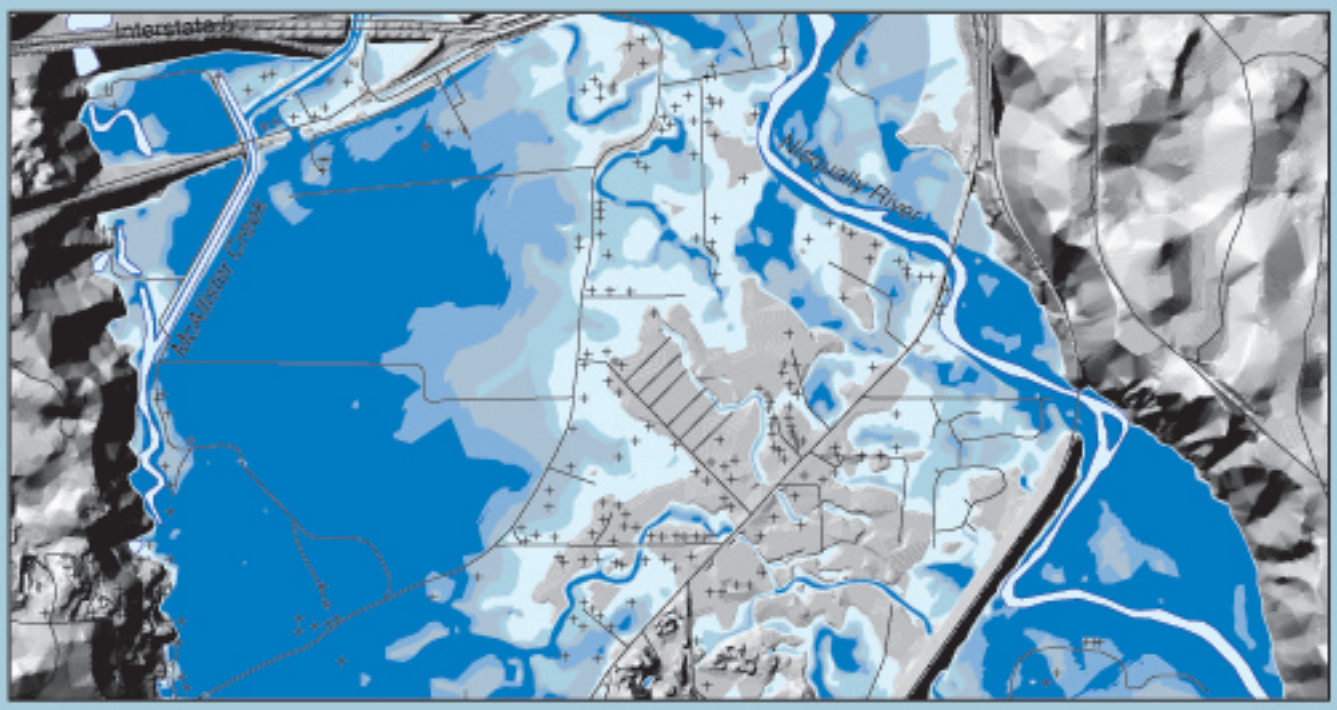
UPDATING FLOOD MAPS EFFICIENTLY USING EXISTING HYDRAULIC MODELS, VERY-HIGH-ACCURACY ELEVATION DATA, AND A GEOGRAPHIC INFORMATION SYSTEM— A PILOT STUDY ON THE NISQUALLY RIVER, WASHINGTON

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 01-4051



Flood depths for the Nisqually River 100-year flood with roads and buildings.

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Updating Flood Maps Efficiently Using Existing Hydraulic Models, Very-High-Accuracy Elevation Data, and a Geographic Information System— A Pilot Study on the Nisqually River, Washington

By Joseph L. Jones, Tana L. Haluska, and David L. Kresch

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4051

Tacoma, Washington
2001

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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CONTENTS

Abstract 1
Introduction 2
    Need for New Maps and Methods 2
    Purpose and Scope 3
Nisqually River Flood Mapping Pilot 4
    Description of the Pilot Study Area 4
    Very-High-Accuracy Land-Surface Elevation Data 6
    Digital Elevation Maps 6
Updating Flood Information 11
    Flood Frequency 11
    Flood Stages 12
        Stage-Discharge Relations from Existing Hydraulic Model Output 12
        Comparison with Original Hydraulic Model 12
Updating Flood Maps 16
    Overview of Data Processing 16
    Creating a 3-Dimensional Digital Representation of the Land Surface 17
    Creating a 3-Dimensional Digital Representation of the Flood Surface 17
    Creating an Inundation Map 21
    Additional Benefits of GIS-Generated Flood Maps 21
Data Management 28
Limitations and Opportunities for Further Study 28
Summary 29
References Cited 30

FIGURES

Figure 1. Map showing location map of the pilot study area on the lower reach of the Nisqually River Basin in western Washington 5
Figure 2. Map showing differences in elevation between field survey points tied to elevation monuments from the 1970's flood study and points on the Digital Elevation Model derived from Thurston County Geodata Center data 7
Figure 3. Map showing availability of very-high-accuracy elevation data in the Puget Sound Region, Washington, 1998 8
Figure 4. Map showing comparison of level of detail in a standard U.S. Geological Survey 10-meter Digital Elevation Model and one produced from newer 1-foot vertical accuracy elevation data 9
Figure 5. Map showing examples of production artifacts found in standard U.S. Geological Survey Digital Elevation Models 10
Figure 6. Graph showing differences between flood elevations estimated by log transform regression and by the step-backwater model 14
Figure 7. Graph showing differences between flood elevations estimated by square-root transform regression and by the step-backwater model 15
Figure 8. Map showing example of very-high-accuracy elevation data for the Nisqually River from Thurston County Geodata Center 18
Figure 9. Map showing comparison of land surface Digital Elevation Models generated by the TOPOGRID and TIN/TINLATTICE generation methods: (A) shaded relief maps, and (B) difference assessments 19
Figure 10. Map showing comparison of digital elevation models at 10-meter and 1-meter horizontal resolutions 20
Figure 11. Map showing updated flood inundation map for the 100- and 500-year floods. 22
Figure 12. Map showing comparison of the original Flood Insurance Rate Map (FIRM) for the 100-year flood with updated flood maps made using high-accuracy land elevation models and with an aerial photograph of the Nisqually River flood of February 9, 1996 23
Figure 13. Map showing flood depths for the 100-year flood. 25
Figure 14. Map showing flood depths for the 100-year flood, with roads and buildings. 26
Figure 15. Map showing areas of uncertain flood hazard for the 100-year flood. 27

TABLES

Table 1. Comparison of flood discharges from the Flood Insurance Study (FEMA, 1982) and those updated for the pilot study (1997) for selected recurrence intervals 11
Table 2. Percentages of flood elevations estimated by logarithmic regression that were within 0.1, 0.2, and 0.3 foot of elevations calculated with the step-backwater model, for the four recurrence intervals 13
Table 3. Statistical comparison of differences, in feet, between flood elevations estimated by logarithmic regression and calculated from the step-backwater model, for the four recurrence intervals 13
Table 4. Percentages of estimated 500-year flood elevations within 0.1, 0.2, and 0.3 foot of elevations calculated from the step-backwater model 13

LIST OF ACRONYMS

GIS	Geographic Information System
FIS	Flood Insurance Study
NFIP	National Flood Insurance Program
FIRM	Flood Insurance Rate Map
FHBM	Flood Hazard Boundary Map
FEMA	Federal Emergency Management Agency
LOMR	Letter of Map Revision
LOMA	Letter of Map Amendment
LIDAR	LIght Detection And Ranging
NFIRA	National Flood Insurance Reform Act
TCGC	Thurston County Geodata Center
RMSE	Root Mean Squared Error
USGS	U.S. Geological Survey
DEM	Digital Elevation Model
TEC	Technical Evaluation Contractor
ESRI	Environmental Systems Research Institute
TIN	Triangular Irregular Network
TOPOGRID	(an Arc/INFO command)
Arc/INFO	(a GIS)
TINLATTICE	(an Arc/INFO command)

Updating Flood Maps Efficiently Using Existing Hydraulic Models, Very-High-Accuracy Elevation Data, and a Geographic Information System—A Pilot Study on the Nisqually River, Washington

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ABSTRACT

A method of updating flood inundation maps at a fraction of the expense of using traditional methods was piloted in Washington State as part of the U.S. Geological Survey Urban Geologic and Hydrologic Hazards Initiative. Large savings in expense may be achieved by building upon previous Flood Insurance Studies and automating the process of flood delineation with a Geographic Information System (GIS); increases in accuracy and detail result from the use of very-high-accuracy elevation data and automated delineation; and the resulting digital data sets contain valuable ancillary information such as flood depth, as well as greatly facilitating map storage and utility. The method consists of creating stage-discharge relations from the archived output of the existing hydraulic model, using these relations to create updated flood stages for recalculated flood discharges, and using a GIS to automate the map generation process.

Many of the effective flood maps were created in the late 1970's and early 1980's, and suffer from a number of well recognized deficiencies such as out-of-date or inaccurate estimates of discharges for selected recurrence intervals, changes in basin characteristics, and relatively low quality elevation data used for flood delineation. FEMA estimates that 45 percent of effective maps are over 10 years old (FEMA, 1997). Consequently, Congress has mandated the updating and periodic review of existing maps, which have cost the Nation almost 3 billion (1997) dollars. The need to update maps and the cost of doing so were the primary motivations for piloting a more cost-effective and efficient updating method. New technologies such as Geographic Information Systems and LIDAR (Light Detection and Ranging) elevation mapping are key to improving the efficiency of flood map updating, but they also improve the accuracy, detail, and usefulness of the resulting digital flood maps. GISs produce digital maps without manual estimation of inundated areas between cross sections, and can generate working maps across a broad range of scales, for any selected area, and overlayed with easily updated cultural features. Local governments are aggressively collecting very-high-accuracy elevation data for numerous reasons; this not only lowers the cost and increases accuracy of flood maps, but also inherently boosts the level of community involvement in the mapping process. These elevation data are also ideal for hydraulic modeling, should an existing model be judged inadequate.

INTRODUCTION

Flood inundation maps for the Nation are produced primarily for Flood Insurance Studies (FIS) as part of the National Flood Insurance Program (NFIP). Many of these maps—Flood Insurance Rate Maps (FIRMs), and Flood Hazard Boundary Maps (FHBM)—were produced in the late 1970's and early 1980's, prior to the advent of digital mapping technologies and the very-high-accuracy elevation data that are now available, and they have not been updated. Also, changes in flood frequency estimates create the need to assess the applicability of existing flood maps. Flood frequency estimates may change for a variety of reasons, including changes in land use or other watershed characteristics, development of new regional regression methods, or simply an increase in the number of years of peak flow record available for the calculations.

