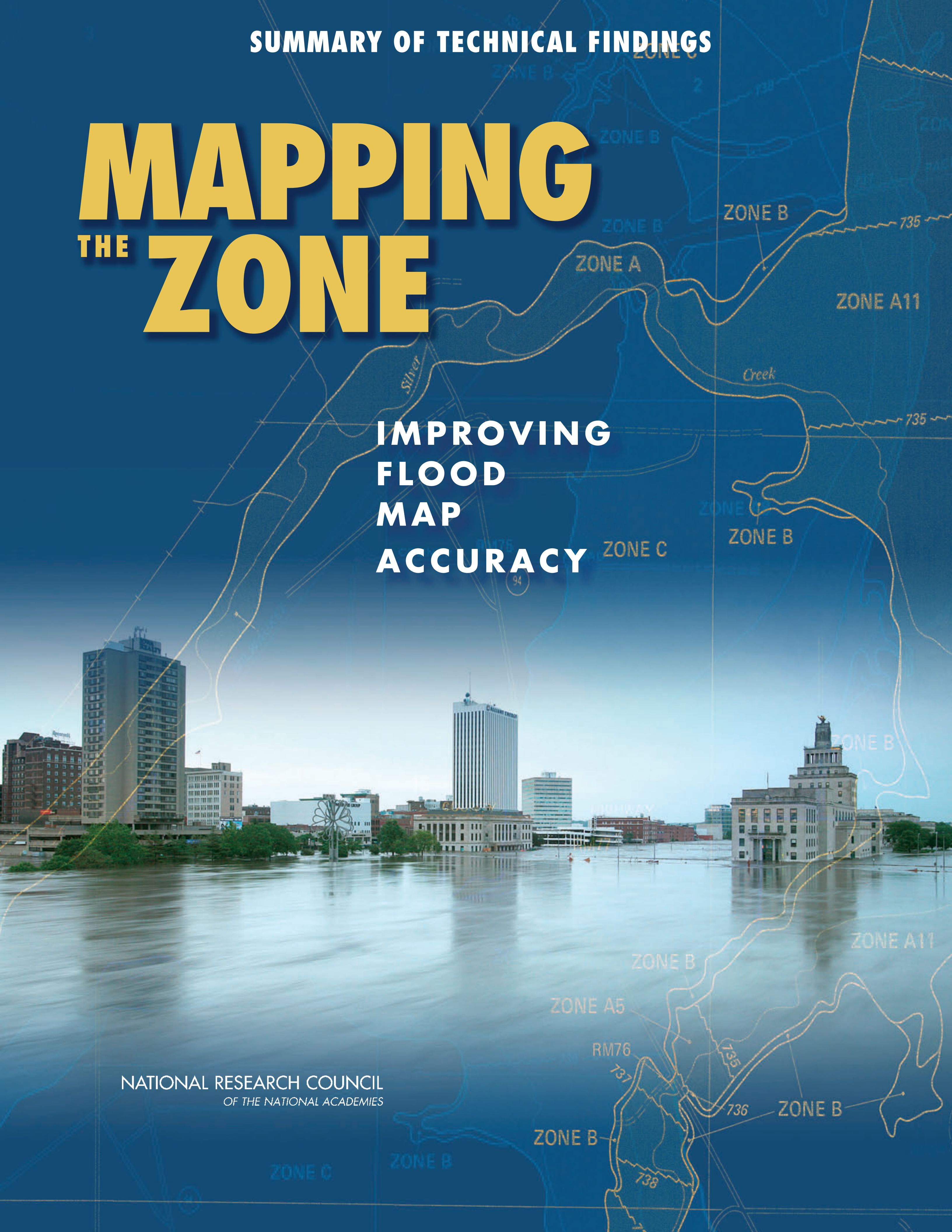
SUMMARY OF TECHNICAL FINDINGS

MAPPING THE ZONE

IMPROVING FLOOD MAP ACCURACY



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ABOUT THIS BOOKLET

This booklet summarizes some of the key technical findings from *Mapping the Zone: Improving Flood Map Accuracy*, a National Academies report released in 2009 that was sponsored by the Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration. The report was produced by an ad hoc committee of experts convened by two units within the Academies: the Board on Earth Sciences and Resources' Mapping Science Committee and the Water Science and Technology Board.

ABOUT THE NATIONAL ACADEMIES

For more than 140 years, the National Academies have been advising the nation on issues of science, technology, and medicine. Created by an 1863 Congressional charter signed by President Lincoln, the organization was to honor top scientists with membership and to serve the nation whenever called upon. Today the National Academies—National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and the National Research Council—continue that dual mission.

Mapping the Zone
IMPROVING FLOOD MAP ACCURACY

Introduction

Flooding is the nation's leading cause of disaster, contributing to nearly two-thirds of all federal disasters and causing approximately $50 billion in property damage in the 1990s. Much of the damage occurs in floodplains—the low, relatively flat areas adjoining inland and coastal waters, including areas subject to a 1 percent or greater chance of flooding in any given year. A house in the 1 percent annual chance (100-year) floodplain has a 26 percent chance of being damaged by flooding at least once during a 30-year mortgage, compared to a 9 percent chance of being damaged by fire. Insurance companies generally consider residential flooding too costly to insure because floods can be widespread and cause catastrophic losses.

The National Flood Insurance Program was established in 1968 to offer federal flood insurance to owners of property in floodplains, provided their communities regulate new development in these areas. The premium that property owners pay is related to their risk of flooding, which is determined by the location of their property on Flood Insurance Rate Maps (FIRMs; hereafter called flood maps) produced by the Federal Emergency Management Agency (FEMA). The accuracy of floodplain boundaries drawn on these maps directly determines how well communities and individuals understand and are insured against their true flood risk.

Making and maintaining an accurate flood map is neither simple nor inexpensive. FEMA's Map Modernization program (2003-2008) was aimed at improving the accuracy of the nation's flood maps and making the maps available in digital form. The $1 billion federal budget for the project, to which many state and local communities contributed additional matching funds, led to the collection or validation of flood data in many areas and the production of more versatile maps. Yet even with this investment, as of March 31, 2008, only 21% of the U.S. population had flood maps that meet or exceed national flood hazard data quality thresholds.

