Logs, Pocono-NE RR Tracks. W-B Installs Barrier at rear of C.H. |
| | 556 | 34 | | Kingston Installs Sandbag Closure, RT. 11 Edwardsville. W-B Installs Enclosure at Market St Bridge |
| | 557 | 35 | Inundation: RT.11 Edwardsville, Dundee Area, Hanover Twp. | |
| | 558 | 36 | Inundation: Nescopeck B. | County Installs Sill, Lehigh Valley RR Tracks, Swoyersville. |
| | 559 | 37 | Levee topped - Inundation W-B | County Installs Sandbag Closure, Wilkern St. Exeter. |
| Wilkes-Barre City | 540 | 31 | Duryea & W. Pittston affected | Hanover Twp. Installs Stop Logs Canadian Pacific RR Tracks Hollenback PK. W-B Mark Plaza EDW. |
| | 541 | 32 | Main St. Shickshinny Inundated | County Installs Barrier Erie-Lackawanna RR Tracks, Swoyersville |
| | 542 | 33 | Inundation: Mocanaqua | Kingston Installs Stop Logs, Pocono-NE RR Tracks. W-B Installs Barrier at rear of C.H. |
| | 543 | 34 | | Kingston Installs Sandbag Closure, RT. 11 Edwardsville. W-B Installs Enclosure at Market St Bridge |
| | 544 | 35 | Inundation: RT.11 Edwardsville, Dundee Area, Hanover Twp. | |
| | 545 | 36 | Inundation: Nescopeck B. | County Installs Sill, Lehigh Valley RR Tracks, Swoyersville. |
| Shickshinny Borough | 519 | 28 | Inundation: Canal St. W. Nanticoke | Close RT. 11 W. Nanticoke |
| | 520 | 29 | Inundation: PP&L Riverlands, River Rd, Por Balanchard, Ws Pittston | Close RT. 11 Shickshinny |
| | 521 | 30 | Inundation: RT.11 Avondale Flooding C.H. Subbasement, Main St. Shickshinny from sewers. | Activate W-B Brookside Flood Protection System |
| | 522 | 31 | Durya & W. Pittston affected | Hanover Twp. Installs Stop Logs Canadian Pacific RR Tracks Hollenback PK. W-B Mark Plaza EDW. |
| | 523 | 32 | Main St. Shickshinny Inundated | County Installs Barrier Erie-Lackawanna RR Tracks, Swoyersville |
| | 524 | 33 | Inundation: Mocanaqua | Kingston Installs Stop Logs, Pocono-NE RR Tracks. W-B Installs Barrier at rear of C.H. |

**Figure 11. Example Summary Flood Impact Response Table.**

Flood Damage Tables

Summary damage tables are available from the FWRS. These computations are performed on the fly using depths computed from the associated forecast. These computations require depth vs. % damage functions for the occupancy types. The summary structure damage table summarizes damages by impact area and county. The table also indicates the number of structures used for damage calculations with the total number of impacted (inundated) structures. Many structures are included in the inventory but do not have structure values. Therefore their damage could not be calculated, but whether they were impacted could. An example flood damage table is shown in Figure 12.

Flood Damage by Structure

Print ... Copy ...