The National Flood Insurance Reform Act (NFIRA) of 1994 (Public Law 103-325) addresses the need to update maps using modern mapping technologies and updated flood frequency statistics. The Federal Emergency Management Agency (FEMA), which administers the NFIP, estimates that between 18,000 and 30,000 FIRM maps need updates, and estimates costs of between $800 and $1,000 million for updating or conducting new detailed studies for 30,000 to 50,000 map panels (Federal Emergency Management Agency, 1997; 1998; and 2000).

The use of modern very-high-accuracy elevation data that are being developed in many areas can produce the most accurate maps and minimize the need for subsequent adjustments such as Letters of Map Revision (LOMRs) and Letters of Map Amendment (LOMAs). In places where existing hydraulic models from previous FISs still apply, their use, as appropriate, can minimize the cost of map revisions.

In 1997, the U.S. Geological Survey (USGS) conducted a pilot study on a 10-mi (mile) stretch of the Nisqually River in the Puget Sound Lowlands of western Washington State to evaluate a new and more time- and cost-effective method of updating flood inundation maps. The pilot study was conducted under the auspices of the USGS Urban Geologic and Hydrologic Hazards Initiative, also referred to as the Seattle Area Natural Hazards Project. The initiative is being conducted by the Geologic, Water Resources, and National Mapping Divisions of the U.S. Geological Survey, and addresses natural hazards in five counties in the Seattle area: Snohomish, King, Pierce, Thurston, and Kitsap.

Need for New Maps and Methods

FEMA and others in the flood-plain management community acknowledge the need for new maps:

- Existing paper maps are difficult to use and archive and are costly to publish;
- The hydrologic analyses sometimes need updating because of available improved flood frequency information or changes in a watershed that affect its hydrologic characteristics, or both;
- Many original maps were made with elevation data of insufficient accuracy (many maps were based on 1:24,000-scale topographic maps accurate to only around 10 feet).

Each of 15 million mortgages and all building permits approved annually require the inspection of the appropriate flood map. Existing paper maps are large scale (typically 1:12,000 and as large as 1:4,800) and are so numerous that they are difficult to store and distribute. Many maps also lack up-to-date features such as buildings, roads, and other landmarks, so that once the appropriate map is located and acquired, a specific property or location on it can be difficult to find with confidence.

In some areas the original flood flow statistics were based on limited peak-flow data (either in the basin under study, or a nearby basin serving as the basis for regional flow estimation). Since then, 20 years or more of additional peak-flow data have been collected, allowing the calculation of more accurate flood frequency estimates. Especially significant to flow statistics are any exceptionally large peak flows that have occurred in the intervening period.

Flood plains are characteristically of low relief, and vertical inaccuracies in a land-surface elevation map used for inundation mapping can result in relatively large inaccuracies in mapping an area of flood inundation. At the time many of the original FISs were conducted, the best available topographic map, which was used to delineate the 100-year flood inundation, was a USGS 1:24,000-scale quadrangle

map. These maps are considered accurate to within half a contour interval (typically 20 feet). For some areas, more accurate maps were available, such as a USGS quadrangle with 10-foot contours (which were sometimes prepared for low relief areas) or a 5-foot contour map prepared for a FIS. Elevation data accurate to 1 ft (foot) would greatly improve the accuracy of flood maps and are necessary to credibly map differences in 100- and 500-year floods that differ in elevation by less than 2 ft. The general availability of very-high-accuracy (1 ft or better vertical accuracy) digital elevation data, comparable in price to traditional photogrammetrically derived elevation models, is a recent development. Traditional methods, such as low-altitude aerial photography with photogrammetric interpretation, are capable of providing 1-foot vertical accuracy at reasonable costs (on the order of $1,000 per square mile); however they are time consuming to process, and in difficult terrain, such as one with dense vegetation, the vertical accuracy may not reach 1 ft, and the cost would increase. New data collection methods, such as Light Detection and Ranging (LIDAR), offer increased accuracy and lower costs, and if appropriately gathered and processed, can effectively remove structures and most vegetation from the elevation model. (LIDAR— analogous to RADAR—combines laser ranging, global positioning systems and inertial navigation from an airborne platform to gather tremendously dense and accurate elevation data very quickly.) The data are gathered in digital form and are thus well suited to import into a GIS, whereas photogrammetric products are traditionally (though not necessarily) processed into contour maps, which by nature are more difficult to make into representative digital models.

FEMA also recognizes the need for a more efficient mapping method. Between 1968, when the flood mapping program began, and 1997, $2.7 billion (1997 dollars) had been spent on preparing, maintaining, and updating flood maps. That alone is strong incentive to seek less costly mapping procedures. In addition, the NFIRA also requires a review of the adequacy of existing maps every 5 years, which can require costly map updates. Currently, map updates take nearly 5 years to complete (FEMA, 1997), and a FEMA objective is to streamline the process by implementing more efficient analyses and mapping, increasing coordination with communities, and conducting reviews concurrently with the analyses (FEMA, 1997).

The method developed in the pilot study has the potential to address two of these objectives directly. First, it greatly reduces the time required for analysis and mapping. Time-consuming hydraulic analyses are not repeated where the original model remains valid. The actual inundation areas of original flood maps were manually determined by visually interpolating on a paper map between cross sections (where specific flood water elevations were determined by hydraulic modeling); using a GIS allows the inundation areas associated with given flood elevations at and between cross sections to be determined more efficiently, and yields detailed depth-of-flood information across the entire flood plain. Second, it increases community involvement by promoting the use of locally produced very-high-accuracy digital elevation data for creating land-surface elevation models. FEMA's objective of conducting reviews concurrently with analyses also fits in well with the approach presented here, in that the decision to reuse an existing hydraulic model should be made with the concurrence of FEMA's technical staff.

Purpose and Scope

This report presents a time- and cost-efficient method of updating flood inundation maps using existing hydraulic models, very-high-accuracy elevation data, and GIS mapping technology. The method assumes that information from existing hydraulic models can be used to derive new water-surface elevation data. Descriptions and details of the development and application of the method include updating flood frequency statistics; using GIS for flood elevation modeling; accuracy requirements, availability, and cost of elevation data; detailing of quality-assurance steps for flood surface and land surface generation; generating flood inundation maps with a GIS; comparing results with the aerial photographs of an actual flood on the Nisqually River; and assessing the advantages of using GIS and this procedure.

NISQUALLY RIVER FLOOD MAPPING PILOT

The flood mapping method developed in the pilot study includes these steps:

- Obtain peak-flow data representative of current conditions;
- Calculate updated discharges for the desired flood frequencies;
- Develop stage-discharge relations for each cross section using the output from the original hydraulic model;
- Use the stage-discharge relations to update the flood stage(s);
- Create digital representations of the elevations of the flood and land surfaces; and
- Subtract the land elevation from the flood elevation: the resulting data set represents the depth of inundation (negative values indicate no inundation).

The approach was based on traditional flood mapping procedures used since the inception of the flood mapping program. Steps in the traditional procedures were evaluated with regard to cost, time required, and value added. The conclusion was that of all of the steps used traditionally, constructing, verifying, and applying the hydraulic model appeared to require the most time and effort. Consequently, if the results of a previous study were available, significant time and cost savings could be realized in situations where it is reasonable to use the results of a previous hydraulic model to estimate flood stages for updated flood flows. (It is not appropriate to use existing hydraulic models in all cases, and additional study is needed to develop generally applicable guidelines about when their use is most appropriate.) The new approach differs from the traditional approach in two other ways: the use of very-high-accuracy elevation data and the application of modern Geographic Information Systems (GISs) to produce inundation maps and valuable ancillary flood maps, such as depth-of-flood maps.

Description of the Pilot Study Area

The area selected for the pilot study is about 10 miles of the lower reach of the Nisqually River in western Washington (**fig. 1**). The pilot study area was selected because of local concern about inaccuracies in the existing flood maps and the availability of high-accuracy elevation data, and aerial photography of an approximate 100-year flood, and the original hydraulic model code and input data sets.

The Nisqually River originates in the foothills of the Cascade Range in western Washington, empties into Puget Sound, and drains more than 700 mi^2 (517 mi^2 at the USGS gage at McKenna, about 22 miles upstream from the mouth). At the upper end of the study reach, adjacent to Fort Lewis Military Reservation, the flood plain is less than a mile wide and is incised into 91st Division Prairie, a broad (about 3-miles wide) flat, geologically young (less than 20,000 years old) unconsolidated glacial outwash plain. The sides of the flood plain are formed by 7th Infantry Bluff and 38th Infantry Bluff and are about 150 feet high. The Nisqually River, since the end of the most recent glacial advance, has incised the valley and flood plain. The streambed (Holocene alluvium) is reworked unconsolidated glacial deposits and sediments from the Cascade Range. The lower reach occupies the broad glacial outwash plain; because the volumes of glacial meltwater that created the valley were much larger than current streamflow, the river is underfit in the approximately 2-mile-wide valley.

The U.S. Geological Survey conducted the original FIS for the study area during the late 1970's. The flood frequency discharges for the 10-, 50-, 100-, and 500-year recurrence intervals were computed using a combination of methods. The hydraulic model used for that study was J635 (Shearman, 1977), a steady-state one-dimensional step-backwater computer program developed by the USGS. Cross-sectional elevation data were acquired from photogrammetric interpretation of 1:9,600-scale aerial photography supplemented by field surveys of channel cross sections and bridge openings. Original maps and Mylar transparencies were available for the pilot study as sources of cross-section location information. The inundation areas were manually interpolated between cross sections on 4- and 5-foot contour maps (1:4,800 and 1:9,600 scale).

