Hydrologic Hazards

Best Practices in Dam and Levee Safety Risk Analysis
Part B - Hazards and Loading
Chapter B-1
Last modified July 2018, presented July 2019
Objectives

• Understand the methods used to characterize hydrologic hazards

• Understand how hydrologic hazards are used to estimate risks
Key Concepts – Hydrologic Hazards

• Variables, magnitudes, and ranges of interest for risk estimate
  • Stage, discharge, volume, velocity, others
  • Peak, timing, duration

• Entire distribution shape matters

• Load partitioning important to develop a proper event tree

• Integration of hazard with failure modes and consequences

• Deterministic floods not easily mapped to hazard curves

• Quantify and understand uncertainty
Outline

• Why are hydrologic hazards important?
• Some Hydrologic-Related Potential Failure Modes
• What’s a Hydrologic Hazard Curve?
• Hydrologic Hazards - Current Guidance
• Hydrologic Hazard Curve Estimation – Key Principles and Methods
• Hydrologic Hazards and use in Risk Analysis
Why Flood Hazards are Important

![Cause of Dam Failures: 1975-2001](https://example.com/case_of_dam_failures.png)

<table>
<thead>
<tr>
<th>Dam</th>
<th>Year</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Fork, PA</td>
<td>1889</td>
<td>2,209</td>
</tr>
<tr>
<td>Walnut Grove, AZ</td>
<td>1890</td>
<td>100</td>
</tr>
<tr>
<td>Buffalo Creek, WV</td>
<td>1905</td>
<td>125</td>
</tr>
<tr>
<td>Swift Dam, MT</td>
<td>1964</td>
<td>19</td>
</tr>
<tr>
<td>Canyon Lake, SD</td>
<td>1972</td>
<td>237</td>
</tr>
<tr>
<td>Laurel Run, PA</td>
<td>1977</td>
<td>40</td>
</tr>
<tr>
<td>Kelly Barnes, GA</td>
<td>1977</td>
<td>39</td>
</tr>
<tr>
<td>Rainbow Lake, MI</td>
<td>1986</td>
<td>3</td>
</tr>
<tr>
<td>Callaway, TX</td>
<td>2002</td>
<td>2</td>
</tr>
<tr>
<td>Ka Loko, HI</td>
<td>2006</td>
<td>7</td>
</tr>
</tbody>
</table>
Why Flood Hazards are Important

Levee Overtopping
Mississippi River
July 1993

Floodway Operation
Mississippi River
May 2011

Dam Overtopping
Iowa
July 2010

Refer to Case Histories for More Details and More Examples
Why are Flood Hazards Important

Annualized Failure Probability

\[ f = P_l \times P_{r|l} \]

Risk: Annualized Life Loss

\[ Risk = P_l \times P_{r|l} \times C \]

\( P_l \) = Probability of Load – *Hydrologic Hazard Curve*

\( P_{r|l} \) = Probability of Adverse Response Given Load

\( C \) = Consequences (or Loss of Life, N)
Potential Failure Modes

• Almost all of them
  • No water = No failure mode

• Overtopping of Dams and Levees
  • erosion of downstream toe, foundation, or dam crest

• High Reservoir Levels or River Stages
  • Internal erosion, instability, and many others

• Spillway and Stilling Basin
  • erosion, cavitation, wall overtopping

• Misoperation or malfunction
  • Gate electrical/mechanical, pump stations, closures
What is a Hydrologic Hazard Curve?