Mapping the Zone: Improving Flood Map Accuracy is the second report undertaken by the National Research Council to examine FEMA flood maps. The first study, *Elevation Data for Floodplain Mapping* (NRC, 2007), assessed the terrain data needed to support flood maps. It concluded that a major source of terrain data, the National Elevation Dataset (NED), is not sufficiently accurate and recommended that a program be established to collect high-accuracy, high-resolution digital terrain data nationwide. *Mapping the Zone* broadens the analysis to other factors that affect flood map accuracy.

Mapping the Zone provides original analyses, mostly carried out in collaboration with the North Carolina Floodplain Mapping Program, that examine the relative role of uncertainties in the hydrology (how much water there will be), hydraulics (how high the water will rise), and terrain (elevation data) inputs to flood maps. The findings provide the analytical basis for gathering high accuracy digital elevation data in regions that still need it, and they reveal new insights about the effects of alternative choices in floodplain mapping and modeling.

About the Analyses

The purpose of a flood study is to predict the height of water and the extent to which it will inundate the landscape in a modeled flood event. The elevation of the land, water, and hydraulic structures (e.g., bridges) are key elements in a flood study, and the accuracy to which these elements are determined is a critical factor in the accuracy of the final flood map. Calculations begin with estimating the *base flood discharge,* the flow of water brought on by a 100-year flood (in cubic feet per second). That is used to estimate the *base flood elevation* (BFE), the height of water in a 100-year flood (in feet). The BFE, combined with *terrain data,* determines the boundaries of the floodplain—the goal of this computational process.

To quantify the effects of uncertainties on flood map accuracy, the authoring committee of *Mapping the Zone* collaborated with the North Carolina Floodplain Mapping Program to conduct case studies of riverine flood mapping in North Carolina and Florida. North Carolina was selected because flood maps developed using high-accuracy lidar elevation data were available for nearly the entire state, enabling comparison of traditional and new data and techniques. The North Carolina studies covered a range of topographies that include the mountainous city of Asheville (Buncombe County), the rolling hills of Mecklenburg County, and the flat coastal plain of Pasquotank and Hertford Counties (Figure 1). Additional studies were conducted in Florida, where the topography is flat and porous with depressions where water can pond.

For the hydrology and hydraulics analysis, the committee distinguished two sources of uncertainty: natural variability and knowledge uncertainty. The inherent variability of nature leads to uncertainty that can never be eliminated. For example, the magnitude of future floods cannot be forecast precisely, no matter how much time, effort, or money is invested

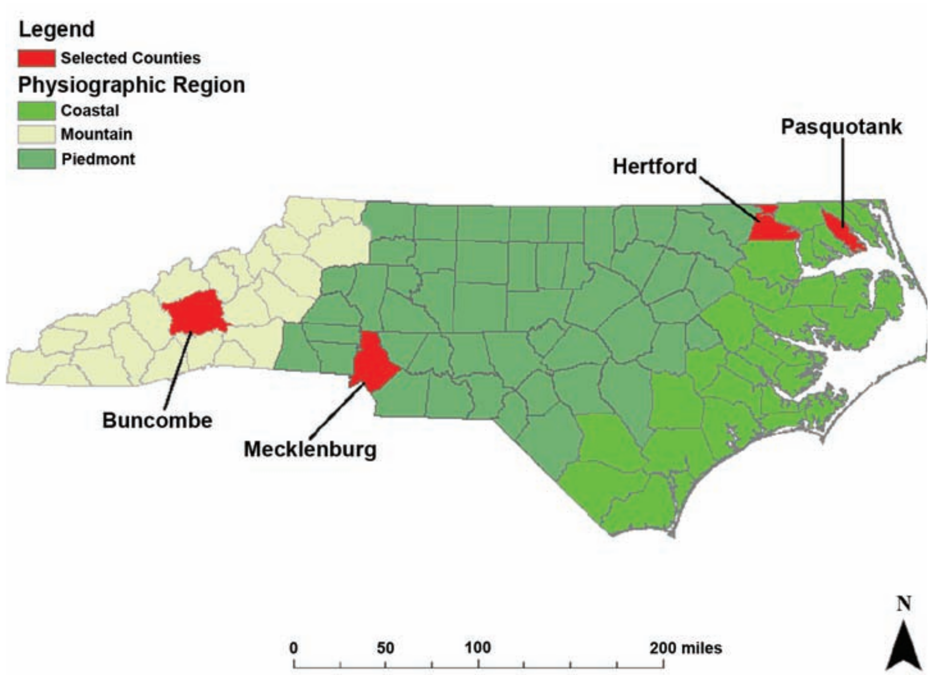

FIGURE 1 Location of flood mapping case studies in North Carolina. *Source:* North Carolina Floodplain Mapping Program (2008)

Illustration of Natural Variability and Knowledge Uncertainty

The estimation of flood peaks for 100-year and 500-year floods (having a 1 and 0.2 percent chance, respectively, of occurring in any given year) illustrates the concepts of *natural variability* and *knowledge uncertainty.* Figure 2 shows a flood frequency curve and the computed confidence limits for specific flood probabilities. These data are for the French Broad River (in Asheville), which has the longest flow record in this study—85 years. The central red line represents natural variability and expresses the relation between the magnitude of the flood discharge and its return period or likelihood of occurrence. Knowledge uncertainty is expressed by the spread of the confidence limits around this estimated line. As more data are used in a frequency analysis, the confidence band around the flood frequency curve becomes narrower, and the analysis shows more reliable results.

For this gage, reading up from the horizontal axis value of 100 years return period for flood discharge and across to the vertical axis shows an equivalent return period of 50 years for the lower confidence interval discharge and 180 years for the upper confidence interval discharge. The corresponding values for the 500-year flood range from a 200-year to a 1,000-year return period. Similar results were obtained for confidence limits on the 100-year flood stage.

