

Article

Inundation Mapping Initiatives of the Iowa Flood Center: Statewide Coverage and Detailed Urban Flooding Analysis

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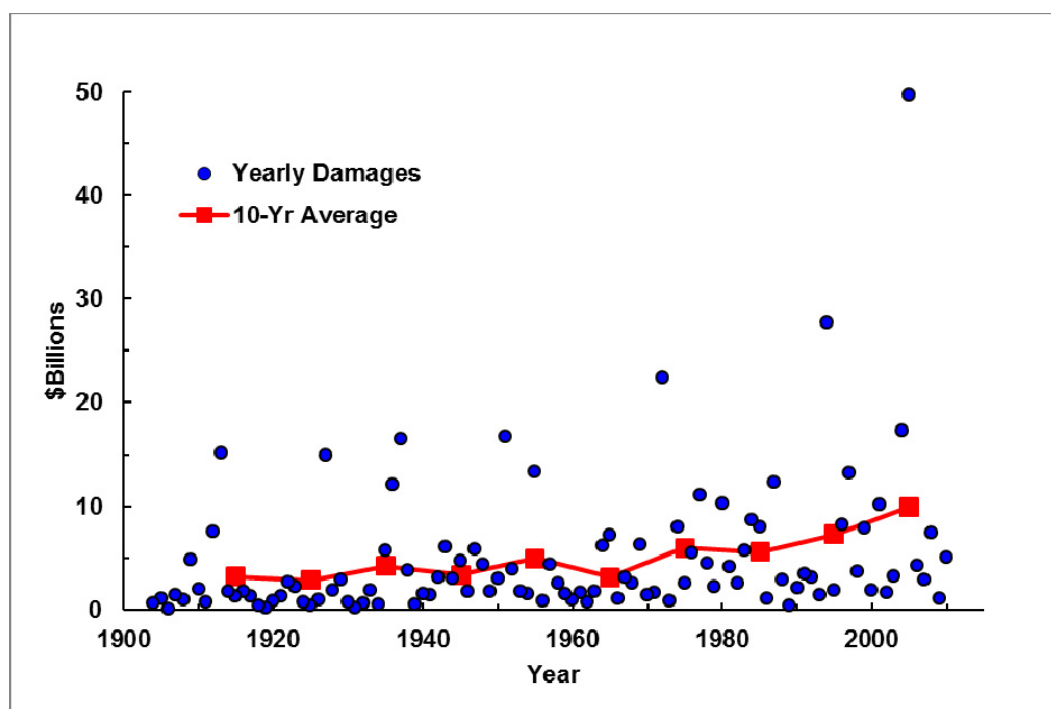
Abstract: The State of Iowa, located in the Midwestern United States, has experienced an increased frequency of large floods in recent decades. After extreme flooding in the summer of 2008, the Iowa Flood Center (IFC) was established for advanced research and education specifically related to floods. IFC seeks to improve Iowa’s flood hazard awareness through the development of easily accessible, high-quality mapping products. Mapping initiatives consist of two model development approaches: (1) statewide floodplain delineation using one-dimensional (1D) models, and (2) urban flood mapping using detailed one-dimensional/two-dimensional (2D) coupled models. The statewide floodplain project will benefit Iowans through the creation of a comprehensive set of floodplain maps developed under a single consistent methodology. These will be important tools in evaluating flood risk, regulating floodplains, and participating in the National Flood Insurance Program. Detailed urban flood analyses are used to develop inundation map libraries. These map libraries are meant to supplement National Weather Service river stage flood forecasts by providing a visual representation of potential flood extent according to predicted river stage at stream gage locations.

Keywords: Iowa Flood Center; hydraulic; flood; maps; statewide; coupled

1. Introduction

According to the National Weather Service (NWS), flood damages in the US have averaged nearly \$8.4B per year since 1990 [1]. Inflation-adjusted yearly estimates of US flood damage since 1904, shown in Figure 1, indicate an increasing trend. While the methodology used by NWS in estimating damages has been questioned, there have been several studies that have confirmed an increasing trend of US flood damages over the past century [2–4]. This increasing trend could be attributed to an increased frequency of extreme rainfall events as a result of climate change [5]. The projected effects of climate change include alteration of precipitation patterns and increased frequency of extreme rainfall events in many parts of the world [5–7]. Flood magnitudes will likely be amplified by these climatological changes, exacerbating damages sustained by already vulnerable communities [8].

Figure 1. Inflation-adjusted yearly estimates of flood damage in the US [1].



In addition to the effects of climate change, increased development in hazard-prone areas could be contributing to the positive trend in flood damages. Typical factors contributing to continued development in flood prone areas include: (1) lack of knowledge, (2) low real estate prices, (3) high demand for housing near larger cities and (4) false sense of security due to flood defense systems [9–12]. While the responsibility of investigating personal flood hazard falls on the individual, other parties such as real estate developers and local governments may share the responsibility of continued development in flood prone areas [8,13]. Any steps taken to deter development in flood prone areas must begin with educating citizens and government officials. This education must include accurate flood hazard information.

2. Background

The US Congress established the National Flood Insurance Program (NFIP) in 1968 to allow purchase of subsidized flood insurance in exchange for community-scale adoption of floodplain management regulations that reduce future flood damages [14]. There are approximately 20,600 communities participating in the program, with over 5 million active insurance policies nationwide [15]. While many potential improvements to the program regarding risk identification, mitigation, and communication have been identified [8,16–19], the program continues to provide usable flood hazard information to communities that would otherwise have none. In 2003, the Federal Emergency Management Agency (FEMA) began a flood map modernization project to produce more accurate and accessible flood maps by implementing new data standards and transitioning all future studies to digital formats [20]. As of 2004, FEMA reported 70 percent of the nation's 92,000 flood maps were more than 10 years old, and many reflected inaccurate data [20]. Many of these maps were developed using the United States Geological Survey (USGS) National Elevation Dataset (NED) [21]. Independent studies have concluded that NED data has an overall vertical accuracy of 14.9 feet at the 95 percent confidence level [22]. This lack of accuracy does not meet FEMA's own requirements of 1.2 feet in flat terrain and 2.4 feet in hilly terrain at the 95 percent confidence level [21].