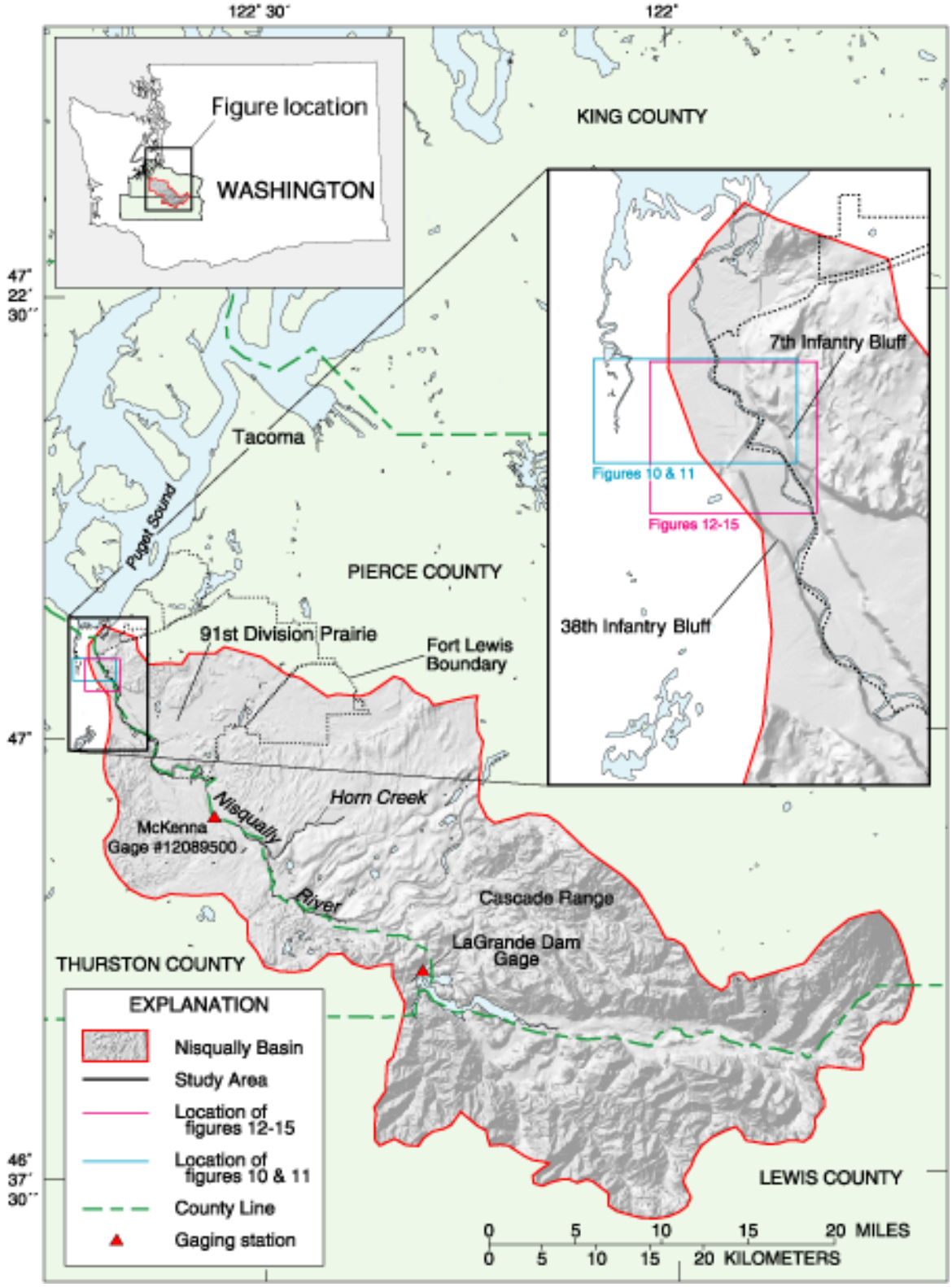


Figure 1. Location map of the pilot study area on the lower reach of the Nisqually River Basin in western Washington.

Very-High-Accuracy Land-Surface Elevation Data

Perhaps the most significant aspect of the pilot approach is the use of digital elevation data with very high accuracy (better than 1-foot vertical accuracy) and high resolution (around 3 feet horizontal, in order to preserve vertical accuracy). In the pilot study, these data were made available by the Thurston County Geodata Center (TCGC) in the form of digital 2-foot contours produced from low-altitude aerial photography with automated photogrammetric interpretation. To ensure consistency with the elevation data used in the original study, the vertical datum was verified with the TCGC. The data were also verified by field surveys that were tied vertically to elevation monuments used in the original 1970's field surveys. The field verification consisted of surveying 310 elevation points in the vicinity of cross sections used in the original study. The field surveys could not precisely locate the survey points horizontally, making the comparison somewhat subjective; however, the comparison appeared to verify the accuracy of the data as well as the datums reported by the contractor who executed the elevation project for TCGC. The differences between the TCGC data and the field survey points are shown in **figure 2**. The median difference is 0.39 ft, the mean is 0.87 ft, the standard deviation is 3.5 ft, and the root mean squared error (RMSE) is 4.0 ft. The standard deviation and RMSE are large because there were differences larger than 3 ft. The nominal accuracy of the TCGC data is 1 ft, or one-half contour interval, based on USGS National Mapping Division criteria, which state that the RMSE of verifiable elevations be within one-half contour interval and that no errors exceed one contour interval. However the RMSE of the differences (4.0 ft) exceeds the expected value of 1 ft, and a number of differences are considerably larger than the contour interval of 2 ft. Inspection of **figure 2**, however, reveals that the survey points that are more than a foot different from the TCGC data are close to a steeply sloped surface such as the river channel or oxbow, a valley wall, or a transportation embankment. Visual inspection also indicates that the elevation errors of survey points that are not located near a sloped surface are consistently within 1 ft of the Digital Elevation Model (DEM) derived from TCGC data. Thus, the apparent cause of the large RMSE is poor relocation of the original surveyed elevation points, and so, at least qualitatively, the accuracy and the consistency of TCGC data with the original elevation data are verified.

A survey of the local governments in the Puget Sound region revealed that very-high-accuracy elevation data are being aggressively acquired in the region (**fig. 3)**. The data are highly sought by local governments for a host of reasons other than their usefulness in mapping flood inundation, such as stormwater runoff analysis and design; road and utility mapping; facility planning and construction (for wastewater, for example); watershed planning; evaluation of building and development permits; identifying buildable or critical areas; and for public information (P. Drury, Kitsap County Department of Public Works, written commun., 1998). In the Puget Sound region, these data were typically acquired at a cost of about $1,000 per square mile. New data collection methods, such as LIDAR, promise to increase the accuracy and reduce the cost of high-accuracy elevation data in the near future. **Figure 4** illustrates the level of detail available in the high-accuracy TCGC data as compared to USGS 10-meter level II DEMs.

Digital Elevation Maps

The most common DEM currently available is the standard USGS level II 30 m (or, in our case, 10 m) gridded DEM. However, because of the importance of the high-accuracy data to the study method described here, these were deemed unsuitable because of low vertical accuracy, low horizontal resolution, and production artifacts inherent in them. The level of accuracy is especially relevant to this and other methods that propose the use of DEMs as a means of identifying inundation areas. Standard USGS DEMs are derived from the elevation contours on USGS 1:24,000-scale topographic maps and have a vertical accuracy of half a contour interval (typically 10 feet, 5 feet in some low-relief areas). This vertical accuracy is not sufficient for delineating inundations for flood stages that may differ by as little as 1 ft. For the Nisqually River, the average difference in flood elevation for the 100- and 500-year floods (from the original FIS) is 2.2 feet.

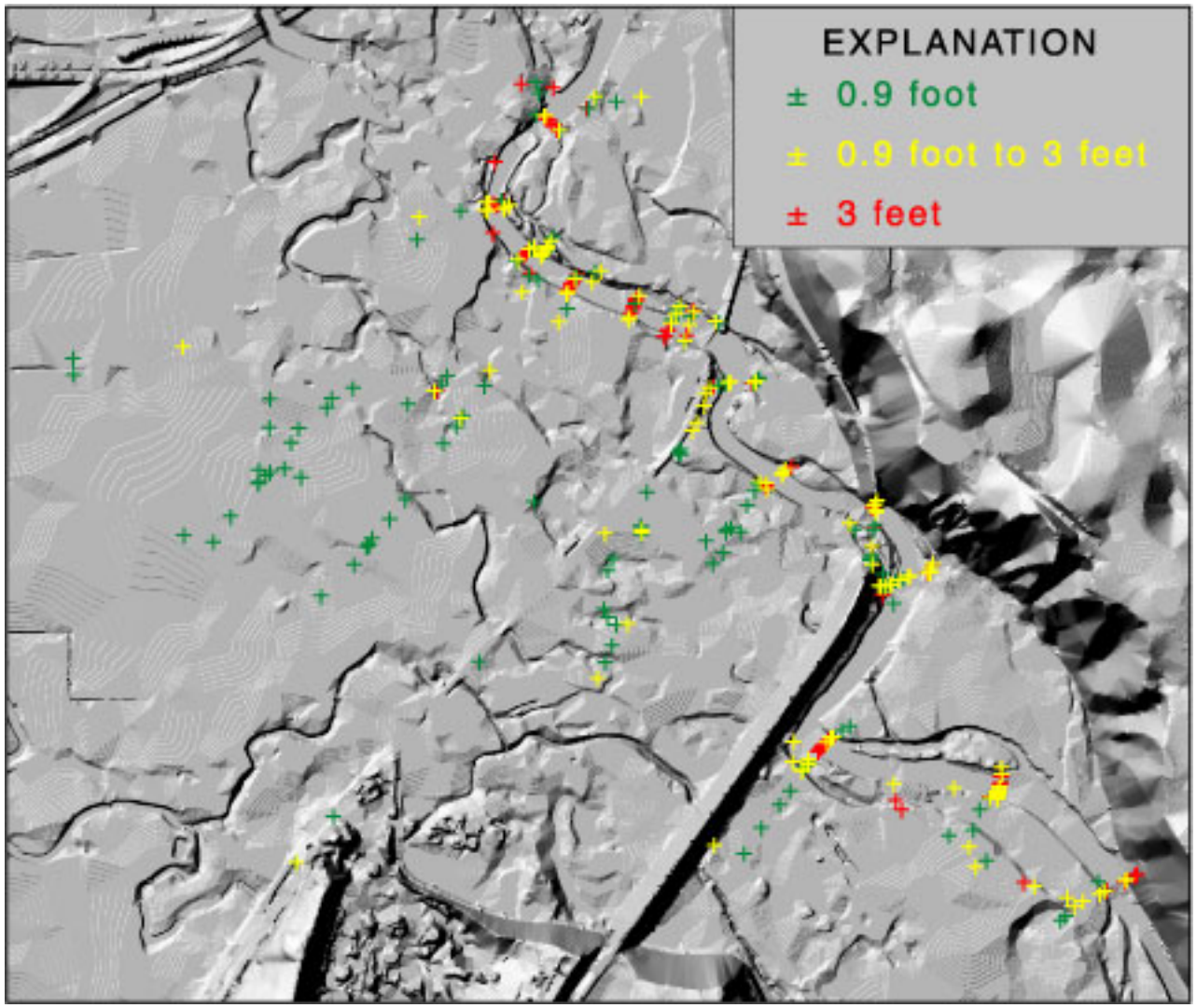


Figure 2. Differences in elevation between field survey points tied to elevation monuments from the 1970's flood study and points on the Digital Elevation Model derived from Thurston County Geodata Center data.