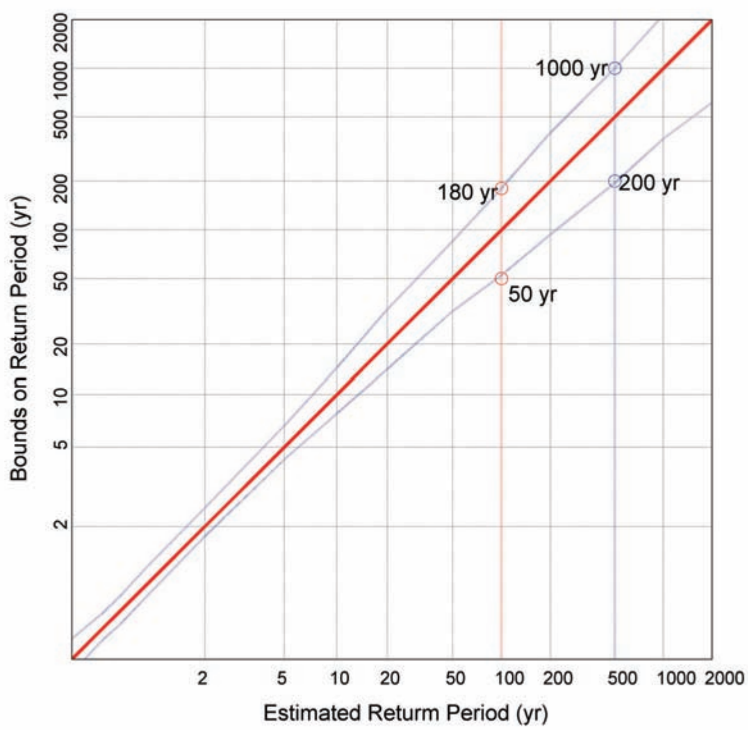

FIGURE 2 Return periods for flood discharge at the French Broad River in Asheville, North Carolina, for the expected flood discharge and its upper and lower confidence limits (dotted lines).

CONCLUSION

Knowledge uncertainty is significant even where long stream gage records exist.

in flood modeling and mapping. In contrast, knowledge uncertainties arise from either incomplete understanding of events and processes or a lack of data, and they can be reduced with additional information.

The committee examined knowledge uncertainty associated with riverine flooding by analyzing flood frequency data from 21 U.S. Geological Survey (USGS) stream gages in Mecklenburg and Hertford Counties and the City of Asheville, and from 10 stream gages in Florida. The importance of accurate elevation data was evaluated by comparing maps made with the NED and with lidar.

Hydrologic Uncertainty

Stage Height Data: Applying Flood Frequency Analysis

Flood mapping practitioners have typically inferred stage height from flow—the water level that results from a particular discharge of water. Although flood frequency analysis is commonly used to define flood discharge, the committee demonstrated that stream gage records of stage height can be subjected to frequency analysis in the same way the flow data are.

The study analyzed records of flood discharges and flood stage at six stream gages around mountainous Asheville in Buncombe County, seven gages in the rolling hills in Mecklenburg County, eight gages distributed along the flat coastal plain of North Carolina, and 10 gages in southwest Florida (Figure 3). The 31 stream gages have an average period of record of 54 years and an average drainage area of 458 square miles. The drainage areas varied by three orders of magnitude—from approximately 5 square miles to approximately 5,000 square miles—a reasonable representation of the range encountered in floodplain mapping.

As illustrated in Figure 4, for the 78 years of record on the Swannanoa River at Biltmore, flood discharges and stage heights have a similar frequency pattern. A good measure of the sampling

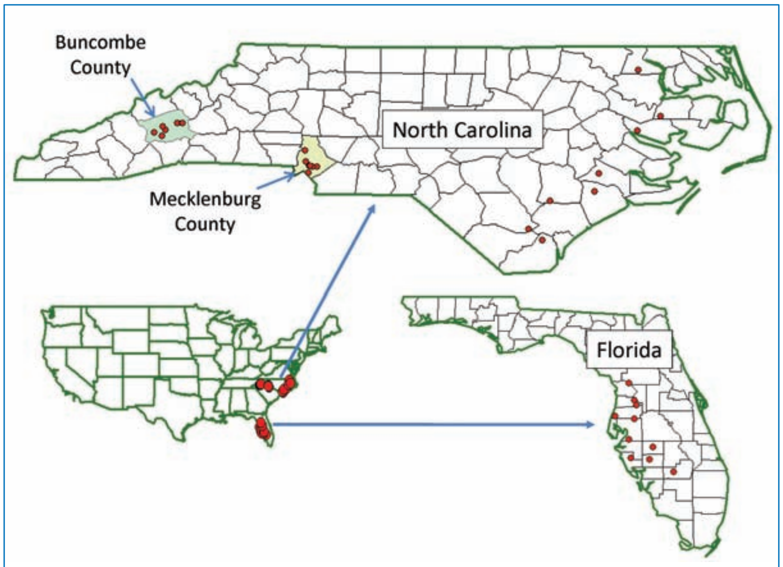

FIGURE 3 Stream gage sites analyzed in *Mapping the Zone*.

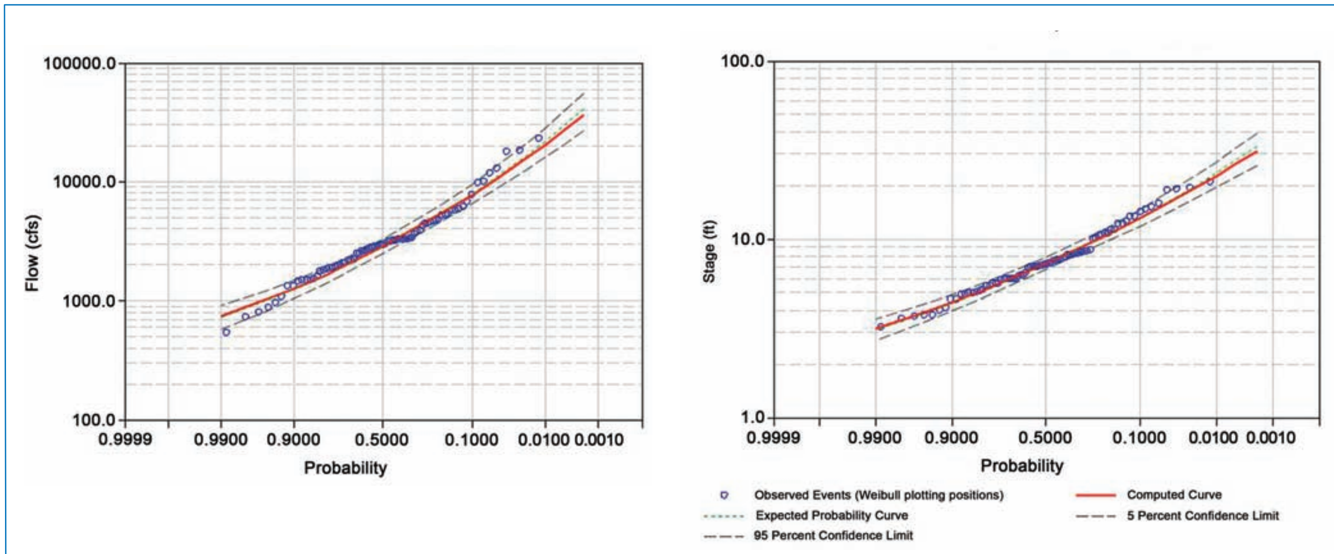

FIGURE 4 The frequency analysis of flood discharge data (left) and stage height data (right) for a gage at the Swannanoa River at Biltmore (in Ashcombe County, North Carolina), shows a similar pattern. The analysis was computed using USGS peak flow data and the U.S. Army Corps of Engineers Statistical Software Package HEC-SSP, with the log-Pearson III distribution.

error in the BFE can be derived from the range in the confidence limits, which in this case is 1.645 standard errors.