| | # Res. | Res. Damage($) | # Comm. | Comm. Damage($) | # Total | Total Damage($) | # Impacted |
|---|---|---|---|---|---|---|---|
| **Columbia County** | | | | | | | |
| Berwick Borough | 2 | 16482 | 0 | | 2 | 16482 | 28 |
| Bloomsburg Town | 149 | 3102107 | 27 | 2024688 | 176 | 5126801 | 826 |
| Briar Creek Borough | 0 | | 0 | | 0 | | 25 |
| Catawissa Borough | 15 | 243954 | 3 | 74175 | 18 | 318129 | 107 |
| Franklin Township | 0 | | 0 | | 0 | | 19 |
| Mifflin Township | 0 | | 0 | | 0 | | 33 |
| Montour Township | 18 | 350549 | 1 | 24172 | 19 | 374721 | 90 |
| Scott Township | 100 | 2349826 | 4 | 86557 | 104 | 2436383 | 561 |
| South Centre Township | 9 | 133369 | 10 | 6379108 | 19 | 6512477 | 96 |
| Total | 293 | 6196287 | 45 | 8588699 | 338 | 14784990 | 1785 |
| | | | | | | | |
| **Lackawanna County** | | | | | | | |
| Ransom Township | 0 | | 0 | | 0 | | 19 |
| Total | 0 | | 0 | | 0 | | 19 |
| | | | | | | | |
| **Luzerne County** | | | | | | | |
| Conyngham Township | 48 | 319218 | 0 | | 48 | 319218 | 238 |
| Duryea Borough | 0 | | 0 | | 0 | | 32 |
| Edwardsville Borough | 0 | | 0 | | 0 | | 26 |
| Exeter Borough | 19 | 279502 | 2 | 32851 | 21 | 312353 | 178 |

**Figure 12. Flood Damage Table.**

Individual damage calculations may be performed on a selected set of structures. As shown in Figure 13, along with dollar damage, the structure damage tables list name, address, and flood depth properties. Each table provides easy access to print or save the summary results of impacted structures.

Flood Damage by Structure

Print ... Copy ...

| Name | Address | City | Depth (ft) | Damage ($) |
|---|---|---|---|---|
| MCCULLOUGH MAUREEN M | 4 EXETER AVE | E STROUDSBURG | 5.2 | 14215 |
| LOKUTA STEPHEN | WYOMING AVE | DUPONT | 10.1 | 24230 |
| BANOS PETER | 206 WYOMING AVE | WEST PITTSTON | 5.6 | 30236 |
| ELKO STEPHEN B JR ETAL | 212 WYOMING AVE | W PITTSTON | 5.9 | 17064 |
| PAGNOTTI LOUIS III & MARIA | 220 WYOMING AVE | WEST PITTSTON | 1.9 | 16105 |
| REILLY EILEEN A TRUSTEE | 222 WYOMING AVE | W PITTSTON | 2.0 | 13569 |
| ECONOMOPOULOS CHRIS & | 5 EXETER AVE | W PITTSTON | 8.8 | 11171 |
| FERRETTI DOROTHY | 209 WYOMING AVE | DUPONT | 7.6 | 6014 |
| WALSH ANN M | 211-213 WYOMING AVE | W PITTSTON | 5.2 | 19626 |
| MEDICO CHARLES | 215 WYOMING AVE | W PITTSTON | 4.7 | 37473 |
| BLAZOSEK JOSEPH M ETAL | 225-27 WYOMING AVE | W PITTSTON | 3.6 | 23803 |
| BUFALINO GAETANA V & | 221 WYOMING AVE | W PITTSTON | 4.5 | 25300 |
| ADONIZIO PETER J & ALICIA M | 802 SUSQUEHANNA AVE | PITTSTON | 5.9 | 35151 |
| KINGSTON DODGE INC | 303 11 WYOMING AVE | KINGSTON | 3.5 | 57533 |
| CEFALO MICHAEL & ELIZABETH | 301-303 LUZERNE AVE | W PITTSTON | 4.3 | 13460 |
| AGOLINO JOSEPH & | 20 LUZERNE AVE | PLAINS | 7.7 | 18600 |
| CEFALO MICHAEL & ELIZABETH | 311/313 WYOMING AVE | WEST PITTSTON | 2.8 | 16382 |
| JEDDIC MARY ANN | 205 WYOMING AVE | WEST WYOMING | 6.5 | 11170 |

**Figure 13. Flood Damage by Structure.**

### Software Testing

The flood warning and response system software was tested extensively by HEC during development and refinement. The Philadelphia District also tested each version of the software.