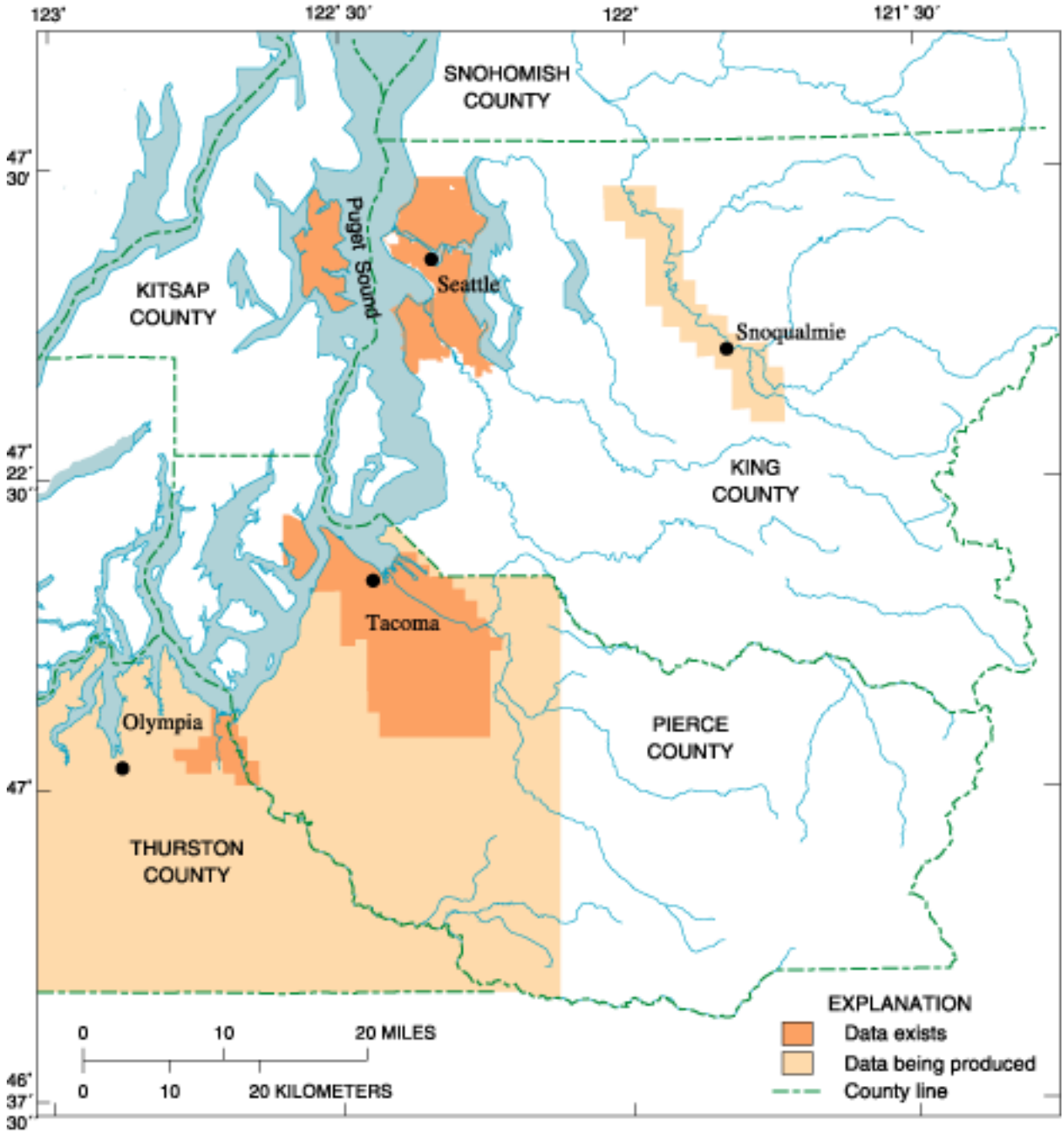


Figure 3. Availability of very-high-accuracy elevation data in the Puget Sound Region, Washington, 1998.

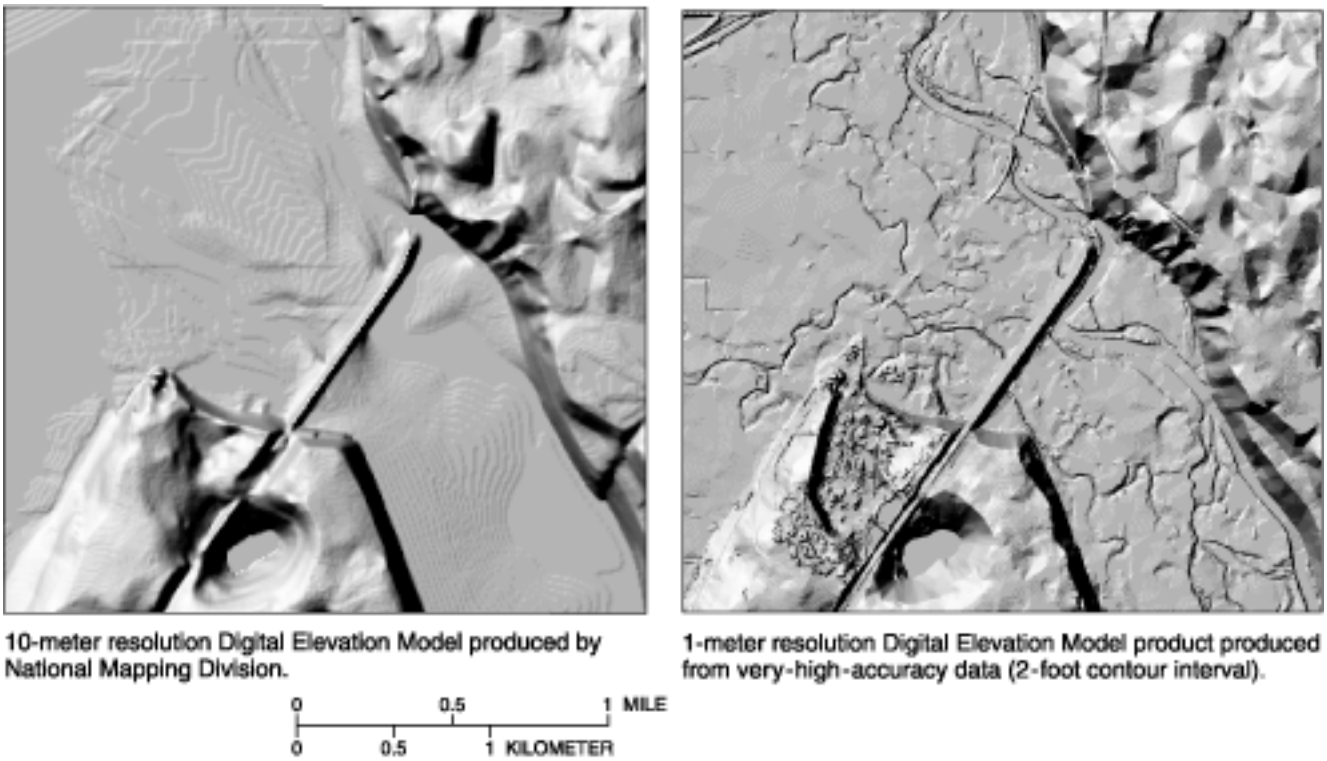


Figure 4. Comparison of level of detail in a standard U.S. Geological Survey 10-meter Digital Elevation Model and one produced from newer 1-foot vertical accuracy elevation data.

Existing USGS DEMs include artifacts of production that can impede flood delineation **(fig. 5)**. Artifacts formed during the automated DEM generation process include these:

- *'Starburst'* – an artificially elevated or depressed star-shaped area generated because of a discontinuity in the input contours; the star may have up to 16 radial arms that correspond to the 16-way interpolation used in DEM creation algorithm; and
- *'Rice Paddy'* or *'Pocket Terrace'* – a contour-biasing artifact that occurs where contours are strongly curved; the DEM creation algorithm incorrectly interpolates between one side of the curved section and the other, generating a flat area that causes a 'layered' or 'stepped' appearance.

Other artifacts may be created in subsequent editing processes. They include these:

- *Outlines around bodies of water* – cells in a body of water (a lake, for example) are set to an arbitrary value as large as one-half contour interval below the edge of the water, effectively recessing the water body into the terrain; and
- *'Stream Editing'* – streams represented by double lines on the source 1:24,000-scale topographic quadrangle may be edited such that the stream retains the elevation of the last contour that crossed the stream, and jumps in elevation up to the next contour at the point they intersect.

The USGS is currently adopting new DEM production methods that will eliminate or minimize these artifacts (J. E. List, USGS National Mapping Division, Elevation Program, written commun., 1998). Nevertheless, the bulk of DEMs currently available include production artifacts.