Surprisingly, no pattern emerges when sampling errors are plotted against drainage area and terrain. Figure 5 displays the results for all 31 stream gages.

This frequency analysis had three limitations: (1) it could not be adjusted for regional variations in stage height (these data do not exist); (2) the number of stream gages was small (31 gages of 27,000 for which the USGS has peak gage records); and (3) only a small part of the nation was examined. Despite the limitations, a reasonable interpretation of the result is that the accuracy of the 100-year stage height, within the range of sampling errors, or equivalently the accuracy of the 100-year BFE, does not vary with drainage area or geographic location for these sites.

The average sampling error was 1 foot for 30 of the 31 sites. In other words, even at locations with long records of measured peak floods, as at the three study sites, the BFE cannot be estimated more accurately than approximately 1 foot. This represents an unavoidable limit set by natural variability; improved mapping methods will not reduce it. This value also provides a benchmark against which the effects of various hydrologic methods can be evaluated. At ungaged sites, uncertainties in the estimated BFE are necessarily higher.

CONCLUSION

The sampling uncertainty of the BFE inferred from frequency analysis of maximum stage heights at 31 stream gages does not vary with drainage area, topography, or geographic location.

CONCLUSION

Even at locations with long records of measured peak floods, the BFE cannot be estimated more accurately than approximately 1 foot.

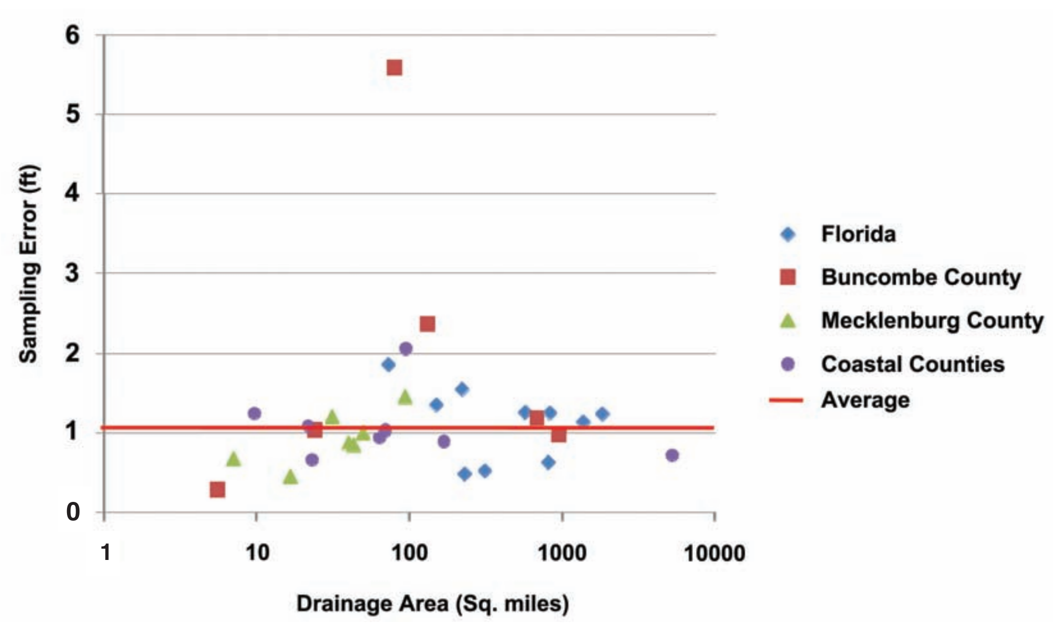

FIGURE 5 Sampling error of the computed 100-year stage height at 31 stream gage sites in Florida and North Carolina show that the accuracy of the 100-year stage height is plus-or-minus approximately 1 foot and that it does not vary with drainage area or geographic location. For 30 of the sites, the average value of the standard errors is 1.06 feet, with a range of 0.3 foot to 2.4 feet. One large outlier (5.6 feet sampling error) occurs at Hominy Creek in Candler, Buncombe County, North Carolina, where unusually large floods significantly skewed the stage frequency curve.

Flood Peak Discharge: Comparison of Hydrologic Methods

Flood peak discharge defines the magnitude of water flow produced by a given flood. The committee examined four hydrologic methods for determining the flood peak discharge in the three study reaches in North Carolina. The reaches have similar lengths, from 5 to 7 miles, but significantly different upstream drainage areas, ranging from 8 to 108 square miles. The hydrologic methods analyzed were:

1. *Rainfall runoff model.* Modeling programs developed by the U.S. Army Corps of Engineers (HEC-1 and HEC Hydrologic Modeling System) were calibrated using historical peak flows recorded at stream gages. The calibrated models were then used to calculate the 100-year flood peak flow.
2. *Regional regression.* Regional regression equations for rural watersheds in North Carolina, calculated by the USGS, were used to obtain the 100-year peak flow.
3. *95 percent lower and upper confidence limits (REGLOW and REGUP).* The limits of the 95 percent confidence interval around the regional regression value (plus or minus 42 to 47 percent of the base flood discharge) were used to estimate the 100-year peak flow.
4. *Adjusted regional regression.* Peak discharges from the rural regional regression equations were adjusted at and near the gages to match estimates from flood frequency analysis of stream gage data.

In all cases, the effect of the hydrologic method was compared to a base case of hydrology using a rainfall-runoff model (if available), hydraulics (estimated using Army Corps of Engineers' software) with a survey of structures in the floodplain, and terrain mapped by lidar. The result shows the sensitivity of the BFE to each method analyzed.