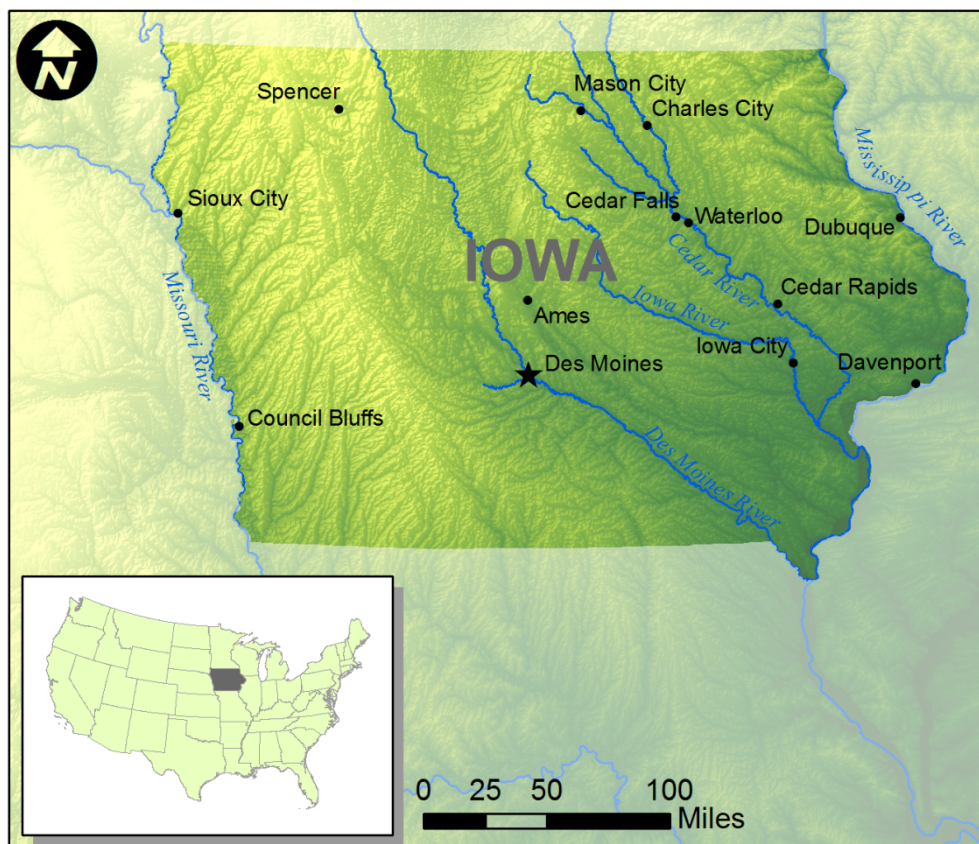
The increasing affordability of high resolution Light Detection and Ranging (LiDAR) data have made updating of flood studies and large-scale mapping efforts more feasible than ever. The State of North Carolina, in partnership with several state and federal agencies, is nearing completion of a pioneering statewide floodplain mapping project that relied heavily on LiDAR data to produce flood hazard maps [23]. In addition to these valuable data, North Carolina has a high concentration of USGS stream gages at approximately 280 locations. Approximately 200 gages measure discharge [24]. These stream gages are key sources of data used in estimating flood quantiles for hydraulic simulations. Efforts to implement similar large-scale floodplain mapping projects must also have access to high-quality LiDAR and stream flow data. In addition to vast data requirements, there must be support from state and federal governments in the form of funding, concerted efforts amongst stakeholders, and expertise to execute the analyses.

3. Floods in Iowa

3.1. Study Area

The state of Iowa is located in the Midwestern US and is bordered by the Missouri River to the west and the Mississippi River to the east, as shown in Figure 2. Major interior streams include the Cedar River, Des Moines River, and Iowa River. Prior to European settlement, Iowa's landscape consisted of vast fields of tall grass prairie. This native landscape has since been drastically altered to produce high yields of corn and soybean row crops [25]. These alterations have the potential to increase peak stream flow response to rainfall in Iowa [26].

Figure 2. The state of Iowa located in the Midwestern United States. Most of Iowa's major cities are located along rivers.



3.2. Historic Floods

The Midwestern United States experienced widespread, summer-long flooding during 1993. This event was the result of intense, persistent weather patterns producing widespread precipitation from January to September, with accumulated precipitation approaching 2.3 times the summer average [27]. Many stream flow records were observed at USGS stream gages throughout the region [28]. The NWS estimated inflation-adjusted damages totaling approximately \$26.5B for the Midwest, with Iowa sustaining damages totaling \$9.7B alone [1,29]. However, many of Iowa's streams experienced flooding of larger magnitude during the summer of 2008.

Much like the floods of 1993, antecedent conditions were significant factors contributing to the June floods of 2008. Precipitation from December of 2007 to May 2008 was the second wettest period on record from 1895 to 2008 [30]. Precipitation during June, shown in Figure 3, averaged nearly 10 inches across the state. Record-setting stream discharges were observed at approximately 30 of Iowa's 140 USGS stream gages. Peak discharges at nine gage locations were estimated to exceed the 500-year event, most notably at Cedar Rapids, shown in Figure 4 [31]. At present, no official estimates of damages sustained by the state of Iowa as a result of the 2008 floods exist, but preliminary estimates range from \$8B to \$10B, nearly equaling damages sustained by Iowa from the 1993 floods [32]. The floods of 2008 caused 85 of 99 Iowa counties to be declared federally recognized disaster areas.

Figure 3. State of Iowa rainfall totals for the month of June 2008 [33].

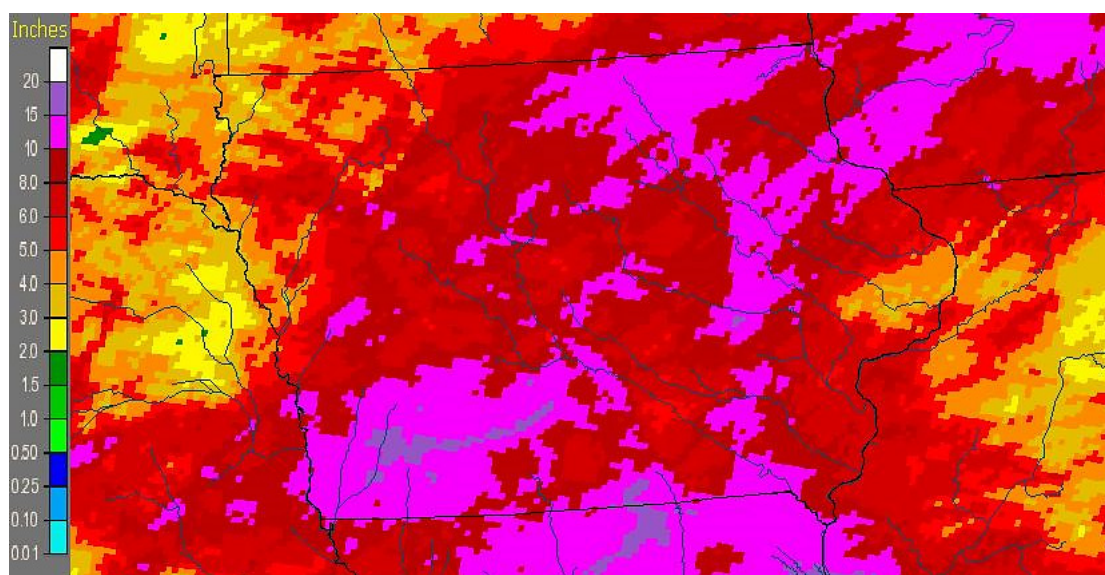


Figure 4. Downtown Cedar Rapids, Iowa at the peak of the 2008 flood, taken from Buchmiller [31].