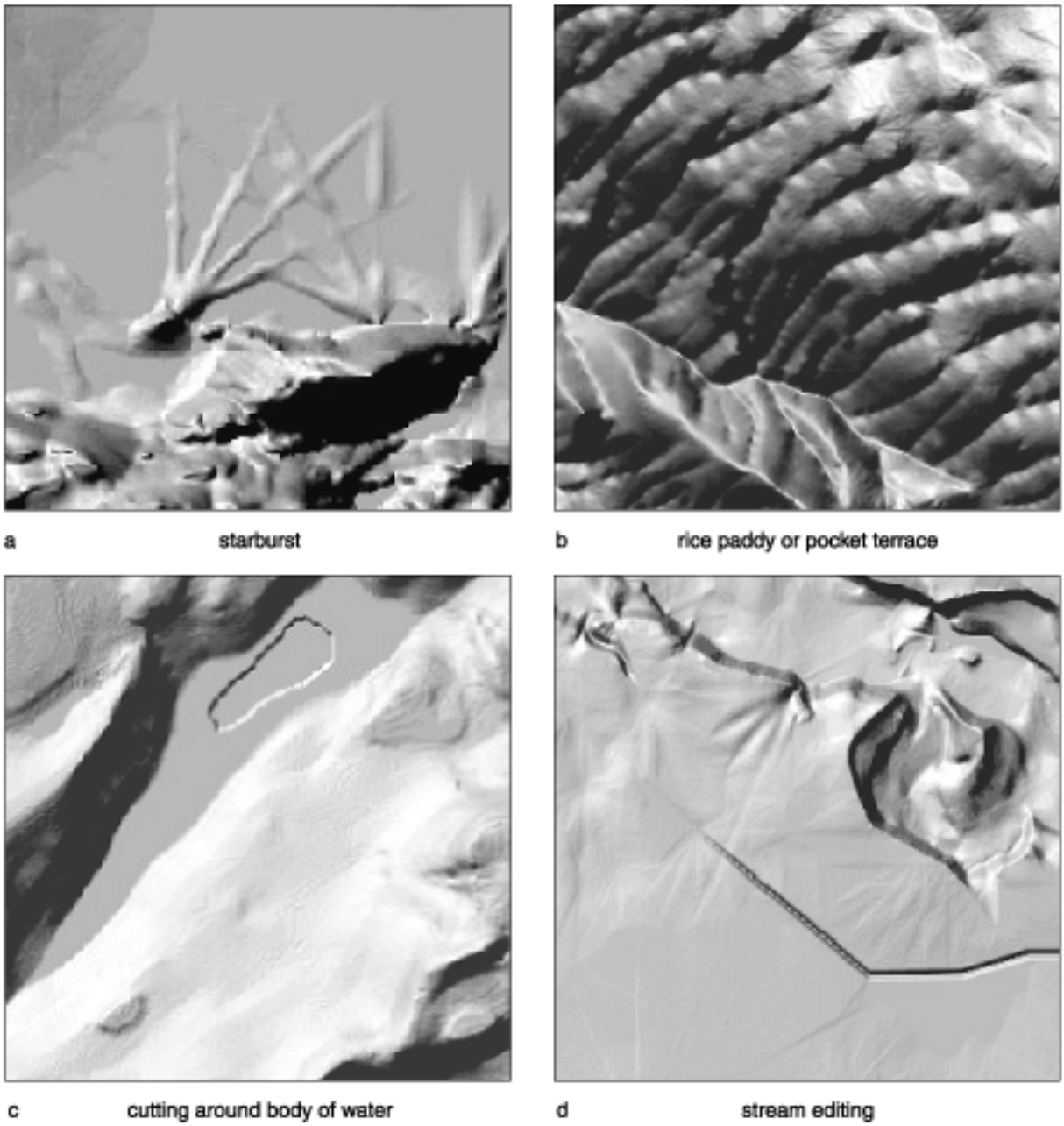


Figure 5. Examples of production artifacts found in standard U.S. Geological Survey Digital Elevation Models.

UPDATING FLOOD INFORMATION

The information required to prepare a flood map are the flood flow to be mapped and the elevation associated with that flood. Flood flows are determined statistically and are based on flood recurrence intervals of 10, 50, 100, and 500 years (a 100-year recurrence interval correlates to a 1 percent chance of that flow occurring any year). These flood frequency statistics are based on historical records of annual peak flows. Flood stages, or elevations, for each of the flood flows are traditionally determined with numerical computer models; in this pilot, flood stages are determined using the results of the numerical model developed for the existing flood map.

Flood Frequency

The original flood frequency discharges used for the Nisqually River downstream from its confluence with Horn Creek, at river mile 25.8, are in the FEMA FIS Reports for Thurston County (1982) and Pierce County (1987). They were determined by summing the discharges from the outlet of La Grande Dam with the discharges from tributaries between the dam and the farthest downstream gaging station on the Nisqually River (station 12089500, located at river mile 21.8). The La Grande Dam outlet discharges were furnished by Tacoma City Light, the owner and operator of a hydroelectric facility at the dam. The inflow discharges from downstream tributaries were estimated from regional regression equations developed for the two FIS reports. Similarly, discharges at the mouth of the Nisqually River were estimated by adding the estimated tributary discharges for the entire reach of the Nisqually River between the dam and the river's mouth to the discharges from the outlet of the dam. These discharges were all within about 1 percent of those determined for just the upstream reach, which indicates that there is very little tributary inflow along the lower 21.8 miles of the river.

For comparison, flood frequency discharges were also determined for the original study by means of a flood frequency analysis of the annual peak discharges at gaging station 12089500. These discharges were calculated using USGS computer program J407 (Kirby, 1981), which follows the guideline set forth by the Interagency Committee Advisory on Water Data (1982) of using a log-Pearson Type III distribution of the annual peak-discharge data to conduct the analysis. The discharges thus determined were all within 4 percent of those used in the Pierce and Thurston County FIS reports.

The updated flood frequency discharges used for this pilot study were determined using program J407 with all available annual peak-discharge data (including the approximately 20 years of additional data gathered since the original study) for gaging station 12089500. Most of the updated discharges, especially those for longer recurrence intervals, are significantly higher than those used in the Pierce and Thurston County FIS reports (**table 1**). The large increases reflect the effect of including the 1996 peak discharge, 50,000 ft^3/s (cubic feet per second), in the log-Pearson Type III analysis. The 1996 flood was nearly twice as large as the next highest discharge (25,700 ft^3/s in 1965) in the entire 40-year period of record analyzed (1948-68, 1978-96).

Many basins are ungaged, however, and in those cases FISs have used flow estimates based on regional regressions. Additional flow information for the gaged basin(s) serving as the basis for these regional estimates, also allow better estimates to be made for the ungaged basin. In these cases, the regional regressions should be updated as opposed to the direct statistical estimation described here for the Nisqually River.

Table 1. Comparison of flood discharges from the Flood Insurance Study (FEMA, 1982) and those updated for the pilot study (1997) for selected recurrence intervals

[ft^3/s, cubic foot per second; FIS, Flood Insurance Study]

Recurrence Interval	FIS Discharges (ft^3/s)	Updated Discharges (ft^3/s)	Percentage of change
10-year	21,500	21,500	0
50-year	29,000	33,500	+16
100-year	33,000	40,000	+21
500-year	45,000	56,000	+24

Flood Stages

The hydraulic model used to determine the original FIS flood stages—the elevations of the flood surface at cross sections along the length of the river—was the U.S. Geological Survey step-backwater computer program J635. Step-backwater models, in general, use elevation cross sections from selected locations along a stream reach, together with estimates of the effective roughness of the channel at and between cross sections, to calculate the height to which the water surface of the stream at a particular cross section will rise in order to pass a certain streamflow. The approach used in this pilot study was to use the archived results from the original model to estimate flood stages for updated 10-, 50-, 100-, and 500-year flood discharges. This was accomplished by developing a stage-discharge relation for each cross section based on the original hydraulic model results.

Stage-Discharge Relations from Existing Hydraulic Model Output

Stage-discharge relations are regularly developed for USGS streamflow gaging stations. They take the form of log-log plots of stage against discharge, with a log offset applied to obtain the most linear relation possible. The log offset is used to determine the logarithmic depth of flow that is linearly related to the logarithm of discharge for a given size, shape, and slope of the channel. The results of a previous step-backwater analysis can be used as data points for an analogous stage-discharge relation; the model computes the stages associated with specified discharges. If the results from a previous FIS study are used, which is the case for the reach of the Nisqually River used for the pilot study, then there are four data points available for each cross section—the computed elevations associated with the 10-, 50-, 100-, and 500-year discharges. These data points should be obtained from the original step-backwater analyses output files rather than from the flood profile plots contained in FIS reports because the resolution of the profile plots is low (in the pilot study, 5 feet to the inch). The original output files are generally archived and maintained by Technical Evaluation Contractors (TECs) under contract with FEMA.

The stage estimates for the updated discharges corresponding to the 10-, 50-, 100-, and 500-year recurrence intervals were estimated using linear regression of the logarithmic transform of the stage and discharge data (a standard transform applied to these relations). A square-root transform was also applied to the data to estimate the stage of the 500-year flood discharge in order to evaluate the extrapolation process for floods higher than the highest FIS discharge. This is discussed below.

Comparison with Original Hydraulic Model

To evaluate the quality of the updated stage estimates, the original step-backwater hydraulic model was rerun using the updated flood discharges. The starting water surface elevation used in the original model run, the mean higher-high tide of Puget Sound at the mouth of the Nisqually River, was also used in the model rerun. The differences were generally small for either log or square-root transform regression (**figs. 6** and **7**); for the log transform regression, 84 percent were within 0.2 foot (**table 2**). Using either transform, the differences were largest for the 500-year discharge, because the updated discharge (56,000 ft^3/s) is 24 percent larger than the previous 500-year discharge (45,000 ft^3/s) and required extrapolation of the stage-discharge relation. **Table 3** presents the means, medians, and standard deviations of the differences between estimates from the pilot study and the updated model results for each of the four recurrence-interval discharges. As would be expected, the larger differences for the 500-year elevations illustrate the need to perform extrapolations with caution. Nevertheless, 81 percent of the estimates for the 500-year flood elevation were within 0.2 ft when using the regression estimate with the best fit at each cross section (**table 4**).

Table 2. Percentages of flood elevations estimated by logarithmic regression that were within 0.1, 0.2, and 0.3 foot of elevations calculated with the step-backwater model, for the four recurrence intervals

Recurrence Interval	Percentage of elevations		
	0.1 foot	0.2 foot	0.3 foot
10-year	82	99	100
50-year	84	100	100
100-year	97	100	100
500-year	20	38	61
Average	71	84	90

Table 3. Statistical comparison of differences, in feet, between flood elevations estimated by logarithmic regression and calculated from the step-backwater model, for the four recurrence intervals

Statistic	Recurrence Interval (discharge, in cubic feet per second)			
	10-year (21,500 ft^3/s)	50-year (33,500 ft^3/s)	100-year (40,000 ft^3/s)	500-year (56,000 ft^3/s)
Mean	0.04	-0.05	-0.02	0.25
Maximum	0.17	0.11	0.05	0.86
Minimum	-0.23	-0.17	-0.13	-0.48
Median	0.05	-0.05	-0.02	0.25
Standard deviation	0.07	0.06	0.03	0.25

Table 4. Percentages of estimated 500-year flood elevations within 0.1, 0.2, and 0.3 foot of elevations calculated from the step-backwater model

Transformation applied	Percentage of elevations within (in feet)		
	0.1	0.2	0.3
Logarithm (base-10)	20	38	61
Square root	38	49	68
Best of either	57	81	98

This may not be true, however, for other streams where extrapolation is required because extrapolations implicitly assume that the stage-discharge relation (appropriately transformed) continues to be linear above the highest data point (the 500-year discharge), an assumption that could be unjustified in many situations. For example, an updated 500-year flood discharge could conceivably raise the flood elevation to a point where it breaks out of a large historical river channel onto a wide flood plain. Changes in channel geometry or land cover could also significantly alter the stage-discharge relation for the 500-year discharge and other discharges. Regardless of the physical setting, great caution should be exercised if the new 500-year discharge is significantly larger than the one used in the original FIS analyses.