A typical result is shown in Figure 6. The only hydrologic method that produced significant variations in the BFE is REGLOW and REGUP, which changes the water surface elevation profile by an average of 1 to 3 feet in the three study reaches. However, this method was chosen to determine the effect of extreme variation in the discharge; the standard approach for a flood study is to use regional regression values.

So small a difference between these methods seems surprising at first. Rainfall-runoff modeling and flood frequency analysis operate with far greater precision than the simple empirical expressions of regional regression. However, all these methods are calibrated to the flood frequency curves developed at the stream gages, and each of the three study reaches has a USGS stream gage with long-term records. For methods that adjust the regression equation flood estimate to match the results of flood frequency analysis (rainfall-runoff model approach and adjusted regression

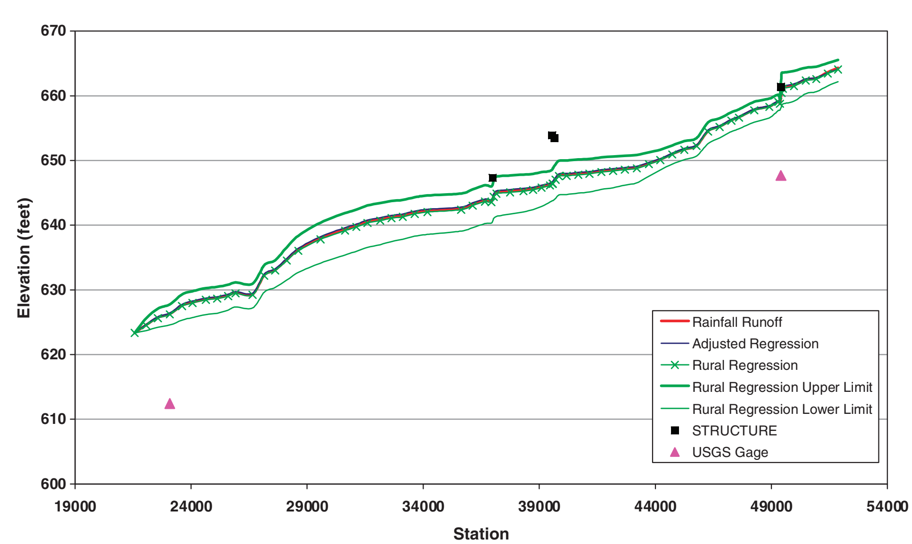

FIGURE 6 Effect of alternative hydrologic methods on the base flood elevation on Long Creek, North Carolina. The only hydrologic method that produced variations greater than 1 foot was the method that used the lower and upper confidence limits of the regression equation. *Source:* North Carolina Floodplain Mapping Program (2008)

method), the flood frequency analysis at the stream gage dominates the results. Regional regression equations, though not adjusted to gages, produce flows that are not sufficiently different from the other methods to create significant changes in water surface elevation at any of the study sites.

Flood frequency analysis of stream gage records is the most reliable method of defining peak flood discharges. For estimating BFEs from peak discharges, three models produce similar profiles in the three study reaches: rainfall-runoff models, the USGS regional regression equations adjusted for flood frequency at a nearby gage, and adjusted regional regression equations.

CONCLUSION

For the three study reaches, the USGS regional regression equation method estimates flood discharges with sufficient precision to support FEMA flood mapping efforts.

CONCLUSION

None of the commonly used hydrologic methods introduces significant variations in the BFE in the three study reaches.

Hydraulic and Terrain Uncertainty

River hydraulics are affected by the presence of structures (e.g., bridges) and the irregular shapes of natural channels, which change the water surface profile. Uncertainties in hydraulic models add to the uncertainties in the BFE. The committee examined several alternative combinations of hydraulic modeling and terrain data.

Comparison of Lidar Terrain Data to the USGS National Elevation Dataset

The NED, which was built from tagged vector contour data from USGS topographic maps, is used in many Approximate studies. However, the overall vertical accuracy of topographic data in the NED is 14.9 feet at the 95 percent confidence level, a level of uncertainty about 10 times larger that FEMA standards for floodplain mapping. In contrast, lidar data are accurate within 15-20 centimeters, well in line with FEMA requirements.

To quantify the differences between topographic data sources for flood mapping, pairs of flood maps were made in the North Carolina case study areas, one from the NED and one from lidar. Figure 7 and Table 1 show the elevation differences between the two data sources around streams in flat Hereford County, hilly Mecklenburg County, and mountainous Buncombe County.

The data in Table 1 demonstrate that at Ahoskie Creek and the Swannanoa River, there are small average differences between lidar and NED elevation data but the random differences

TABLE 1 Elevation Difference Statistics, NED Minus Lidar

Stream	Mean (feet)	Standard Deviation (feet)	Minimum (feet)	Maximum (feet)
Ahoskie Creek	0.5	3.9	34.8	−25.3
Long Creek	14.7	15.6	81.5	−46.0
Swannanoa River	−2.0	17.5	89.7	−139.3

between the two are very large. At Long Creek, there is a large systematic difference in which the NED is 14.7 feet on average higher than lidar for the same area. This difference may result in part from misalignment of the stream centerline and the underlying terrain elevation information. Figure 8 maps predicted flood inundations in Pamlico Sound in Beaufort County, North Carolina, using digital elevation models (DEMs) from the NED and from lidar. Uncertainties in the area of land inundated are much greater with the NED-based DEM. The large differences represent potential error in determining the flood boundary and, thus, the flood risk.

CONCLUSION

The accuracy of elevation data has an enormous impact on the accuracy of flood maps.