3.3. Establishment of the Iowa Flood Center

The Iowa Flood Center (IFC) was established by the State of Iowa in response to devastating floods of 2008. IFC serves as a central location for advanced research and education specifically related to floods. Some of IFC's responsibilities include development of hydrologic models for physically-based flood frequency estimation and real-time forecasting of floods, including hydraulic models of floodplain inundation. Community outreach activities include development of programs to improve

flood monitoring and prediction along Iowa's major waterways and to support ongoing flood research. IFC is charged with sharing resources and expertise to assist in the development of a workforce knowledgeable regarding flood research, prediction, and mitigation strategies. Web-based inundation maps have been of particular interest among citizens and government officials. IFC inundation mapping initiatives consist of two model development approaches: (1) statewide floodplain delineation using one-dimensional (1D) models, and (2) urban flood mapping using detailed one-dimensional/two-dimensional (2D) coupled models.

4. Statewide Floodplain Delineation

4.1. Introduction

The state of Iowa, like many areas, has never had a comprehensive set of flood inundation maps. Until recently, a general lack of organization, funding, and data prevented development of such a comprehensive set of maps. In 2006, the Iowa Department of Natural Resources (IADNR) initiated a statewide LiDAR survey with foresight that one of the uses would be a statewide floodplain mapping project. The LiDAR data points have an average spacing of 5 feet or less, and have been interpolated to develop 3.28 foot (1 meter) resolution raster-based digital elevation models (DEMs). These high-density data are available across the entire state.

Availability of LiDAR data together with the commendable flood recovery efforts of Iowans following the 2008 floods led the U.S. Department of Housing and Urban Development (HUD) to provide a \$15M grant to the State of Iowa for modernizing and developing flood maps for the 85 counties declared federal disaster areas. The State of Iowa directed \$10M of these funds to IFC and IADNR to execute the statewide floodplain mapping effort. The project began in 2010 and will take approximately five years to complete. The goal of the project is to provide web-based floodplain maps that will aid in planning, guide emergency management, and allow citizens and officials to better understand flood hazards. An additional purpose of the statewide floodplain mapping initiative is to provide FEMA-approved Flood Insurance Rate Maps (FIRMs), which regulate new construction and determine which property owners must purchase flood insurance as part of the NFIP. These maps will be defined by FEMA as "Zone A", which identify special flood hazard areas for which no base (100-year) flood elevations have been provided [14].

While the scale of the statewide floodplain mapping is sizable, Iowans will reap several benefits from the analyses. Flood analysis and mapping will be completed through a single, consistent methodology, rather than several methodologies unique to different institutions. Counties and cities that would otherwise lack the resources to organize a mapping project will have the opportunity to participate in the NFIP. Many existing floodplain mapping analyses were completed using topographic data that is outdated and of low-quality compared to currently available LiDAR data. Analysis using the latest topographic data will more accurately delineate floodplains.

4.2. Data Sources

Datasets are utilized in the analysis of either hydrologic or hydraulic properties of basins and streams. The bulk of data used for developing floodplain maps is derived from LiDAR data using

geographic information systems (GIS). IFC, in partnership with IADNR, is currently developing a highly accurate stream centerline dataset for streams draining greater than 24 acres using LiDAR data. Other datasets derived from LiDAR data include drainage area, basin boundaries, cross-section geometry, and DEMs. Peak annual stream flow records are provided by the USGS and United States Army Corps of Engineers (USACE) at approximately 207 locations across the state. Land use data are provided by the United States Department of Agriculture (USDA) in the form of the National Land Cover Dataset (NLCD) [34]. Drainage area along streamlines is calculated using GIS tools.

4.3. Hydrologic Analyses

Stream discharge estimates are calculated to establish hydrologic conditions associated with 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent-annual-chance flows (2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return period flows, respectively). The USGS developed methods in 1987 by Lara [35], and in 2001 by Eash [28] to calculate annual exceedance discharges in Iowa streams at ungaged locations using regression equations. The IADNR and Iowa Department of Transportation (IDOT), through experience applying the USGS methods in the state, have developed recommendations on use of the 1987 and 2001 regression equations based upon proximity to stream gages, periods of gage records, and drainage area [36]. These recommendations have been adopted for the statewide floodplain mapping effort. The methods are summarized in Table 1 and thoroughly discussed in the following sections. Methods are established for gaged sites, ungaged sites on gaged streams, and ungaged sites on ungaged streams. A gaged stream is defined as having at least one location with peak annual stream flow records.

Table 1. Summary of methods used to estimate annual exceedance discharges.

| Site Description | Gage Record (Years) | Drainage Area (Square Miles) | Method | Reference |
|-----------------------------------|---------------------|------------------------------|---|--|
| ungaged site on an ungaged stream | --- | 1–20 | 1987 methods for return intervals ≤ 100 years, extrapolated 1987 equations > 100 years | Lara 1987 [35], Appendix |
| | --- | 20–50 | average the 1987 or extrapolated 1987 equations and 2001 methods | Lara 1987 [35], Eash 2001 [28], Appendix |
| | --- | > 50 | 2001 single-parameter regression equations | Eash 2001 [28] |
| gaged site | --- | --- | weighted estimates for gaged sites | Eash 2001 [28] |
| ungaged site on a gaged stream | < 25 | --- | regression-weighted estimate for ungaged sites | Eash 2001 [28] |
| | ≥ 25 | --- | area-weighted estimate for ungaged sites | Eash 2001 [28] |

4.3.1. Drainage Areas Between 1 and 20 Square Miles

Annual exceedance discharges for ungaged locations on ungaged streams draining between 1 and 20 square miles are calculated using the regression equations developed by Lara [35]. Lara developed flood regression relations for the 50-, 20-, 10-, 4-, 2-, and 1-percent-annual-chance equations by fitting a log-Pearson Type III (LP3) distribution to sample data. These regression equations were developed for five hydrologic regions; each delineated by differences in topography and geology. The 1987 regression equations are shown in Table 2. Figure 5a shows the geographic extents of the five hydrologic regions.