- A probability distribution
  - Survival function or Exceedance curve
- Annual probability that stage will be exceeded (>
  - Same applies for discharge, volume, velocity, etc.
- Risk estimates need the full range of values, with uncertainty
- Range that drives risk will depend on PFMs and consequences
  - < 1 in 10,000 (dams)
  - < 1 in 1,000 (levees)
Hydrologic Hazard: Discharge and Volume

Leverage all available information
- Gage records
- Historic flood records
- Paleoflood studies

Use current methods
- Bulletin 17C

Do not anchor
- Do use an assigned AEP for the PMF to define the curve
- Ok to report the AEP for the PMF discharge or volume from the curve

Quantify uncertainty
- Typically large due to extrapolation

Identify key parameter
- Peak
- Volume (for the critical duration)

[Bulletin 17C Appendix 10 Example]
Hydrologic Hazard: Reservoir Pool or River Stage

Understand how physical characteristics influence the shape of the curve

- $I - O = \frac{dS}{dt}$
- Downstream controls
- Gate operations
- Spillway crest
- Overtopping flows
- Storage

Leverage available data

- Observed stages
- Reconstruct historic events

No anchoring

- Do not assign an AEP to the PMF to define the curve
- Ok to report the AEP of the PMF stage from the curve

Uncertainty
Stochastic Modeling

- Monte Carlo Simulation
- Used to combine uncertainties
  - Precipitation
  - Discharge or volume
  - Starting reservoir or river level
  - Hydrograph shape
  - Many others possible
- No single point estimates
- Some items are typically reserved for the event tree based on needs and preference
  - Gate reliability and debris blockage
  - Develop separate hazard curves for several assumed gate and debris scenarios
  - Address probabilities for the gates and debris scenarios in an event tree
  - Easier to attribute the contribution of gates and debris to project risk

Sample a Discharge or Volume Distribution
Sample a Flood from the Sample Distribution
Sample a Starting Reservoir Level
Sample a Hydrograph Shape
Route the Flood Through the Reservoir
Record Peak Stage
Develop a Sample Stage Frequency Curve from Many Peak Stages
Develop a Mean or Expected Stage Frequency Curve with Uncertainty From Many Sample Curves
Current Guidance on Hydrologic Hazard Estimation

Reclamation, USACE and FERC implementing and using similar methods for hydrologic hazards; some technical details on methods in these reports

Reclamation, 2006

USACE, 2015; under development/revision

FERC, 2014; draft for public

USACE, 2018; SQRA

See Chapter References for links to documents

Hydrologic Loading Methodology for Risk Assessment
January 2015

Introduction

Hydrologic loading for dam safety risk assessment shall provide guidance for developing the loading used in evaluating potential failure modes for dams and levees. Hydrologic loading serves as a critical part of determining risk for various potential failure modes. Typically the flood produces HIC for a period of time or frequency curve with uncertainty bounds for flood and flood frequency curve parameters. For some potential failure modes, other hydrologic loading information may be required such as overtopping load, discharge and duration of flood through the spillway and outlets works, etc. These loadings are site specific and will not be dealt with in detail within this document. The level of detail will vary by the level of study and its impact on the analysis as outlined below.

Applicability

This document will supersede two previous draft documents: Info Design Hydrologic Methodology and Ongoing Evaluation, November 2008, and 1105 Frequency Curve Estimates for Palmer Flood Control, December 2012. Some of these concepts are briefly utilized in this document with revisions based on experience in developing hydrologic loading curves within USACE. The document is also supplemented by previous draft methodology "D: Introduction – Hydrologic Loading" dated 15 November 2013.

The purpose of this document is to lay out an overview of the methods and level effort required for various risk assessment study. The document will not explore specific techniques in developing hydrologic loading curves in these ways further explained in existing literature and references.

As USACE continues to assess the hydrologic loading curves and increasing additional methods, this document will require periodic updating. Currently examples in the form of workshops are being developed to assist with understanding the concepts and issues presented in this document.

FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R19
Probabilistic Flood Hazard Analysis

Chapter R19: Probabilistic Flood Hazard Analysis

Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments

RMC-TR-2018-03
An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams
Hydrologic Hazard Guiding Principles

• No Single Approach Describes Flood Hazards Over the Range of AEPs Needed – *Multiple Methods: combine flow frequency curves and rainfall-runoff curves*

• Greatest Gains From Incorporating Regional Precipitation, Streamflow, Paleoflood Data – *Lots of Data*

• Honestly Represent Uncertainty – *Explicitly Quantify Uncertainty*

• Temporal Information: expand data in time
• Spatial Information: expand data in space
• Causal Information: utilize hydrological understanding of flood-producing processes

• Do Not Assign an AEP to the PMF
Expertise

Meteorology  Hydrology  Statistics  Paleoflood

Interdisciplinary Skills Needed
Storm Types and Processes

Examples
- Hurricanes and TCs – Eastern US
- Convective Thunderstorms - Flash floods

Comparison of Hourly Gage and MPR Accumulated Rainfall
Hurricane Floyd: September 14 - 17, 1999

Precip. (in.)
- No Precip
- 0.01-0.10
- 0.10-0.25
- 0.25-0.50
- 0.50-1.00
- 1.00-1.50
- 1.50-2.00
- 2-3
- 3-4
- 4-5
- 5-6
- 6-8
- 8-10
- 10-15
- 15-20
- 20-25
- 25-30
- >30

Precipitation map showing concentrated area of rainfall over the eastern United States.
Credible Extrapolation

USBR - USU (1999), Swain et al. (2006)

Also in: Australian Rainfall & Runoff (2016) Book 8
Estimation of Very Rare to Extreme Floods by Nathan and Weinmann

<table>
<thead>
<tr>
<th>Type of data used for flood frequency analysis</th>
<th>Range of credible extrapolation for Annual Exceedance Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>At-site streamflow data</td>
<td>Typical: 1 in 100, Optimal: 1 in 200</td>
</tr>
<tr>
<td>Regional streamflow data</td>
<td>Typical: 1 in 500, Optimal: 1 in 1,000</td>
</tr>
<tr>
<td>At-site streamflow and at-site paleoflood data</td>
<td>Typical: 1 in 4,000, Optimal: 1 in 10,000</td>
</tr>
<tr>
<td>Regional precipitation data</td>
<td>Typical: 1 in 2,000, Optimal: 1 in 10,000</td>
</tr>
<tr>
<td>Regional streamflow and regional paleoflood data</td>
<td>Typical: 1 in 15,000, Optimal: 1 in 40,000</td>
</tr>
<tr>
<td>Combinations of regional data sets and extrapolation</td>
<td>Typical: 1 in 40,000, Optimal: 1 in 100,000</td>
</tr>
</tbody>
</table>
Data Sources

• Extreme Rainfall Data
  • NCDC gages
  • Depth-Area Duration storm catalog from USACE, Reclamation, NWS
  • MPE and MPR gridded precip (NWS)

• Extreme Flood Data
  • USGS stream gages: peaks, hydrographs
  • Historical information (photos, eye witness accounts, newspapers, flood reports
  • Paleoflood data

• Snow Data
  • Snow Course, SNOTEL, SNODAS

• Climate Data
  • Projections and models
  • CMIP5 Downscaled archive
Hydrologic Hazard – Extreme Storm data
Hydrologic Hazard Data – Peak Flows

Battle Creek, Shasta County, CA: Dec. 22, 1964

Wind River near Crowheart, WY: Jul. 01, 2011

USGS National Water Information System and flood studies
Paleoflood Data

House et al. (2002) AGU Paleoflood Monograph
Data Acquisition and Evaluation

- Understand data source (collection interval, what is being measured)
  - Daily average, peak, something else
  - Recorded (stage) or calculated (computed from observed stage using a rating curve)
- Check for missing data, data shifts, and erroneous data
- Check that data is representative of conditions assumed for the risk analysis
## Hydrologic Hazard Methods - Stream flow