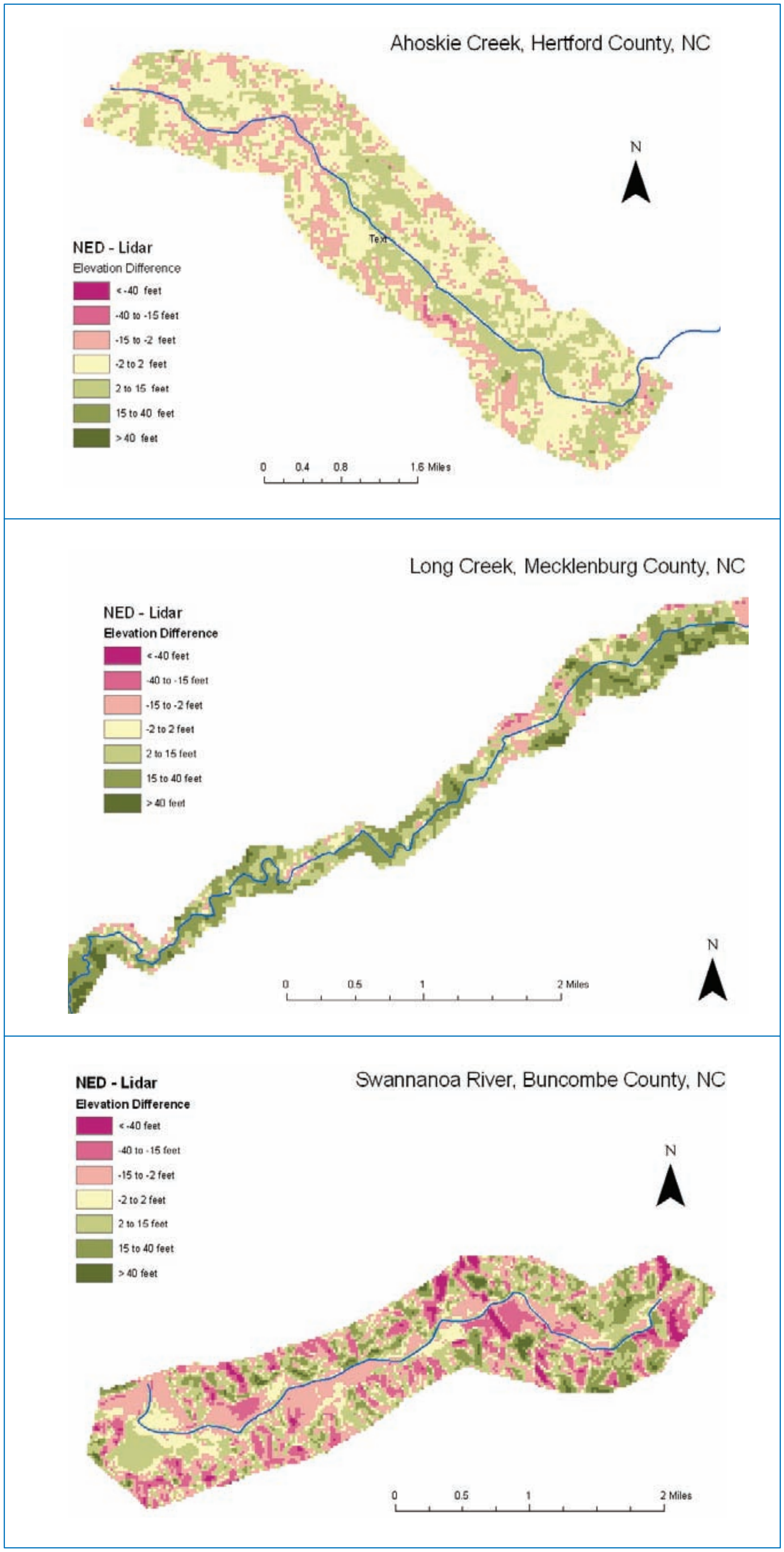

FIGURE 7 Differences in land surface elevation between the USGS NED and the North Carolina Floodplain Mapping Program lidar can be very large along rivers in three counties in North Carolina. In the red and pink areas, lidar elevations are higher than the NED, and in green areas, the NED is higher than lidar. Only in the yellow areas do the NED and lidar data give approximately the same results. *Top:* Eastern coastal plain—Ahoskie Creek, elevation ranging from 1 foot to 74 feet. *Middle:* Central piedmont—Long Creek, elevation ranging from 566 feet to 767 feet. *Bottom:* Western mountains—Swannanoa River, elevation ranging from 1966 feet to 2202 feet.

Source: Courtesy of T. Langan, North Carolina Floodplain Mapping Program

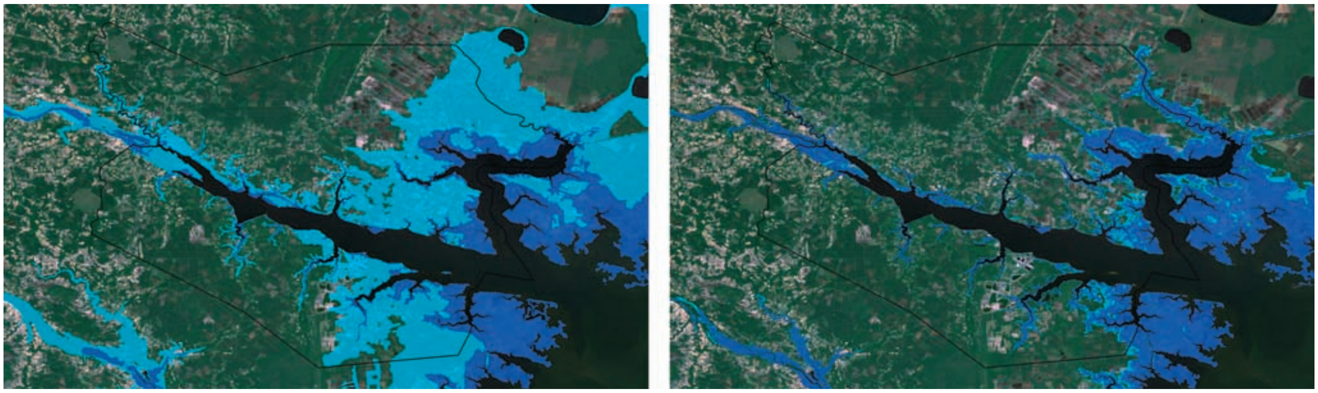

FIGURE 8 Inundation maps of Beaufort County, North Carolina, where the Tar-Pamlico River empties Pamlico Sound show the difference in a 30-meter digital elevation model (DEM) created from the USGS National Elevation Dataset (left) and a 3-meter DEM created from North Carolina Floodplain Mapping Program lidar data (right). The dark blue tint represents land that would become inundated with 1 foot of storm surge or sea level rise. The light blue area represents uncertainty in the extent of flooding at the 95 percent confidence level. *Source:* Gesch (2009)

Comparison of Hydraulic Models and Terrain Data

Five variations in hydraulic and terrain data were examined by the North Carolina Floodplain Mapping Program:

1. *Detailed Study (DS).* Lidar data were used for topography, field surveys for channel cross sections and for bridge and culvert openings; ineffective flow areas and channel obstructions were defined; and Manning's *n* (for channel roughness, or flow resistance) could vary along the channel.
2. *Limited Detailed Study North Carolina (LDSNC).* Same as a detailed study except that field surveying of channel structures was estimated or limited.
3. *Limited Detailed Study National (LDSNAT).* Same as for LDSNC except no channel structures or obstructions were included and ineffective flow areas were removed near structures.
4. *Approximate (APPROX).* Same as for LDSNC except that Manning's *n* was uniform along the channel profile (although it can have separate values for the channel and the left and right overbank areas).
5. *Approximate-NED (APPROX-NED).* Same as APPROX but the NED, rather than lidar, was used for terrain representation.