Table 2. Lara (1987) [35] USGS regional regression equations for the state of Iowa.

| Region 1 | Region 2 | Region 3 | Region 4 | Region 5 |
|----------------------------------|----------------------------------|---------------------------------|---------------------------------|--------------------------------|
| $Q_2 = 211 \times A^{0.62}$ | $Q_2 = 196 \times A^{0.57}$ | $Q_2 = 129 \times A^{0.62}$ | $Q_2 = 31 \times A^{0.77}$ | $Q_2 = 30 \times A^{0.66}$ |
| $Q_5 = 502 \times A^{0.60}$ | $Q_5 = 402 \times A^{0.55}$ | $Q_5 = 265 \times A^{0.59}$ | $Q_5 = 67 \times A^{0.72}$ | $Q_5 = 37 \times A^{0.71}$ |
| $Q_{10} = 757 \times A^{0.60}$ | $Q_{10} = 570 \times A^{0.55}$ | $Q_{10} = 381 \times A^{0.57}$ | $Q_{10} = 98 \times A^{0.70}$ | $Q_{10} = 41 \times A^{0.74}$ |
| $Q_{25} = 1140 \times A^{0.57}$ | $Q_{25} = 821 \times A^{0.54}$ | $Q_{25} = 555 \times A^{0.55}$ | $Q_{25} = 145 \times A^{0.68}$ | $Q_{25} = 45 \times A^{0.77}$ |
| $Q_{50} = 1500 \times A^{0.60}$ | $Q_{50} = 1020 \times A^{0.53}$ | $Q_{50} = 695 \times A^{0.54}$ | $Q_{50} = 180 \times A^{0.66}$ | $Q_{50} = 47 \times A^{0.79}$ |
| $Q_{100} = 1880 \times A^{0.60}$ | $Q_{100} = 1230 \times A^{0.53}$ | $Q_{100} = 851 \times A^{0.53}$ | $Q_{100} = 227 \times A^{0.65}$ | $Q_{100} = 50 \times A^{0.80}$ |

Figure 5. Hydrologic regions for utilizing annual exceedance regression equations (a) 1987 regions and (b) 2001 regions.



Since equations for estimating the 0.5- and 0.2-percent-annual-chance (*i.e.*, the 200- and 500-year discharges) were not developed by Lara [35], an approach to extrapolate the 1987 regression relations is applied according to Bradley [37] using the LP3 method, as detailed in the Appendix. The regional regression equations for 0.5- and 0.2-percent-annual-chance flows are shown in Table 3.

Table 3. Extrapolated 0.5- and 0.2-percent regional regression equations using Lara 1987 equations assuming a Log-Pearson Type III distribution.

| Region 1 | Region 2 | Region 3 | Region 4 | Region 5 |
|----------------------------------|----------------------------------|----------------------------------|---------------------------------|----------------------------------|
| $Q_{200} = 2300 \times A^{0.60}$ | $Q_{200} = 1460 \times A^{0.52}$ | $Q_{200} = 1020 \times A^{0.52}$ | $Q_{200} = 274 \times A^{0.64}$ | $Q_{200} = 52.1 \times A^{0.81}$ |
| $Q_{500} = 2910 \times A^{0.61}$ | $Q_{500} = 1780 \times A^{0.52}$ | $Q_{500} = 1270 \times A^{0.51}$ | $Q_{500} = 342 \times A^{0.63}$ | $Q_{500} = 54.5 \times A^{0.83}$ |

4.3.2. Drainage Areas Between 20 and 50 Square Miles

Eash [28] developed single-parameter regional regression equations, shown in Table 4, for three hydrologic regions, shown in Figure 5b. Eash also identified two- and three-parameter regression equations for some areas. While these equations have lower standard errors than the single-parameter equations listed in Table 4, the complexity of the calculations prevents broad implementation. Therefore, annual exceedance discharges for ungaged locations on ungaged streams draining between 20 and 50 square miles are calculated as the arithmetic mean of estimates from the regional regression equations developed by Lara and the single-parameter equations from Eash in this study.

Table 4. Eash (2001) Single-Parameter USGS Regional Regression Equations for the State of Iowa [28]. (Equivalent years of record associated with the equations are shown in parentheses).

| Region 1 | Region 2 | Region 3 |
|---|--|--|
| $Q_2 = 33.8 \times A^{0.656}$ (4.2) | $Q_2 = 182 \times A^{0.540}$ (3.6) | $Q_2 = 286 \times A^{0.536}$ (3.6) |
| $Q_5 = 60.8 \times A^{0.658}$ (5.8) | $Q_5 = 464 \times A^{0.490}$ (7.9) | $Q_5 = 737 \times A^{0.466}$ (6.9) |
| $Q_{10} = 80.1 \times A^{0.660}$ (7.7) | $Q_{10} = 728 \times A^{0.465}$ (13.5) | $Q_{10} = 1180 \times A^{0.431}$ (11.0) |
| $Q_{25} = 105 \times A^{0.663}$ (10.1) | $Q_{25} = 1120 \times A^{0.441}$ (20.5) | $Q_{25} = 1900 \times A^{0.397}$ (17.5) |
| $Q_{50} = 123 \times A^{0.666}$ (11.5) | $Q_{50} = 1440 \times A^{0.427}$ (24.0) | $Q_{50} = 2550 \times A^{0.376}$ (22.2) |
| $Q_{100} = 141 \times A^{0.669}$ (12.5) | $Q_{100} = 1800 \times A^{0.415}$ (25.9) | $Q_{100} = 3300 \times A^{0.357}$ (26.2) |
| $Q_{200} = 159 \times A^{0.672}$ (13.2) | $Q_{200} = 2200 \times A^{0.403}$ (26.5) | $Q_{200} = 4160 \times A^{0.340}$ (29.0) |
| $Q_{500} = 183 \times A^{0.676}$ (13.7) | $Q_{500} = 2790 \times A^{0.389}$ (26.0) | $Q_{500} = 5490 \times A^{0.321}$ (31.0) |

4.3.3. Drainage Areas Greater than 50 Square Miles

Annual exceedance discharges for sites draining greater than 50 square miles are calculated exclusively using the single-parameter regression equations, shown in Table 4, developed by Eash [28].

4.3.4. Gaged Locations

At locations where a stream gage is operated by the USGS or USACE, annual exceedance discharges are estimated by the USGS. A comprehensive analysis of Iowa gages was last conducted by Eash in 2001 [28]. Eash recommended adjusting annual exceedance discharge estimates using a regional weighting scheme. Weighted discharge estimates are calculated using Equation (1).

$$Q_{t(wg)} = [(Q_{t(pg)})(ERL) + (Q_{t(rg)})(EYR)] / (ERL + EYR) \quad (1)$$

where: $Q_{t(wg)}$ is the weighted discharge estimate for a gaged site for recurrence interval t , $Q_{t(pg)}$ is the flood-discharge estimate (log-Pearson Type III) for a gaged site for recurrence interval t , ERL is the effective record length for a gaged site, in years (equivalent to the systematic record length if historical data are not considered; calculated according to Eash [38] when historical data are used), $Q_{t(rg)}$ is the regional-regression discharge estimate for a gaged site for recurrence interval t ; calculated using the 2001 single parameter regression equations, EYR is the equivalent years of record for the regional regression equations used to determine $Q_{t(rg)}$ [28].