<table>
<thead>
<tr>
<th>Method (Agency)</th>
<th>Description (reference)</th>
<th>Inputs</th>
<th>Assumptions</th>
<th>Hydrologic Hazard Curve</th>
<th>Why Choose</th>
<th>Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulletin 17C (EMA-LP-III, USGS PeakFQ, HEC-SSP (USACE, USBR, FERC))</td>
<td>Peak-flow and volume frequency analysis with historical/peakflow data - EMA (Cohn et al., 1997; England et al., 2018)</td>
<td>Peak flow, historical data, peakflow data, regional skews</td>
<td>LP-III flood frequency distribution with moments and regional skew</td>
<td>Peak flow frequency and confidence intervals, Volume Frequency</td>
<td>Federal guidelines for flood frequency, uses historical and peakflow data when available</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>FLDFRQ3 (USBR)</td>
<td>Bayesian Peak-flow frequency analysis with historical/peakflow data - FLDFRQ3 (O’Connell et al., 2002)</td>
<td>Peak flow, detailed peakflow</td>
<td>Various flood frequency distributions with likelihood</td>
<td>Peak flow frequency and confidence intervals</td>
<td>Detailed peakflow data available; need FEA confidence intervals, choice of distribution</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Hydrograph Scaling (USACE and USBR)</td>
<td>Balanced Hydrographs and Pattern Scaling (England, 2003, Smith et al., 2018)</td>
<td>Hydrographs and volumes</td>
<td>Hydrographs represent extreme flood response; requires FEA for scaling</td>
<td>Hydrographs and volumes based on peak flow and volume frequency</td>
<td>Ratios of the IDF hydrograph and statistically based balanced and patterned hydrographs</td>
<td>Low</td>
</tr>
<tr>
<td>Reservoir Frequency Analysis (RMC-RFA) (USACE)</td>
<td>Streamflow Volume Stochastic Modeling with reservoir routing (Smith, 2018)</td>
<td>Volume frequency, hydrographs, flood season, initial reservoir stage</td>
<td>Inputs defined by distributions, volume-frequency, observed hydrographs, and pool duration frequency</td>
<td>Reservoir elevation and confidence intervals</td>
<td>Monte-Carlo methods to sample inputs; combine inflows and routing, quantify uncertainty</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>Watershed Analysis Tool (HEC-WAT) (USACE)</td>
<td>Streamflow Volume Stochastic Modeling for Flood Risk Analysis with HEC-ResSim (within HEC-WAT)</td>
<td>Pool duration, volumes, and Hydrographs</td>
<td>Inputs defined by distributions, volume-frequency observed hydrographs, and pool duration frequency</td>
<td>Reservoir elevation and confidence intervals</td>
<td>Monte-Carlo methods to sample inputs; quantify uncertainty, system/downstream effects with coincident frequency</td>
<td>High</td>
</tr>
</tbody>
</table>
Bulletin 17C Streamflow - Example

Arkansas River at Pueblo, CO – record flood (1921), historical and paleoflood data, reservoir records

- 1,000 years of at-site flood information; additional data at 3 upstream sites spanning several thousand years

Arkansas River Bulletin 17C Example (Appendix 9): Available in HEC-SSP 2.1.1
## Hydrologic Hazard Methods: Rainfall-Runoff

<table>
<thead>
<tr>
<th>Method (Agency)</th>
<th>Description (Reference)</th>
<th>Data Inputs</th>
<th>Assumptions</th>
<th>Hydrologic Hazard Curve Product</th>
<th>Why Choose</th>
<th>Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian Rainfall-Runoff (USBR, FERC)</td>
<td>Australian Rainfall-Runoff Method (Nathan and Weinmann, 1999)</td>
<td>PMP design storm; rainfall frequency; watershed parameters</td>
<td>Exceedance Probability of PMP; average watershed parameter values; runoff frequency same as rainfall frequency</td>
<td>Peak flow and hydrographs; based on rainfall frequency and PMP</td>
<td>Similar runoff model as PMP/PMF; familiar design concepts</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>SEFM (USBR, FERC)</td>
<td>Stochastic Event-Based Precipitation Runoff Modeling with SEFM (MGS, 2005, MGS, 2009; Schaefer and Barker, 2002)</td>
<td>Rainfall gages/detailed regional rainfall frequency, watershed parameters, snowpack, reservoir data</td>
<td>Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEVL-moments</td>
<td>Peak flow frequency, hydrographs, volume frequency, reservoir elevation frequency</td>
<td>Monte-Carlo methods to sample input distributions</td>
<td>High</td>
</tr>
<tr>
<td>HEC-WAT (USACE and USBR)</td>
<td>Watershed analysis tool coupling rainfall-runoff model (HEC-HMS), river routing (RAS), and reservoir operations for system-wide basin flood studies</td>
<td>Can be Regional extreme storm DAD data or meteorologic extreme storm data, watershed parameters, snowpack</td>
<td>Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEVL-moments or weather generator</td>
<td>Monte Carlo inputs and resampling; Reservoir elevation (pool) frequency curves, flood volumes, and hydrographs</td>
<td>Flexible framework for system-wide flood modeling with coupled components</td>
<td>High</td>
</tr>
</tbody>
</table>
Hydrologic Hazard Methods
Rainfall-Runoff after NRC (1988)