The analysis showed that as long as lidar terrain data are used, the effect of the alternative hydraulic methods is small. The cascading appearance of the water surface profile for the APPROX-NED model, evident in Figure 9, is due to a horizontal misalignment between the base map horizontal information and the elevation information. In other words, detailed mapping of the stream network within Mecklenburg County shows the correct location of the stream centerline, and when lidar data are used to define elevation, the topographic (vertical) and base map (horizontal) imagery are correctly aligned. However, when the NED is used to define topography, the stream centerline and the topography are not correctly aligned, and the stream appears to flow over ridges and gullies rather than down a stream channel. This is why the BFE profile shown in Figure 9 forms a stair-step pattern.

As Figure 9 clearly shows, there is little difference among the study types (a standard deviation of 1 to 3 feet), except for the Approximate study using the NED, which yields a BFE at Long

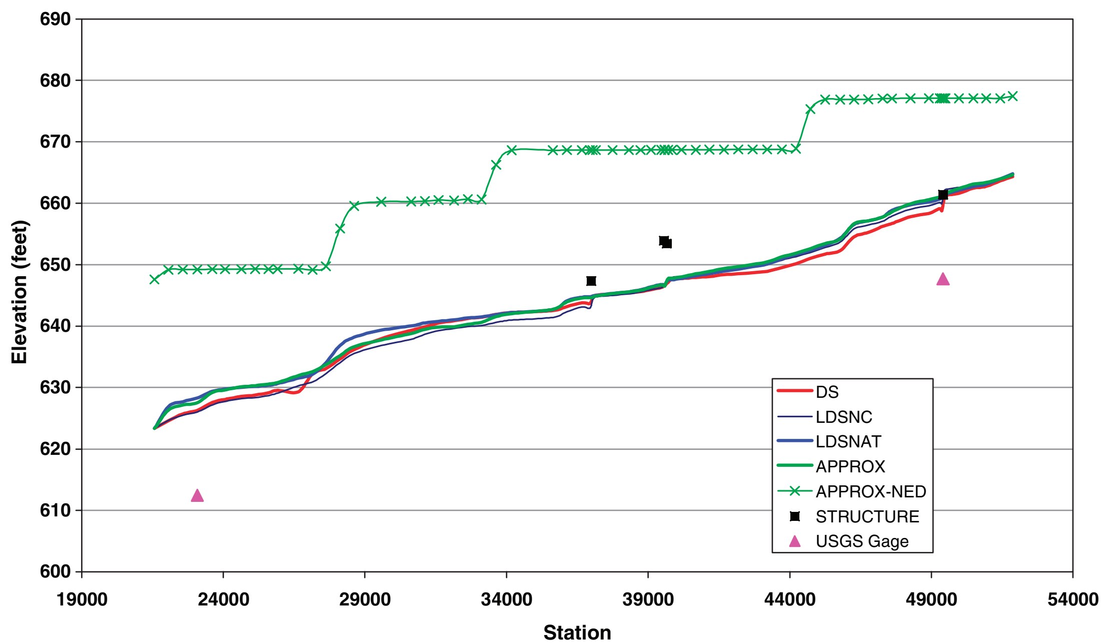

FIGURE 9 Base flood elevation profiles for different hydraulic study types on Long Creek.

Source: North Carolina Floodplain Mapping Program (2008)

Creek that is 21 feet higher than that produced by a Detailed study. This large systematic discrepancy results because of a similar difference between the mean elevation of the lidar and NED data at Long Creek and because of differences in the location of the stream centerline between these two data sources.

At Ahoskie Creek and the Swannanoa River, the NED BFE is, on average, fairly close to the lidar BFE, but at particular cross sections the two elevations may differ by up to 10 feet. Figure 10 reveals significant random variation in the APPROX-NED BFE profile—sometimes it is above the other profiles and sometimes below, and the magnitude of the variations is significantly greater than in other hydraulic study types. The differences are striking, particularly for Long Creek, as shown in Table 2. In the other two study reaches, the NED BFE is, on average, fairly close to the lidar BFE, but at particular cross sections the two elevations may differ by up to 10 feet.

CONCLUSION

Topographic data is the most important factor in the accuracy of flood maps in riverine areas, much more important than the hydraulic model used.

TABLE 2 Base Flood Elevation Differences Between Detailed and Approximate-NED Studies

Stream	Mean (feet)	Standard Deviation (feet)	Minimum (feet)	Maximum (feet)
Ahoskie Creek	0.95	1.30	−3.34	2.87
Long Creek	20.89	3.07	13.11	26.45
Swannanoa River	0.18	3.61	−5.12	9.91