Due to additional years of record since publication of Eash [28], annual LP3 flood discharge estimates ($Q_{t(pg)}$) are calculated according to USGS Bulletin 17B [39] using the USACE Hydrologic Engineering Center Statistical Software Package (HEC-SSP). Analyses are performed using each gage's full record of annual peak stream flow, regional skew coefficients from Eash [28], and a regional skew mean squared error (MSE) of 0.156 from Eash [28]. In cases where individual gages are not included in Eash [28], regional skew coefficients are interpolated from generalized skew isolines developed by Eash [28]. Gages with less than 10 years of systematic record, with the last published discharge being 10 years or older from the analysis date, or that are missing data for more than 10 percent of the period of record are not considered in the analysis.

4.3.5. Ungaged Locations on Gaged Streams

When considering ungaged locations on streams that are gaged, the drainage area ratio between the gaged site and ungaged site is used to determine whether it is appropriate to use gage information in estimating annual exceedance discharges [28]. The drainage area ratio is calculated using Equation (2).

$$DAR = |A_g - A_u|/A_g \quad (2)$$

where: DAR is the drainage area ratio, defined as the absolute value of the difference between the drainage areas of the gage site (A_g) and the drainage area of the ungaged site (A_u) divided by the drainage area of the gaged site (A_g).

When the drainage area ratio is 0.5 or less, the ungaged location is considered to be on a gaged stream segment; and regression- and area-based weighting schemes described in Eash [28] are used to estimate annual exceedance discharges for periods of record less than 25 years and greater than 25 years, respectively.

When the period of record of the gaged site is less than 25 years, annual exceedance discharges are estimated using the regression-weighted method, shown in Equation (3), as described in Eash [28].

$$Q_{t(rw)} = Q_{t(ru)} \left[\left(\frac{Q_{t(wg)}}{Q_{t(rg)}} \right) - (2 \times DAR) \left(\frac{Q_{t(wg)}}{Q_{t(rg)}} - 1 \right) \right] \quad (3)$$

where: $Q_{t(rw)}$ is the regression-weighted discharge estimate for an ungaged site on a gaged stream for recurrence interval t , $Q_{t(ru)}$ is the regional regression discharge estimate for an ungaged site for recurrence interval t , determined using methods described in previous sections, $Q_{t(wg)}$ is the weighted discharge estimate for a gaged site for recurrence interval t , and $Q_{t(rg)}$ is the regional-regression discharge estimated for a gaged site for recurrence interval t , as listed in Table 2 of Eash [28].

When the period of record of the gaged site is greater than or equal to 25 years, annual exceedance discharges are estimated using the area-weighted method, shown in Equation (4), as described in Eash [28].

$$Q_{t(aw)} = Q_{t(wg)} \left(\frac{A_u}{A_g} \right)^x \quad (4)$$

where: $Q_{t(aw)}$ is the area-weighted discharge estimate for an ungaged site on a gaged stream for recurrence interval t , $Q_{t(wg)}$ is the weighted discharge estimate for a gaged site for recurrence interval t , A_u is the drainage area of the ungaged site, A_g is the drainage area of the gaged site, and x is the mean

exponent for 2001 hydrologic regions defined in Figure 5, (for Region 1, the mean exponent is 0.665, Region 2, 0.446, and Region 3, 0.403) [28].

4.4. Hydraulic Modeling

4.4.1 Overview

Hydraulic modeling is performed with the USACE Hydrologic Engineering Center River Analysis System (HEC-RAS). HEC-RAS requires geometric data describing the stream network and boundary conditions describing stream discharges and downstream water surface elevations to complete standard step backwater calculations.

4.4.2. Model Development

Streams at least 0.5 mile long with a drainage area of 1 square mile of area or greater are modeled with HEC-RAS. The necessary geometric data required for model development is constructed using the HEC-GeoRAS extension for ESRI's ArcGIS. HEC-GeoRAS allows the user to create HEC-RAS geometry data within a GIS environment using a DEM and user-defined polylines describing the stream topology. Stream centerlines are taken from the IFC/IADNR centerline dataset. Banklines are manually digitized along the top of bank based on 3.28 foot (1 meter) resolution LiDAR data. Overland flow paths, which define the approximate path taken by the bulk of out-of-bank flow, are somewhat subjective and are digitized at a coarse scale. Cross-sections are used to define the channel and floodplain geometry. Cross-sections are placed approximately perpendicular to anticipated flow paths and are typically spaced a maximum of 1,600 feet apart. Spatially varying roughness maps are based on the 2001 NLCD and published Manning's values in Chow [40]. Ground verifications of roughness estimates were not conducted. Ineffective flow areas, or areas of the cross-section that contain water that is not actively being conveyed, are digitized only in backwater areas or areas of rapidly expanding or contracting flow.

4.4.3. Boundary Conditions

Standard step backwater calculations performed by HEC-RAS are based on the principle of conservation of energy. Simulations require a discharge and water surface elevation at the upstream and downstream boundaries, respectively. Discharges corresponding to 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent-annual-chance flows are calculated at every cross-section location using methods described in Section 4.3. Downstream water surface elevations are automatically calculated by HEC-RAS based on the assumption of uniform flow conditions. This assumption was selected in accordance with FEMA guidelines [41].

4.4.4. Mapping of Simulation Results

HEC-RAS simulation results are exported to ArcGIS and floodplain boundaries are delineated. Simulated water surface profiles are intersected with a 3.28 foot (1 meter) DEM. Due to the high fidelity of the LiDAR data, there is an abundance of inundated regions disconnected from stream

channels and non-wetted regions inside the floodplain boundaries. These disconnected and non-wetted regions are removed from the inundation maps, using area as the determining factor for removal. At confluences, the inundation results from separate stream models are merged for discrete flows to remain consistent with assumed boundary conditions. Preliminary mapping results of the 1- and 0.2-percent-annual-chance floods for Poweshiek County, Iowa are available on the IFC website [42] (www.iowafloodcenter.org/maps). Results from the 0.2-percent-annual-chance flood is shown in Figure 6.

Figure 6. Preliminary floodplain mapping result for the 0.2-percent-annual-chance flood available on the Iowa Flood Center website [42] (www.iowafloodcenter.org/maps).



4.5. Public Availability and Implementation

A comprehensive set of flood inundation maps developed under a unified methodology will greatly improve Iowa's management of flood risk. However, the accessibility of these maps along with the supporting data will greatly impact the value of the statewide floodplain mapping effort. A database is currently under development to efficiently store and query the statewide floodplain information so it is viewable and downloadable on the Internet. This is the most efficient method of disseminating flood hazard information to the public while providing resources for future updates. After a quality control and quality assurance review, maps of some areas will be submitted to FEMA to begin the adoption process. The adoption process will include periods for public comment and appeal depending on funding availability and time since the effective map was published. After any necessary revisions, communities will have an additional six months to implement new floodplain regulations before the maps become effective [21].