The typical flood discharge used for planning purposes is the 100-year event, however, and interpolated flood elevation estimates for these floods are well within the errors associated with original hydraulic models. In some cases flood insurance

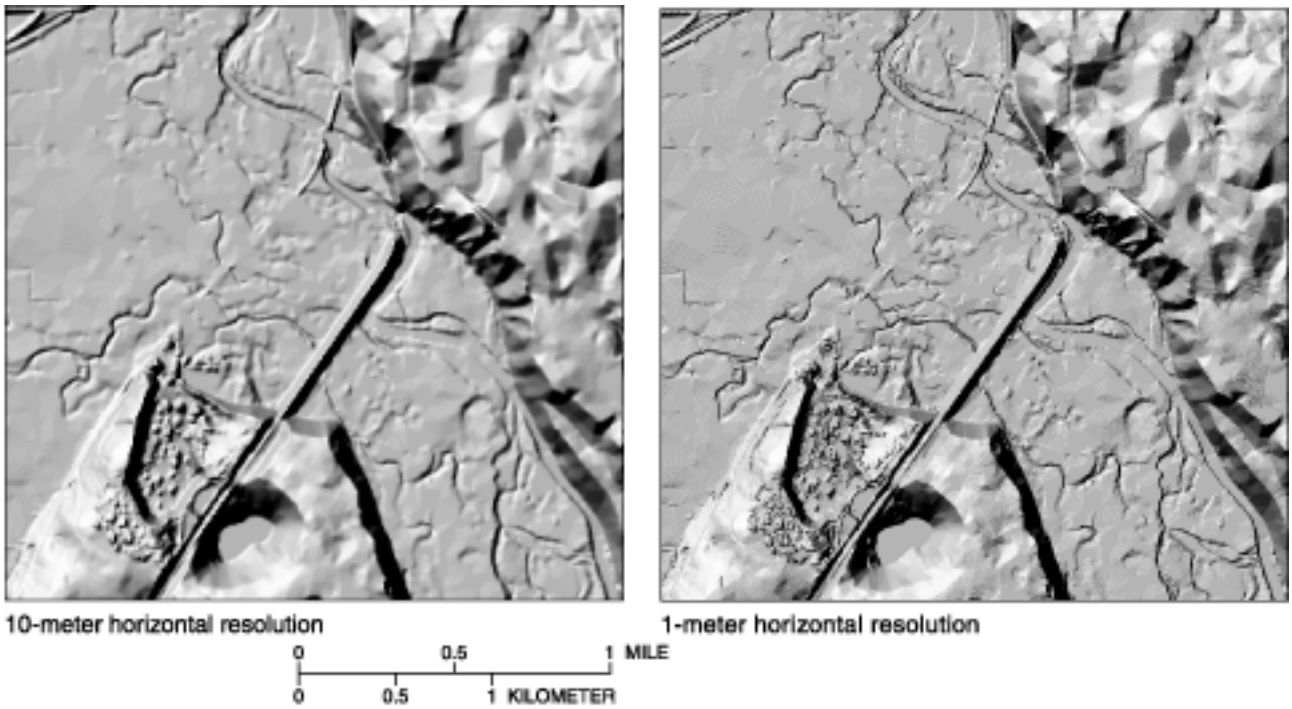


Figure 10. Comparison of digital elevation models at 10-meter and 1-meter horizontal resolutions.

As with land surface generation, TINLATTICE was the program used to generate the flood surface. TOPOGRID was found inadequate because of its treatment of water surface contours along sinuous reaches of the river such as oxbows: elevation information was found to 'leak' between river reaches that were not contiguous. TINLATTICE allows the use of a boundary polygon that eliminates this undesirable effect by automatically prohibiting such inter-reach inter-pollution.

As with creation of the land surface DEM, re-creation of flood-surface elevation contours is an important quality-assurance step that reveals problems with DEM generation. The cross sections used for this pilot were a mile or more apart, and a quality-assurance check revealed significant triangular faceting between cross sections. This was remedied by using an automated GIS feature called densification that adds nodes to the cross sections and polygon boundary to provide a denser network and correspondingly smaller (and therefore less variable) triangular facets.

Creating an Inundation Map

Creating an updated inundation map is trivial once the digital representations of the flood and land surfaces have been created and checked. The DEM representing the land elevation is subtracted from the flood DEM, yielding positive values (inundation) where the flood elevation is numerically greater than the land elevation and negative values elsewhere. The resulting raster data set is then converted to a polygon for storage, display, and further analyses. The updated inundation map for the 100- and 500-year floods on the Nisqually River is shown in **figure 11**. A comparison of (a) the original FIRM, (b) the inundation map determined using the unrevised flood discharge and new elevation data, (c) the updated inundation map determined using the revised flood discharge and new elevation data, and (d) an aerial photograph of an approximate 100-year flood from February 9, 1996, (**fig. 12**) demonstrates the effectiveness of the pilot study approach. The aerial photograph confirms that the updated map more accurately reflects inundations than does the existing FIRM. These maps also illustrate the significance of using high-accuracy, high-resolution elevation data—the flood maps prepared using new elevation data and the unrevised and revised discharges are more similar to each other than to the original FIRM.

Additional Benefits of GIS-Generated Flood Maps

The raster data set created from intersecting the land and water surfaces not only yields areas of inundation, but also provides the depths of inundation (**fig. 13**). In addition to the obvious value of flood depth information—having some idea of whether the water would be 1 or 5 ft deep—this information can be used for loss estimation, such as the application of depth-damage curves. FEMA is currently developing a flood-loss estimation method that will utilize depth information. Adding GIS layers such as roads, buildings, levees, or critical facilities to the flood depth map (**fig. 14**) produces even more useful information about flood damage. An estimated error factor can be added to or subtracted from the flood depths to map areas of uncertain flood hazard (**fig. 15**). For demonstration purposes, the error estimate in **figure 15** is the standard deviation of the differences between the elevation model and the field-surveyed elevations used to check the elevation model, and is about 1 ft.

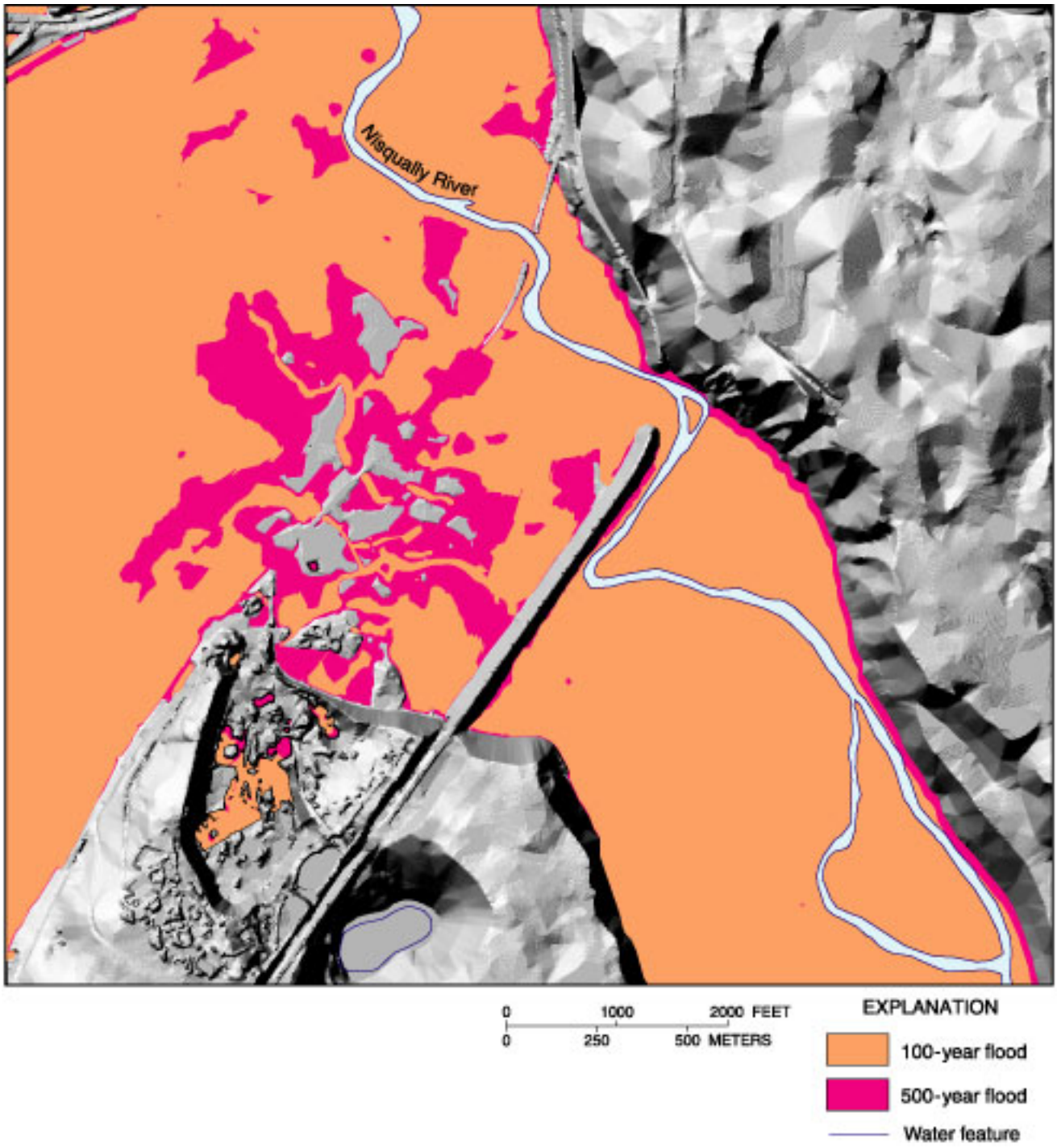
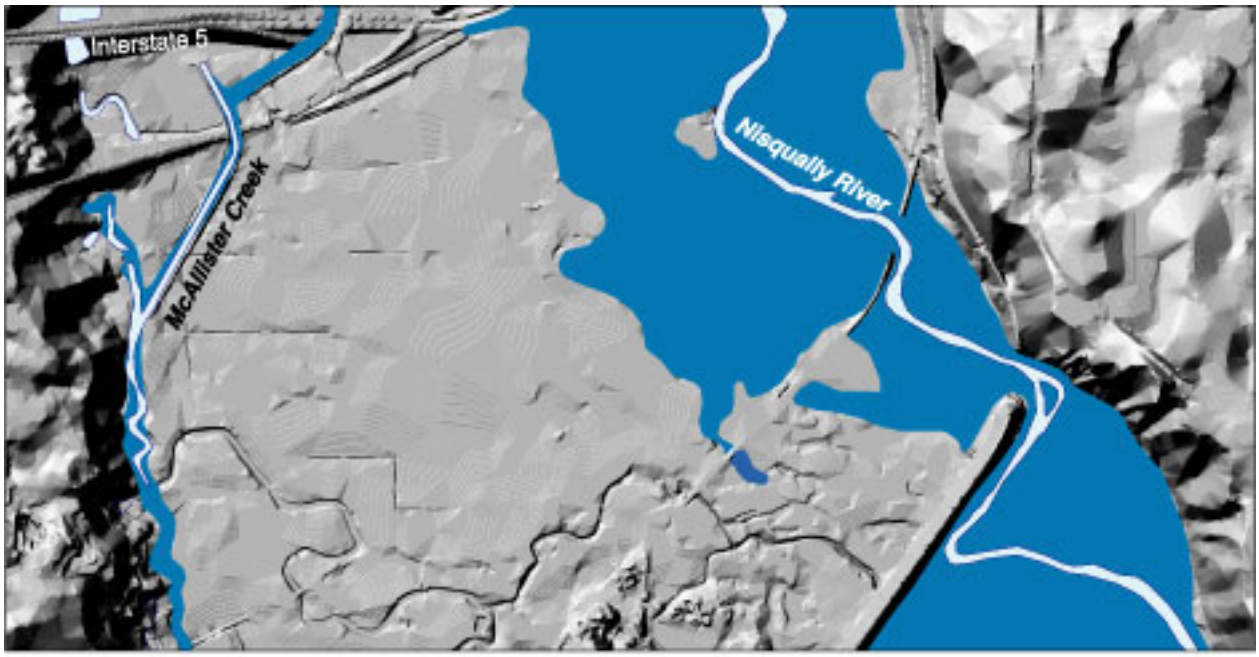