## VII. Uncertainty Analysis

Research in the past ten years has developed practical methods for estimating uncertainty in flow, stage, and hydraulic computation forecasts. Several possibilities exist for incorporating results of this research into the forecast system for the Wyoming Valley: tabulating separately or combined uncertainty from NWS flow/stage forecasts and hydraulic model/inundation map output; assigning probabilities to ranges of forecast inundation, developing inundation map products that implicitly display uncertainty, etc. It was proposed that alternative representations of uncertainty be investigated and presented to the District and partners for evaluation and decision.

Within the investigation, several alternative ways of quantifying uncertainty were reviewed. Based on HEC's analysis, the most appropriate methodology for incorporating uncertainty into this system would be to separately list the uncertainty of the National Weather Service forecast and the uncertainty in the inundation mapping results. If the district office decides to include uncertainty into the final product, a cost estimate can be prepared for the district to evaluate the merit of this information

## VIII. Documentation

Two documents were developed for this study. This document represents the project report. The second document is a User's Guide for the flood warning software. The User's Manual contains information on how to use the software, as well as appendices containing the final flood maps and flood damage tables. Additionally, the User's Manual will contain information on how to update the flood inundation maps and flood damage tables if necessary.

# Appendix A

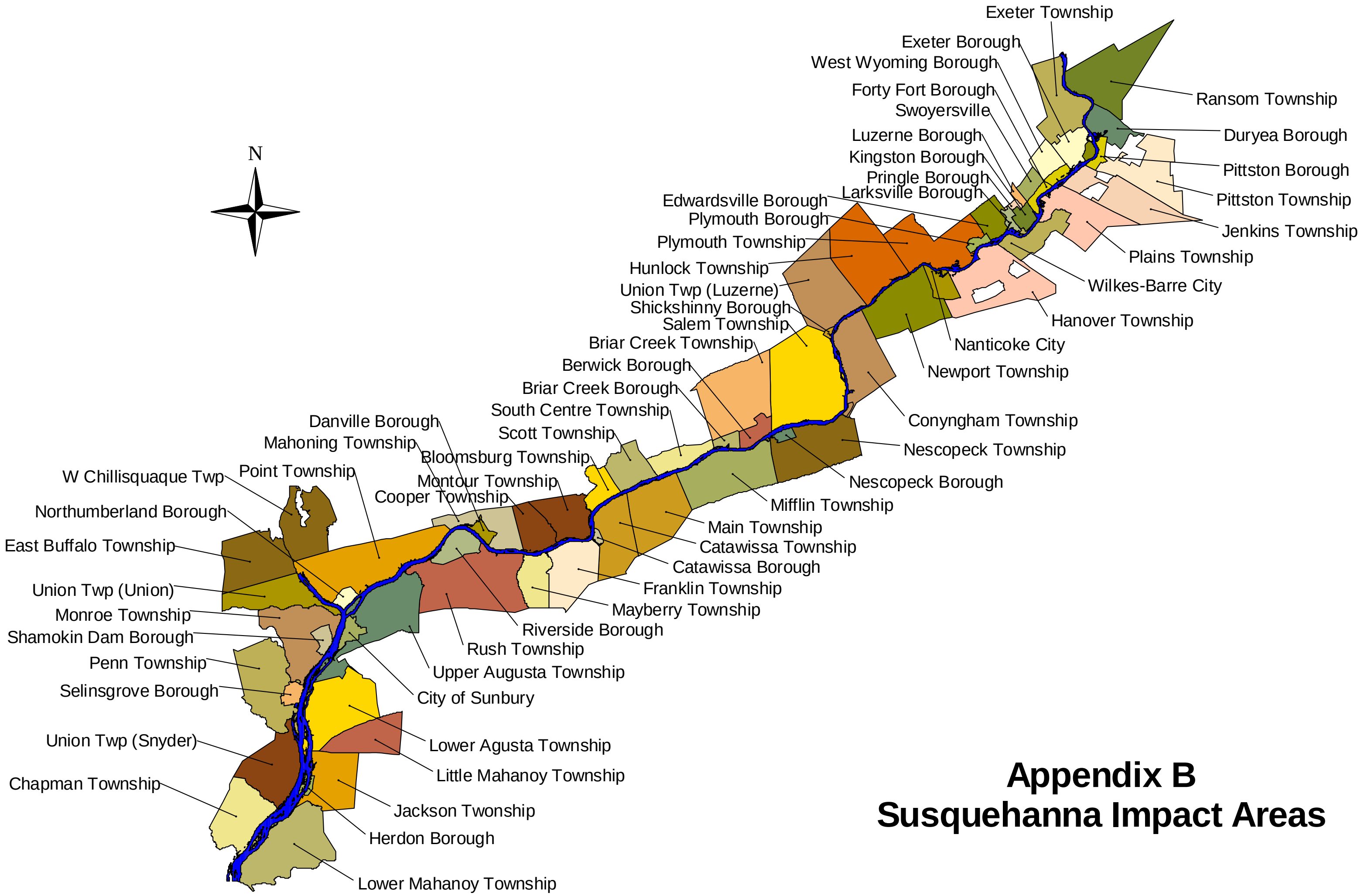
## FEMA Percent Damage vs. Depth Relationships