5. Detailed Urban Flood Mapping

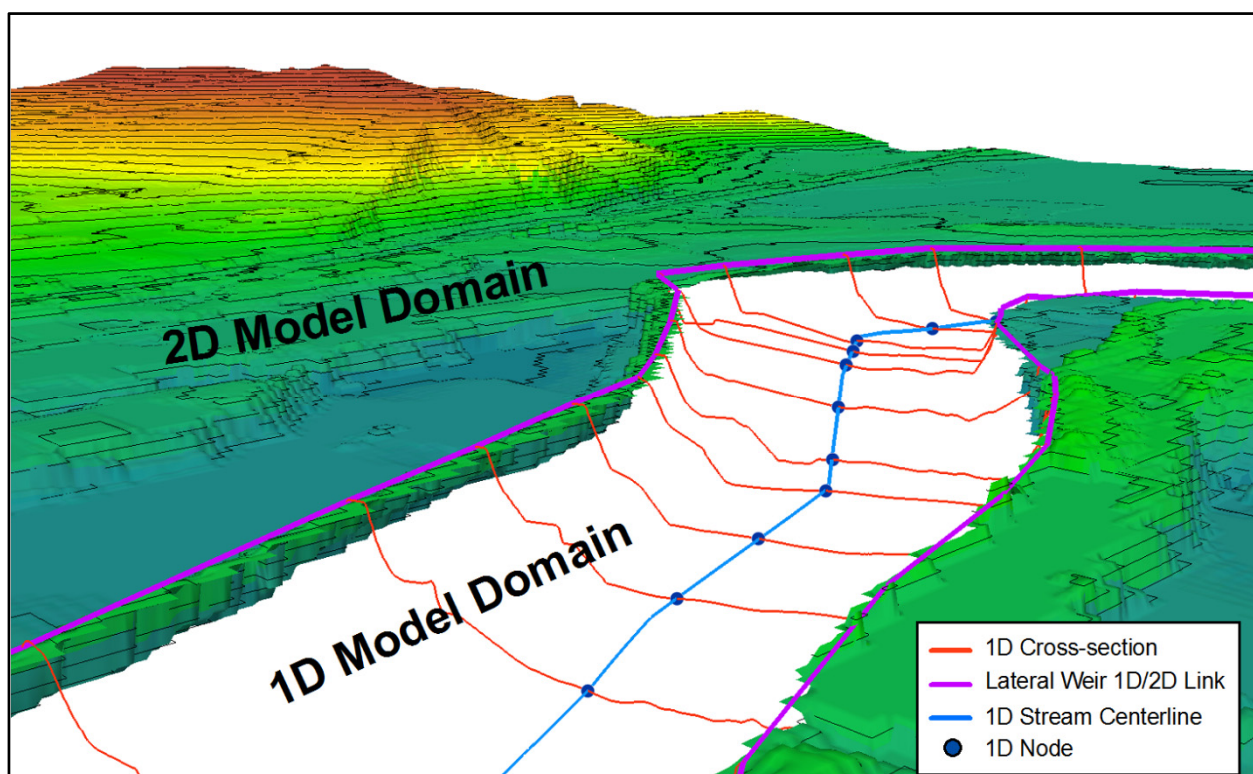
5.1. Introduction

During recent flooding events, particularly the floods of 2008, many Iowa communities relied on NWS river stage forecasts to anticipate potential flood levels and to manage flood fighting efforts. However, NWS forecasts of river stage or discharge are made only at stream gage locations.

Inundation maps are a more effective way to communicate flood risk, but the public's access to this resource is limited. The majority of publicly-available inundation maps are FEMA-distributed FIRMs [20] and are only completed in counties that choose to participate in the NFIP [43]. These maps are typically developed for a limited set of annual return intervals and digital access is limited and complicated [20]. An easy-to-access library of inundation maps corresponding to river stages at forecast locations would supplement the NWS forecasts and would more clearly communicate potential flooding in urban areas.

IFC is developing libraries of urban inundation maps corresponding to river stage using high-resolution hydraulic models. USGS stream gaging stations are located near the center of most large communities in Iowa. Simulation scenarios are based on 0.5 foot river stage increments at the nearest USGS gage. The USGS-published relationships between river stage and discharge are used to develop flow scenarios.

Figure 7. Depiction of a general 1D model of the river channel coupled with a 2D model of the floodplain.



The presence of hydraulic structures (e.g., levees, weirs, and bridges) requires use of the energy equation to correctly predict head loss, while urban floodplain complexity requires the depth-averaged

Saint-Venant equations to accurately predict multi-directional flow patterns. Studies have demonstrated that most effective approach to modeling complex floodplains using the least computational effort is through one-dimensional (1D) treatment of the main channel and two-dimensional treatment of the floodplain [44–46]. A depiction of a general coupled 1D/2D modeling approach is shown in Figure 7. DHI Water and Environment's (DHI) MIKE FLOOD, a 1D/2D coupled hydrodynamic modeling software package, was selected to model flooding within urban communities.

5.2. Data Sources

Many datasets used in the statewide floodplain mapping project are also used in detailed urban flood analyses. Urban flood inundation modeling relies heavily on high-resolution LiDAR elevation data to define geometric properties of floodplains. Land use data are provided by the USDA in the form of the NLCD. The river stage to discharge relationship at stream gage locations is provided by the USGS. Structural information describing levees, weirs, and bridges is provided by managing municipalities or federal agencies, or collected by IFC. Bathymetric mapping is performed by IFC using single- and multi-beam echo-sounding, geo-referenced with a Real-time Kinematic (RTK) Global Navigation Satellite System (GNSS).

5.3. Hydraulic Modeling

5.3.1. Overview

Detailed urban flood modeling is performed using MIKE FLOOD, a coupled hydrodynamic modeling software package. MIKE FLOOD models the river channel using MIKE 11, a 1D model, and the floodplain using MIKE 21, a 2D model. Data required for model development include a high-resolution DEM of the terrain and river bed, distributed roughness, and as-built structural plan sets.

5.3.2. Model Development

Model development begins with the integration of bathymetric data into the LiDAR-derived DEM. LiDAR resolution is insufficient to depict flood walls less than three feet wide. Therefore flood wall elevations are inserted into the DEM. Buildings are inserted into the DEM when building footprint data are available. Distributed roughness values are determined based on the NLCD and Manning's roughness values published by Chow [40].

A 1D hydrodynamic model of the river channel is developed using DHI's MIKE 11 GIS ArcGIS extension to create geometric files. Cross-sections are digitized at an approximate spacing of 300 feet. Bridges and weirs are digitized from as-built plan sets.