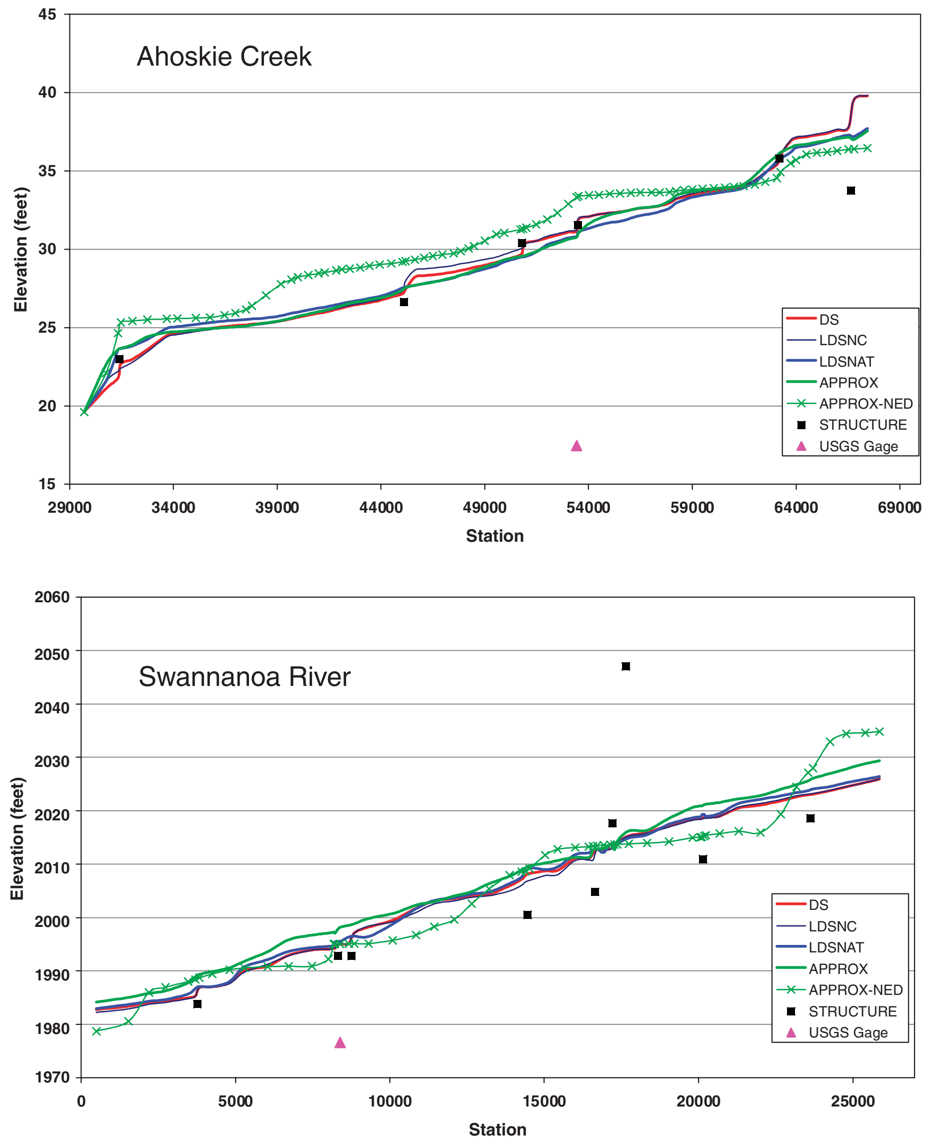

FIGURE 10 Base flood elevation profiles for different hydraulic study types on Ahoskie Creek (top) and the Swannanoa River (bottom) reveal the random variation that occurs when the National Elevation Dataset is used.

Source: North Carolina Floodplain Mapping Program (2008)

Backwater Effects of Structures

A key reason for doing detailed surveys of structures in stream channels is to estimate their backwater effects. The structures are shown as black dots in Figure 10, and the flood profiles jump upwards at some of these locations. Bridges and culverts constrain the movement of flood waters during very large discharges, and the water elevation upstream of a structure increases to create the energy needed to force the water to flow through the structure. Intuitively, these backwater effects should propagate further upstream in flat terrain than in steep terrain, but by how much? The impact of backwater on the surface water profile was the

TABLE 3 Channel and Terrain Slopes

Stream	Number of Structures	Extended to Next Structure[a]	Average Elevation (feet)[b]	Maximum Elevation (feet)[b]	Distance Upstream (miles)[c]
Ahoskie Creek	6	6	0.89	2.54	1.12
Long Creek	4	3	0.34	0.73	0.50
Swannanoa River	9	5	0.20	2.02	0.30

[a] An elevated backwater effect extended from one structure to the next one upstream.
[b] Refers to the difference between the two elevation profiles with and without structures.
[c] Average distance upstream from a structure from which backwater effects propagate.

highest in Ahoskie Creek on the coastal plain, where 6 structures caused backwater effects and all of the effects extended to the next structure upstream (Table 3). On Long Creek and the Swannanoa River, backwater effects reached the next structure in most cases. The average distance that a backwater effect propagated upstream was 1.1 miles on Ahoskie Creek, 0.5 miles on Long Creek, and 0.3 miles on the Swannanoa River. The maximum backwater elevation increase found was 2.5 feet in the coastal plain reach.

CONCLUSION

Backwater effects of structures influence the BFE profile on all three study reaches and are most pronounced in the coastal plain.

Uncertainty in Floodplain Boundaries

To get a sense of how variations in the flood elevation affect the lateral spreading of water, the committee located the point on each channel section where the BFE crosses the land surface terrain and then calculated the slope on the right and left sides. These side slope values were then averaged for each study area. The slope data are presented in Table 4. At Ahoskie Creek, a 1-foot change in vertical elevation changes the horizontal location of the floodplain boundary by 1/0.024 = 42 feet. A 1-foot rise will change the floodplain boundary on average by 10 feet at Long Creek and 8 feet on the Swannanoa River. Since there is no inherent difference in the sampling uncertainty in the BFE by region, it follows that floodplain boundary delineation is more uncertain in the coastal plain than in the piedmont or mountains—in fact, about four to five times more uncertain, in proportion to the rise-run data.

CONCLUSION

Having accurate topographic data for floodplain mapping is especially critical in regions with low relief.

TABLE 4 Channel and Terrain Slopes

Stream	Terrain Slope[a] (percent)	Longitudinal Slope (percent)	Lateral Slope (percent)	Lateral Run/Rise (feet/feet)
Ahoskie Creek	0.3	0.05	2.4	42
Long Creek	6.1	0.13	9.8	10
Swannanoa River	26.7	0.18	12.9	8

[a] Terrain slope is the average for the National Elevation Dataset over the county where the reach is located, except for Ahoskie Creek, in which relevant data were available in an adjacent county (Pasquotank).

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The National Academies appointed the above committee of experts to address the specific task requested by the Federal Emergency Management Agency's Risk Analysis Division and the National Oceanic and Atmospheric Administration's Coastal Services Center. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This technical summary was prepared by the National Research Council based on the committee's report.

EXPERT CONSENSUS REPORT

For more information or copies, contact the Board on Earth Sciences and Resources at (202) 334-2744 or visit http://nationalacademies.org/besr, or see the Water Science and Technology Board at http://nationalacademies.org/wstb. Copies of *Mapping the Zone: Improving Flood Map Accuracy* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.