Figure 11. Updated flood inundation map for the 100- and 500-year floods.



(A) 100-year flood map from original FIRM 1982 study.

(B) 100-year flood map using new land elevation only.

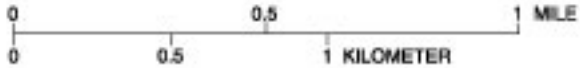


Figure 12. Comparison of the original Flood Insurance Rate Map (FIRM) for the 100-year flood with updated flood maps made using high-accuracy land elevation models and with an aerial photograph of the Nisqually River flood of February 9, 1996.

(C) 100-year flood map using new very-high-accuracy land elevation and updated flood elevation.

(D) Aerial photograph of the Nisqually River flood of February 9, 1996, in the mapped area.

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 12. *Continued.*

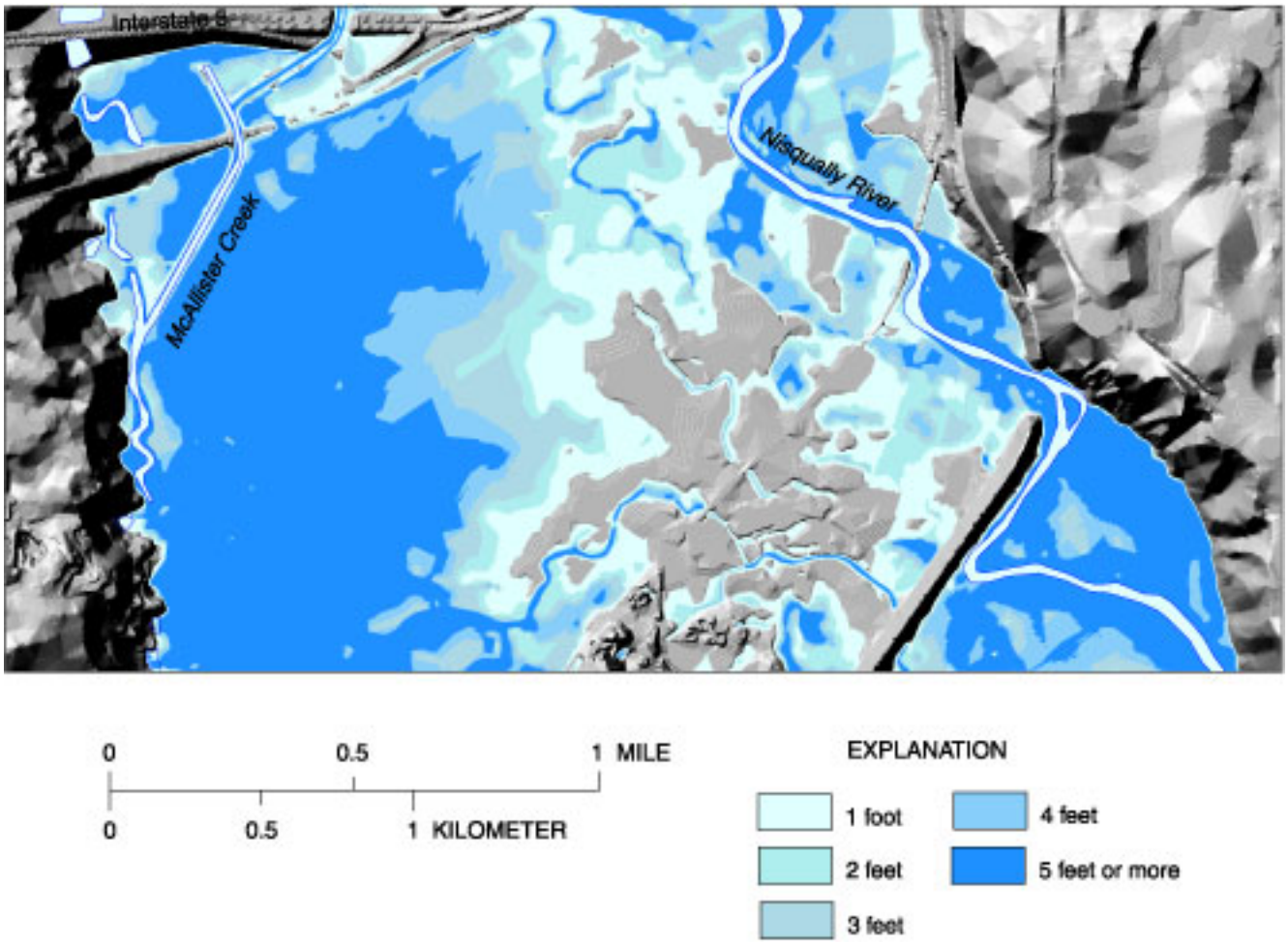


Figure 13. Flood depths for the 100-year flood.

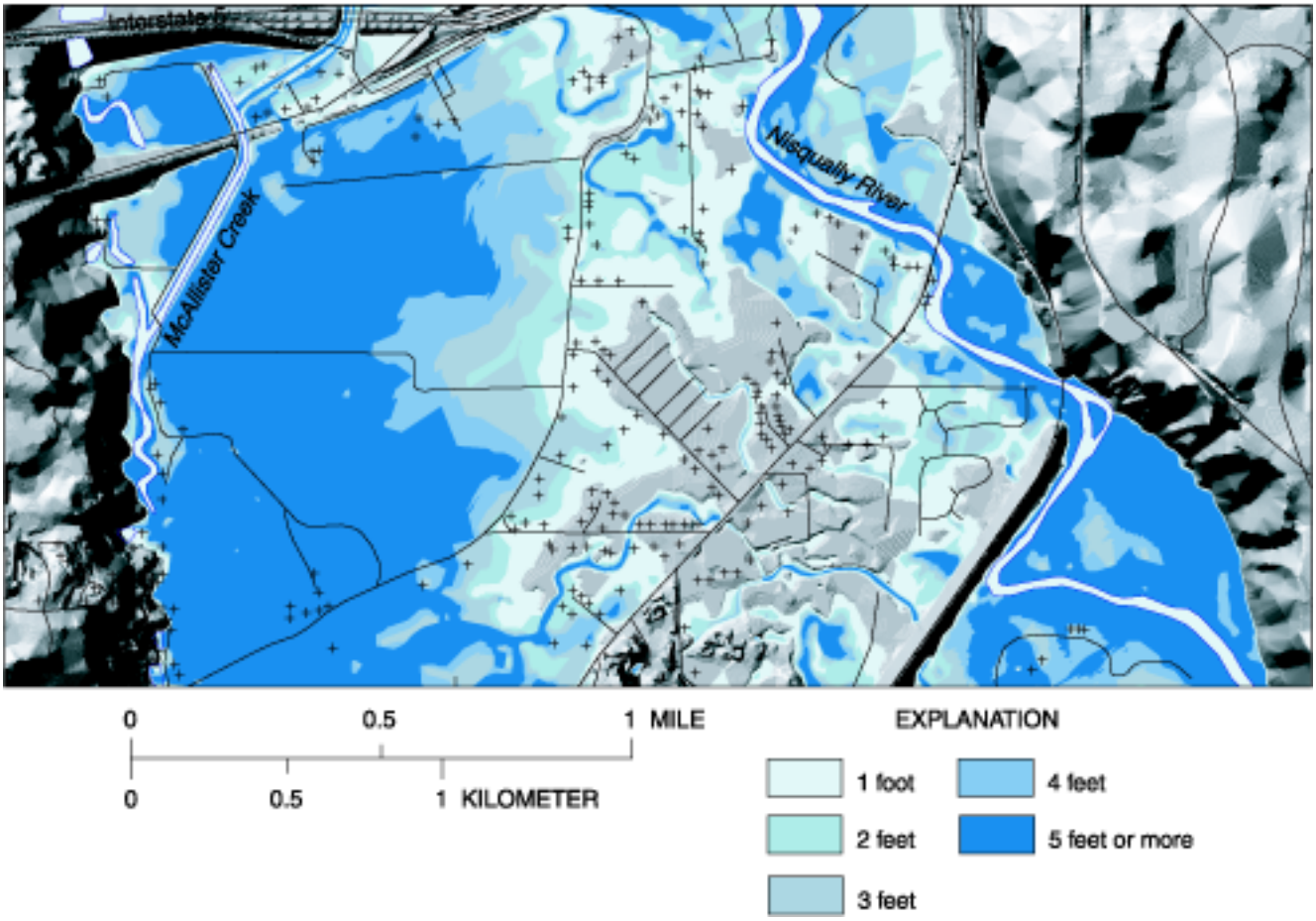


Figure 14. Flood depths for the 100-year flood, with roads and buildings.