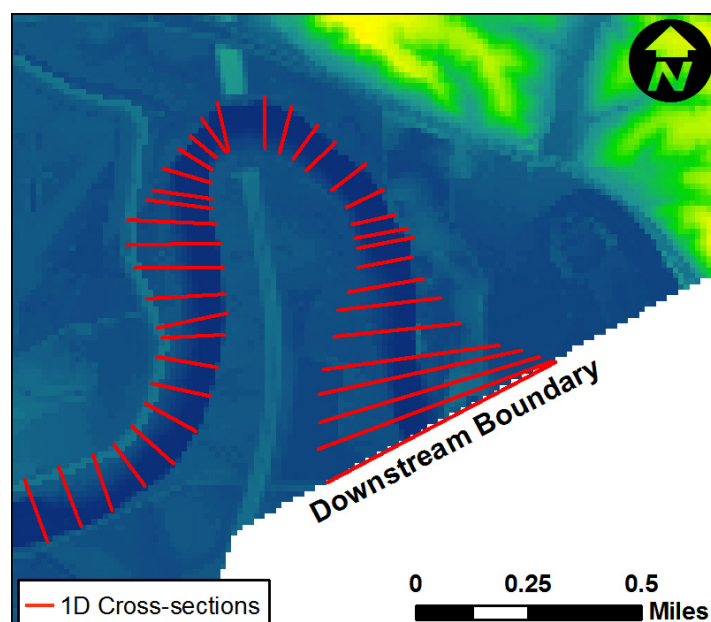
A 2D structured computational mesh is created by aggregating the 3.28 foot (1 meter) resolution DEM to a resolution that is less computationally intensive, typically 32.8 to 65.6 feet (10 to 20 meters). The dilution of levee and floodwall elevations during aggregation of the DEM requires manual insertion of unaltered structure elevations using GIS techniques. While this ensures accurate top-of-levee elevations are included in the mesh, it may overestimate the elevations at which failure of levees or flood walls occur.

The 1D and 2D models are coupled using MIKE FLOOD such that the river channel is represented by fully dynamic, section-averaged solutions to the Saint-Venant equations at discrete cross sections and the floodplain is represented by depth-averaged Saint-Venant equations at structured grid cells. MIKE FLOOD 1D/2D coupling allows two models to dynamically exchange information about water levels and discharge. Due to the large number of structures within study reaches, lateral coupling of the river channel was selected over other link types due to its ease of development. Lateral links are 1D explicit elements intended to model over-topping of a river bank or levee. A simple weir equation calculates flow through the lateral link. Lateral weir structure elevations are based on a bed level determined by cross-section endpoints and a width determined from the resolution of points defined along the structure [47]. The distribution of flow through the linked model nodes is determined by the range of influence each structure has upon each linked node [47].

5.3.3. Boundary Conditions

All hydrodynamic boundary conditions are specified in the 1D model. Flow rate is specified at the upstream 1D boundary and water surface elevation is calculated at the downstream 1D boundary according to a normal-depth rating curve. At the downstream boundary, shown in Figure 8, the lateral extent of the 1D model is broadened to allow water to leave the 2D model more quickly. Water is not allowed to pass through the outer boundary of the 2D model. The upstream and downstream model extents are placed sufficiently far away from the area of interest such that artificial boundary effects are minimized.

Figure 8. Example downstream boundary of coupled 1D/2D model.



5.3.4. Model Calibration

Coupled 1D/2D MIKE FLOOD models are calibrated to low flow and high flow conditions by iteratively modifying bed friction resistance in the channel and floodplain until simulated water surface

elevation in the channel and floodplain matches measured data. Measured data include high water marks, stream gage data, and low flow water surface profiles.

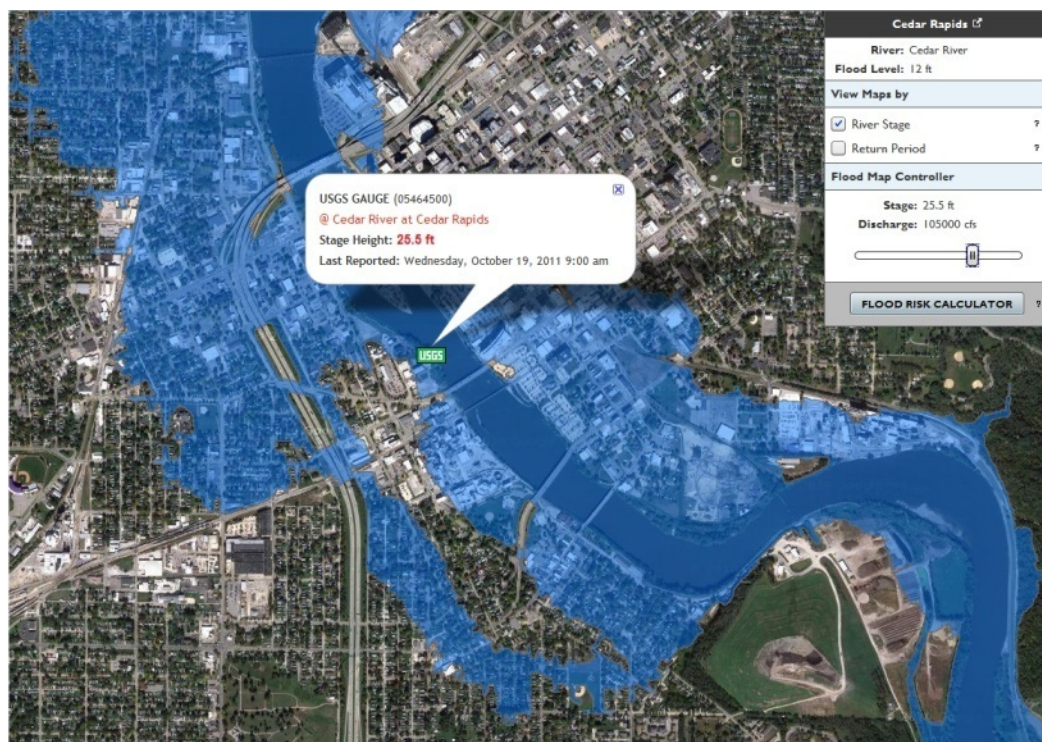
5.3.5. Development of Inundation Map Libraries

Simulation scenarios are based on discharges corresponding to 0.5 foot river stage increments at stream gages with NWS forecasts. Several estimated flood quantiles are also simulated. All simulations are allowed to reach steady state to provide a conservative measure of inundation. Lower-resolution maps of simulated water surface elevation are post-processed in ArcGIS to generate 3.28 foot (1 meter) resolution flood boundaries. Disconnected and not-wetted regions interior to the floodplain boundaries are removed based on area. The final inundation maps are formatted for web-based visualization.

5.4. Public Availability

Inundation map libraries have been developed for the communities of Des Moines, Cedar Rapids, Charles City, Cedar Falls, Waterloo, and Iowa City, and are hosted on IFC's Iowa Flood Information System (IFIS) [48] (www.iowafloodcenter.org/ifis). Inundation map libraries are either under development or planned for Mason City, Elkader, Ottumwa, Ames, Sioux City, Spencer, and others to be determined. The detailed urban flood mapping interface is shown in Figure 9. IFIS uses the Google Maps interface to make the user experience as intuitive and familiar as possible.