- Construct a space-time extreme rainfall model
  - rainfall probability distribution biggest factor
  - Stochastic Storm Transposition
  - Regional Extreme Precipitation Frequency Analysis
- Generate several large storms from model
- Model “deterministic” rainfall-runoff transformation
- Monte-Carlo Simulation
  - Hazard curves for flood peaks, volumes, reservoir stages and Uncertainty
Rainfall-Runoff Calibration and Weighting

Calibrate model results to observed hydrographs and estimated frequency curves (peak/volume) to determine best model input parameters and distributions.
Represent Uncertainty

- Uncertainty of peak flow frequency with paleofloods
- Uncertainty of basin-average rainfall frequency
- Variation in rainfall-runoff parameters and inputs
- Include future Climate projections

Climate change Pilot for Friant Dam
Hydrologic Hazard
Multiple Methods, Data and Extrapolations

Peak Flow, Historical and Paleoflood Data
(single site or multiple sites),
$N \sim 5,000 - 15,000$ years

Peak-Flow Frequency Analysis (EMA/LP-III HEC-SSP) and statistics

$Q_T$
Peak-Flow (volume) Frequency Curve

Comparisons and Potential Rainfall-Runoff Model Parameter and Input Adjustments

Regional Precipitation Data and Precipitation Frequency Analysis,
$N \sim 2,000 - 10,000$ years

Event Rainfall-Runoff Model with soil moisture accounting
(HMS/WAT)

Monte Carlo simulations

Flood Statistics

$Q_T$
Peak-Flow (volume) Frequency Curve
Hydrologic Hazard Methods
Scalable Effort

Hydrologic Hazard estimates are typically made for three levels of risk informed decisions. Data and methods depend on type of study:

- Periodic Assessments/Comprehensive Reviews
  - Screening-level/qualitative information used
- Issue Evaluation Studies
  - Increased regional data collection and level of detail
- Corrective Action/Dam Safety Modification Studies
  - additional site-specific data collection
  - advanced modelling efforts
  - Monte-Carlo rainfall-runoff modelling
  - expert elicitation
$P_l = \text{Probability of Load – Hydrologic Hazard Curve (Reservoir Elevation)}$

$P_{rl} = \text{Probability of Response Given Load (Depth above Dam Crest)}$
Flood Event Tree Partitions

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Bound</td>
<td>Upper Bound</td>
</tr>
<tr>
<td>n/a</td>
<td>1671.5</td>
</tr>
<tr>
<td>1671.5</td>
<td>1675.5</td>
</tr>
<tr>
<td>1675.5</td>
<td>1683.0</td>
</tr>
<tr>
<td>1683.0</td>
<td>1688.0</td>
</tr>
<tr>
<td>1688.0</td>
<td>1695.0</td>
</tr>
<tr>
<td>1695.0</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Questions?

Folsom
Joint Federal Project
Sacramento, CA

Reclamation and USACE Partnership

New spillway for improved flood control