Quantifying Flood Risk Using 2D Probabilistic Modeling and Mapping

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Water Resources Engineer
Outline

• Reasons for a new approach
• The big picture
• Crash course in probabilistic approach
• Results
• Benefits & future work
Reasons for a New Approach

- Account for uncertainty
- Structure-level risk assessment
- Information on wide range of events (2-3000 yr)
- Show graduated risk within floodplain
- Full risk profile (riverine, rainfall, levees)
- Gridded data for nearly any return period
Example Assessment Shift from Zones to Graduated Risk

- Showing annual exceedance probability (AEP) rather than zones
- Especially useful behind levees
Example Risk Discretization
from Zones to Damages

- Spatially varied insurance premiums based on AALs
- Can vary behind levees & account for pluvial
PFRA Overview at a glance

Hydrology:
- Discharge vs. Probability
- Elevation vs. Probability

Hydraulics:
- Discharge vs. Elevation

Loss Calcs:
- Loss vs. Elevation

Damage Curve:
- Elevation vs. Loss
- Probability vs. Loss

Flood Elevation Curve:
- Flood Elevation vs. Annual Exceedance Probability
- Building #: 939043
- Probability: 2.9%, 11.8%

Flood Damage Curve:
- Expected Damage vs. Annual Exceedance Probability
- Building #: 939043
- Avg. Annualized Loss: $3,443
- Probability: 2.9%

*There is a 2.9% annual chance of having a flood that reaches the first floor elevation of this structure.

*The average expected damage from a flood that reaches the first floor is at least $30,220.
Crash Course of Probabilistic Approach
Crash Course of Probabilistic Approach
Sampling Methodology
Crash Course of Probabilistic Approach

Fluvial Hydrology

- Monte Carlo Discharge Curve converges with Mean Discharge Curve
- Can increase consistency and reproducibility
- Model 100 events between the 2- and 3000-year flood events
  - Vary flood durations & hydrographs based on return period
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**Pluvial Flooding**

- Important in urban flooding
- Residual risk in leveed areas
- Currently not mapped on FIRMs
- Used by some catastrophic models
- One cause of repetitive loss
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Pluvial Hydrology

- Sampled between 5% & 95% confidence limits
- Storm durations
  - 6-, 12-, 24-, 96-hr
- Temporal distribution
  - 1st, 2nd, 3rd, 4th quartile

From NOAA Atlas 14 Precipitation Frequency Data Server
Crash Course of Probabilistic Approach

Pluvial Hydrology

- Currently no infiltration in HEC-RAS
- Curve Number selected between +/- one standard deviation
- HEC-HMS creates excess precip used as rain-on-grid in HEC-RAS

**HEC-RAS Version 5.1**

- Will include loss functions
  - Curve Number
  - Green and Ampt
  - Constant and Initial Loss
- Losses will be able to be applied as spatially variable
- Spatially variable rainfall patterns will be included (gridded rainfall data)
- Allows us to take advantage of observed (gage adjusted radar rainfall data) and forecasted data products provided with each grid representing a different temporal pattern
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Pluvial Hydrology

Example: 24 Hour Storm

37 Like Storms replaced with a single curve

Passes Convolution & Volume Test

1. Calculate the mean curve (that will represent this group of events)

2. Adjust the probability for the event using:

\[ P = \sum Weight \]
Crash Course of Probabilistic Approach

**Hydraulics – Simulations**

- 2D model scenarios are run in a batch, automated process
- 100 fluvial runs per scenario, up to thousands of pluvial runs

WHAT IF I TOLD YOU

THERE IS NO CLOUD. IT'S JUST SOMEONE ELSE'S COMPUTER.
Probabilistic Approach (Levees)

<table>
<thead>
<tr>
<th>River Elevation (NAVD 88)</th>
<th>System Response Probability (BL2a) w/ Intervention</th>
<th>System Response Probability (BL2a) w/o Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>415.00</td>
<td>0.000000377%</td>
<td>0.00000419%</td>
</tr>
<tr>
<td>421.25</td>
<td>0.00000346%</td>
<td>0.000230%</td>
</tr>
<tr>
<td>427.50</td>
<td>0.108%</td>
<td>0.553%</td>
</tr>
<tr>
<td>432.90</td>
<td>1.50%</td>
<td>7.05%</td>
</tr>
<tr>
<td>440.00</td>
<td>8.32%</td>
<td>37.0%</td>
</tr>
</tbody>
</table>

System Response Curve - BL2a

- w/ Intervention
- w/o Intervention

River Elevation vs. System Response Probability (SRP)
AEP Generation Concept

Floodplain

<table>
<thead>
<tr>
<th>Floodplain</th>
<th>AEP Database</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 0 0 0 0 0 0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 0 0 0 0 0 0</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0 0 0 0 0 0 0</td>
<td></td>
</tr>
</tbody>
</table>

AEP = grid value/number of events

Example illustration borrowed from USACE
Annual Exceedance Probability Grid

Probability grids generated using results & probabilities from all model runs
Depth-Damage Functions used in Risk Assessments

Depth-Damage Curves (1 Story, No Basement) - STRUCTURE

- RES1N1-AVG
- RES1N1-MAX
- RES1N1-MIN
- FIA (105)
- USACE - IWR (129)
- USACE - Chi (132)
- USACE - Gal (139)
- USACE - New (143)
- USACE - New (144)
- USACE - New (154)
- USACE - St. (173)
- USACE - Wil (179)
- USACE - Wil (180)
Structure-Level Risk

- Detailed Flood Elevation-Probability Curves extracted for any structure of interest based on the underlying model results.
Structure-Level Risk

- Flood Damage Curves can be generated, taking into account uncertainties in structure occupancy and first floor elevations (FFE)
Structure-Level Risk

- Average annualized losses (AAL) much more accurate – little to no extrapolation required, unlike with typical studies.