Figure 9. Example of the detailed urban flood mapping interface available on the Iowa Flood Information System (IFIS). Reported river stage at the gage location is viewable from within the interface. Inundation maps are viewable by river stage or return period using the slider on the right.



6. Summary and Discussion

The state of Iowa has experienced increased frequency of large floods in recent decades that have severely damaged homes, businesses and infrastructure. These floods have revealed vulnerabilities and a general lack of flood hazard awareness amongst community officials and citizens. The Iowa Flood Center seeks to improve Iowa's flood hazard awareness through the development of easily accessible, high-quality mapping products. IFC's mapping initiatives consist of two model development approaches: (1) statewide floodplain delineation using 1D models, and (2) urban flood mapping using detailed 1D/2D coupled models.

Iowa's statewide floodplain mapping project will benefit Iowans through the creation of a comprehensive set of floodplain maps developed under a single consistent methodology. The availability of LiDAR data and stream gage records has been vital in generating support for the project and performing the analyses. Communities that would otherwise lack the resources to conduct flood studies will have the opportunity to participate in the NFIP. Since model data and geo-referenced risk-based inundation maps are developed using a single methodology, products can be hosted in a web-based database for viewing and downloading.

Through the use of coupled 1D/2D hydrodynamic models, the IFC has developed flood inundation map libraries for several Iowa communities. These inundation map libraries are meant to supplement NWS river stage flood forecasts by providing a visual representation of potential inundation extent according to predicted river stage at stream gage locations. Maps are hosted on the IFC's Iowa Flood Information System [48] (www.iowafloodcenter.org/ifis).

Implementation of a large-scale mapping project requires significant funding, government support, coordination among stakeholders, and access to large quantities of data. The topographic detail and accuracy of Iowa's statewide LiDAR dataset facilitated the development of high-quality mapping products on a large scale. Other countries interested in a similar mapping project could justify the initial investment in a full-scale LiDAR survey based on the wide applicability of the dataset for engineering, risk assessment, and education. Although the rate of urban development is increasing in some areas of Iowa, the majority of the state's agricultural landscape will remain unchanged in the coming decades. The time interval for updating the entire statewide LiDAR dataset has not been established. Other regions or countries with higher degrees of urban development may require more frequent updates. A stream gage network of sufficient resolution and record is critical for reach-scale floodplain mapping. Other states or countries interested in large-scale mapping efforts may benefit from completing a pilot study to evaluate data needs and optimize hydrologic and hydraulic methodologies that may be unique to their geographic location and climate.

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Appendix

Since regression equations for estimating the 200- and 500-year discharges were not generated by Lara [1] an approach for extrapolating 1987 regression relations was applied by Bradley [2] using a log-Pearson Type III (LP3) distribution. An LP3 distribution is defined by three parameters, as shown in Equation (1).

$$\log Q_t = \mu + K\sigma \quad (1)$$

where: Q_t is the discharge estimate for recurrence interval t , μ is the mean of the logarithm of the annual maximum peak discharge, σ is the standard deviation of the logarithm of the annual maxima, K is the frequency factor as defined by Kite [3] as

$$K = z_t + (z_t^2 - 1)k + \frac{1}{3}(z_t^3 - 6z_t) - (z_t^2 - 1)k^3 + z_t k^4 + \frac{1}{3}k^5 \quad (2)$$

where: z_t is the standard normal deviate corresponding to a return period of t , k is $\gamma/6$, γ is the skew coefficient of the logarithm of the annual maxima.

Extrapolating the regional flood relations developed by Lara [1] to estimate the flood discharges for the 200- and 500-year return period is as follows. At any given site, the 1987 regression equations can be used to estimate three points (Q_t , t). Assuming the LP3 distribution, these three points are sufficient to define the entire curve and extrapolate to find the 200- and 500-year peak discharges for a given drainage area.

The three points used to define the LP3 distribution are the 2-year (Q_2), the 10-year (Q_{10}), and the 100-year (Q_{100}) return period peak discharges as calculated using Lara [1] equations. Substituting into Equation (1) yields:

$$\log Q_2 = \mu + K(2, \gamma)\sigma \quad (3)$$

$$\log Q_{10} = \mu + K(10, \gamma)\sigma \quad (4)$$

$$\log Q_{100} = \mu + K(100, \gamma)\sigma \quad (5)$$

Log-ratios can be developed using the previous equations and the 100-year return period as a reference:

$$\log[Q_2/Q_{100}] = [K(2, \gamma) - K(100, \gamma)]\sigma \quad (6)$$

$$\log[Q_{10}/Q_{100}] = [K(10, \gamma) - K(100, \gamma)]\sigma \quad (7)$$

Dividing Equation (6) by (7) results in a ratio called f , which only depends on γ :

$$f = [K(2, \gamma) - K(100, \gamma)]/[K(10, \gamma) - K(100, \gamma)] \quad (8)$$

Rearranging Equation (8) results in:

$$(1 - f)K(100, \gamma) + fK(10, \gamma) - K(2, \gamma) = 0 \quad (9)$$

Equations (2) and (9) can be used to solve for the skew coefficient γ using numerical methods. Once the skew coefficient has been determined, it can be used to estimate a discharge for any return period for a given drainage area. Using Q_2 and Q_{100} as parameters, Equation (1) can be rewritten for an unknown Q_t .

$$[\log(Q_t/Q_{100})]/[\log(Q_2/Q_{100})] = m(t, \gamma) \quad (10)$$

where:

$$m(t, \gamma) = [K(t, \gamma) - K(100, \gamma)]/[K(2, \gamma) - K(100, \gamma)] \quad (11)$$

If Equation (10) is solved for Q_t :

$$Q_t = Q_{100}(Q_2/Q_{100})^{m(t, \gamma)} \quad (12)$$

The USGS regression equations developed by Lara [1] relate the flood discharge Q_t to the drainage area A using a power-law model:

$$Q_t = \alpha_t A^{\beta_t} \quad (13)$$

Developing similar mathematical equations for the 200- and 500-year return periods is desirable. To define the two fixed parameters α_t and β_t for a given return interval, two points are required (A , $Q_t(A)$). Two end points over the desired range, $Q_t(1)$ and $Q_t(50)$, estimated for drainage areas of 1 and 50 square miles can be used to develop Equation (13). With these two points, substitution into Equation (13) yields:

$$\alpha_t = Q_t(1) \quad (14)$$

$$\beta_t = \log[Q_t(50)/\alpha_t]/\log[50] \quad (15)$$

The regional regression equations developed by Bradley [2] using this technique for the 0.5- and 0.2-percent-annual-chance flows (200- and 500-year return periods) are shown in Table 3.

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