**Table A1. Percent damage to structure vs. depth of water**

| Structure type | Depth of water in relation to first floor elevation | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 1 Story, w/o Basement | 0 | 0 | 9 | 14 | 22 | 27 | 29 | 30 | 40 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 50 | 50 | 50 | 50 |
| 2 Story w/o Basement | 0 | 0 | 5 | 9 | 13 | 18 | 20 | 22 | 24 | 26 | 29 | 33 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| Split Level w/o Basement | 0 | 0 | 3 | 9 | 13 | 25 | 27 | 28 | 33 | 34 | 41 | 43 | 45 | 46 | 47 | 47 | 47 | 47 | 47 | 47 | 47 |
| 1 or 2 Story with Basement | 4 | 8 | 11 | 15 | 20 | 23 | 28 | 33 | 38 | 44 | 49 | 51 | 53 | 55 | 57 | 59 | 60 | 60 | 60 | 60 | 60 |
| Split Level with Basement | 3 | 5 | 6 | 16 | 19 | 22 | 27 | 32 | 35 | 36 | 44 | 48 | 50 | 52 | 54 | 56 | 58 | 58 | 58 | 58 | 58 |

**Table A2. Percent damage to contents vs. depth of water**

| Structure type | Depth of water in relation to first floor elevation | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -2 | -1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 1 Story, w/o Basement | 0 | 0 | 9 | 14 | 22 | 27 | 29 | 30 | 40 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 50 | 50 | 50 | 50 |
| 2 Story w/o Basement | 0 | 0 | 5 | 9 | 13 | 18 | 20 | 22 | 24 | 26 | 29 | 33 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 | 38 |
| Split Level w/o Basement | 0 | 0 | 3 | 9 | 13 | 25 | 27 | 28 | 33 | 34 | 41 | 43 | 45 | 46 | 47 | 47 | 47 | 47 | 47 | 47 | 47 |
| 1 or 2 Story with Basement | 4 | 8 | 11 | 15 | 20 | 23 | 28 | 33 | 38 | 44 | 49 | 51 | 53 | 55 | 57 | 59 | 60 | 60 | 60 | 60 | 60 |
| Split Level with Basement | 3 | 5 | 6 | 16 | 19 | 22 | 27 | 32 | 35 | 36 | 44 | 48 | 50 | 52 | 54 | 56 | 58 | 58 | 58 | 58 | 58 |
| Comm, indust, etc w/o base | 0 | 0 | 7 | 9 | 17 | 22 | 28 | 33 | 39 | 44 | 50 | 55 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 | 58 |
| Comm, indust, etc w/ base | 7 | 8 | 16 | 20 | 22 | 28 | 33 | 39 | 44 | 50 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 |




# Appendix B
# Susquehanna Impact Areas