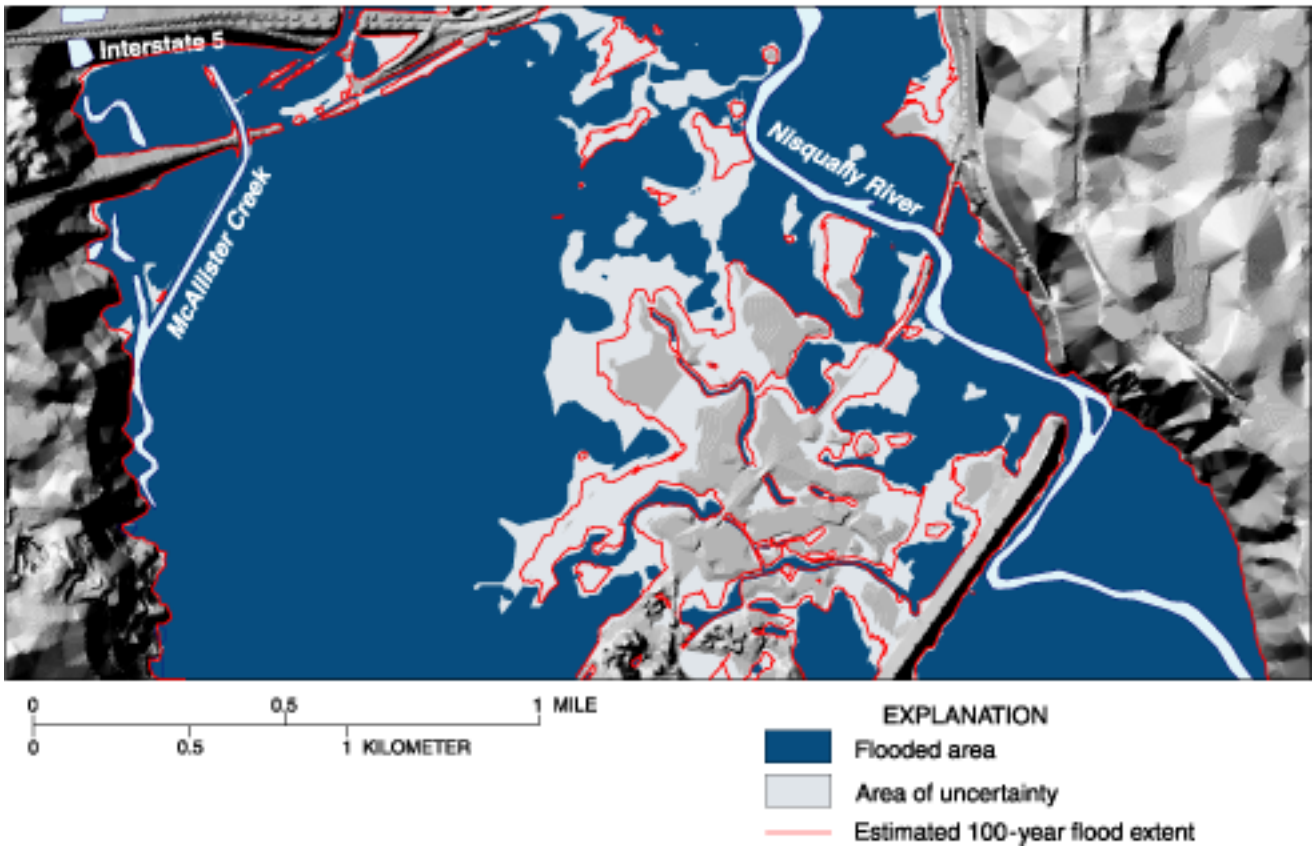


Figure 15. Areas of uncertain flood hazard for the 100-year flood.

DATA MANAGEMENT

The digital format of a GIS provides a more efficient means of storing and generating flood maps than the current method of producing, storing, and retrieving large paper maps. Maps stored in a GIS can be generated for any particular location quickly and precisely, as opposed to the current situation of locating the map or maps depicting an area, and they can be generated at appropriate scales and sizes as needed.

The extent of the contour data sets and the cell resolution and precision of the raster data sets greatly affects storage requirements and processing space and time. To maintain the integrity of the high-resolution contours, a 1-meter cell size was used in generating the raster surfaces. Although a 1-meter cell size results in a large data set, size can be substantially reduced, if needed, by converting the values from floating-point to integer format, with the added benefit of faster processing speeds in subsequent raster operations. For example, floating-point values in meters can be converted to integer values in decimeters without losing accuracy—the accuracy of the input elevation data does not support precision greater than a decimeter. On some computers, disk space can be a consideration when working with high-resolution data. If disk space is a concern, storage requirements can be greatly reduced by (1) reducing the precision of floating-point values to integer format; (2) creating final products, such as flood plains and flood depths, as polygon coverages instead of raster data sets; and (3) deleting intermediate raster products. Original land and water raster surfaces should be retained for surface profiling or display purposes.

LIMITATIONS AND OPPORTUNITIES FOR FURTHER STUDY

In some flood plains, land use has changed significantly since the original flood study was conducted, and the estimated effective roughness of the land cover has changed accordingly. For example, if significant development has taken place in a flood plain, the stage-discharge relation is likely to have changed in response to the substitution of buildings and roads for trees and bushes. In this case, it is unlikely the existing hydraulic model remains applicable, and the cost, in time and money, to prepare a new hydraulic model is justified. Additionally, major land-use changes, such as clear-cutting forests or major development, could change the flood plain characteristics, causing fundamental changes in the stage-discharge relations described by the existing hydraulic model. In either case, however, the preparation of a new model could still be accelerated, and the accuracy of the model improved, by the acquisition and use of very-high-accuracy elevation data. Land-use changes outside of the flood plain do not necessarily void the results of an existing hydraulic model. These changes may affect the flood frequency relation by changing the amount and timing of runoff in the basin, necessitating a revision of the 100-year flood discharge. Because this in itself has no direct effect on the stage-discharge relations in the flood plain, the approach from the pilot study can be applied.

Another situation where a new model would be justified is where major changes to the stream channel have occurred as a result of meandering, avulsion, aggradation, or scour. This would be especially true where the normal stream channel conveys a significant percentage of the flood discharge being considered. In contrast, if the normal stream channel conveys a very small portion of the flood flow, changes in the channel might not be significant enough to warrant preparing a new hydraulic model.

Manmade hydraulic structures that have been built or modified since the original flood study will in all but the most rare of circumstances void an existing hydraulic model in the vicinity of and for a limited distance upstream from the structure.

Wide application of the pilot study mapping approach requires the development of guidelines for evaluating the applicability of existing hydraulic models. Considerations would include degree of land-use changes within the flood plain and the importance of changes in the normal stream channel and other geomorphologic characteristics that either lend themselves to, or resist, significant stream channel changes (for example, the geology of the river bed or the relative size of the normal channel compared with the flood plain).

SUMMARY

The need to develop a more efficient method of producing flood inundation maps, the need to update old and aging maps as quickly as feasible, and the need to bring flood mapping into the digital age are widely recognized. This report presents a methodology piloted in Washington State that used existing hydraulic studies, locally produced high-accuracy elevation data, and Geographic Information System (GIS) technology to improve map detail and accuracy, reduce time and cost requirements, generate useful new types of flood maps, and improve map usability.

$2.7 billion (1997 dollars) has been spent creating existing Flood Insurance Rate Maps (and similar flood maps, revisions, and updates). The National Flood Insurance Reform Act of 1994 mandates that the Nation's flood maps be reviewed and revised in the near term and subsequently reviewed every 5 years. Accordingly, FEMA's Map Modernization Plan emphasizes that more cost-effective methods to produce, store, and use flood maps are essential.

Additional peak-flow data collected, or new regional regression equations developed, since the original flood studies were conducted may significantly improve the hydrologic analyses used to determine the size of the 100-year flood discharge—the standard flood used for planning purposes—simply due to the increased amount of data available. In this pilot study, the 100-year discharge increased from 33,000 to 40,000 cubic feet per second (a 21 percent increase). Changes in watershed characteristics also have the potential to change the discharge associated with the 100-year flood, and require the use of up-to-date peak-flow data.

Advances in elevation mapping allow higher accuracy and resolution that translate into more accurate and detailed flood inundation maps. One-foot vertical accuracy elevation data has recently become readily available, and although some previous studies were conducted using cross-sectional elevation information accurate to that level, few inundation maps were delineated from information with this degree of accuracy.

The digital mapping abilities provided by GIS technology allow the delineation of flood inundation to be executed by computer, speeding the process and removing the need for a hydrologist to manually estimate inundated areas between cross sections. GISs also allow the generation of depth-of-flood maps and maps with up-to-date (and easily updated) cultural features such as roads, houses, and critical facilities. Additionally, the maps are stored digitally and can be reproduced easily for any location at a broad range of map scales, simplifying the storage and usefulness of the maps; digitally georeferenced maps allow specific geographic locations to be located quickly and precisely.

A key time and cost saving aspect of the pilot method is the reuse of the hydraulic modeling results from an existing detailed Flood Insurance Study (FIS)—thus eliminating expensive and time-consuming field collection of elevation and structural information (bridge openings, for example). Mathematical stage-discharge relations are developed for each original cross section and are then used to determine flood elevations associated with updated discharges for selected recurrence intervals (as determined from updated hydrologic analyses). Land-surface elevation data and the flood stages calculated for each cross section (for each of the flood discharges selected for mapping) provide the basis for raster (cell-based) digital representations of the land and flood surfaces in a GIS. Quality assurance is an important aspect of surface generation. Subtraction of the land surface from the flood surface yields a raster representation of the inundation for each of the selected recurrence intervals. Positive values indicate inundation and inherently contain depth-of-flood information; negative values indicate no inundation. In addition to depth-of-flood maps, GISs allow the mapping of other useful information such as areas that are subject to uncertain flooding due to the errors associated with hydrologic and hydraulic computations, elevation data, or other sources of uncertainty.

The continued validity of the existing hydraulic analyses is a requirement of this method and hinges on whether stream channel, stream valley, and structural changes are large enough to significantly alter the stage-discharge relation. Because existing hydraulic models will not remain applicable in all cases, close consultation with FEMA's technical specialists is appropriate.

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