AAL: $104

AAL = area under curve

Probabilistic Mapping

*The average expected damage from a flood that reaches the first floor is at least $18,970*
“Neighborhood” Damage Curves aggregated from structure data can provide insight into expected damages for multiple properties.
Aggregating AEP Maps

Fluvial + Pluvial = Total
Aggregating AALs

**Fluvial**
- # Structures with Damage: 35,197 of 35,236 (99.9%)
- Avg. Annualized Loss (AAL): $4,848,716
- Total AAL: $15,028,131

**Pluvial**
- # Structures with Damage: 21,491 of 35,236 (61%)
- Avg. Annualized Loss (AAL): $10,179,415
Risk Assessment

• How much damage can be expected in any given year?
• Where are the damages coming from? How much is fluvial vs pluvial?
• Which storm duration causes the most damage?
• Which levee breaches have the most potential for damage?
Cost Benefit Analysis for Levees

- Probabilistic approach can consider accredited, breaching, and natural valley levee scenarios (each w/ associated probabilities)

**Natural Valley AEP Map**

<table>
<thead>
<tr>
<th>Annual Exceedance Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50% (&gt;2yr)</td>
</tr>
<tr>
<td>50-10% (2-10yr)</td>
</tr>
<tr>
<td>10-4% (10-25yr)</td>
</tr>
<tr>
<td>4-2% (25-50yr)</td>
</tr>
<tr>
<td>2-1% (50-100yr)</td>
</tr>
<tr>
<td>1-0.2% (100-500yr)</td>
</tr>
<tr>
<td>0.2-0.1% (500-1000yr)</td>
</tr>
<tr>
<td>0.1-0.05% (1000-2000yr)</td>
</tr>
<tr>
<td>0.05%-0.0417% (2000-2400yr)</td>
</tr>
<tr>
<td>&lt;0.0417% (&gt;2400yr)</td>
</tr>
</tbody>
</table>

![Levee](levee1.png)

**Accredited (w/ Levee) AEP Map**

<table>
<thead>
<tr>
<th>Annual Exceedance Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;50% (&gt;2yr)</td>
</tr>
<tr>
<td>50-10% (2-10yr)</td>
</tr>
<tr>
<td>10-4% (10-25yr)</td>
</tr>
<tr>
<td>4-2% (25-50yr)</td>
</tr>
<tr>
<td>2-1% (50-100yr)</td>
</tr>
<tr>
<td>1-0.2% (100-500yr)</td>
</tr>
<tr>
<td>0.2-0.1% (500-1000yr)</td>
</tr>
<tr>
<td>0.1-0.05% (1000-2000yr)</td>
</tr>
<tr>
<td>0.05%-0.0417% (2000-2400yr)</td>
</tr>
<tr>
<td>&lt;0.0417% (&gt;2400yr)</td>
</tr>
</tbody>
</table>

![Levee](levee2.png)
Dear (personal, non-FEMA endorsed) Crystal Ball,

How might this affect the future of engineering studies?
Benefits of PFRA

• Analysis
  • Full risk profile
  • Graduated risk
  • Accounts for uncertainty
  • Focused on damages, not zones

• Products
  • High resolution data
  • AAL for structures & systems
  • AEP maps

• Abilities
  • Benefit-cost analyses for mitigation or CIP
  • Risk-Informed decision making
  • Enhanced outreach and awareness
Limitations & On-Going Research

- Data availability
- Computation time
- Hydraulic structures
- Stormwater systems
- Cell size sensitivity
- Timing rainfall application across large watersheds
- Joint pluvial probability with riverine inflows
- Joint probability at confluences

BUT...

IT’S NOT PERFECT
For more information please contact:
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A special thank you to Geoffrey Uhlemann & Reuben Cozmyer at AECOM for providing material for this presentation.
For more information please contact:
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A special thank you to Geoffrey Uhlemann, AECOM, for providing most of the material for this presentation.
Results

- Grids for any return period (WSEL, depth, d×v)
- AEP grids
- Structure-specific WSEL & damage curves
- AALs for structures, areas, or systems
Model Development

- Terrain & bathymetry
- Model boundary
- Mesh
- Manning’s $n$ (land use layer)
- Breaklines (define high ground in terrain)
- Boundary conditions
- Simulation time & computation interval
- Calibration
- Validation
Traceability – not a black box

- Can ascribe specific AALs from fluvial modeling, pluvial modeling, specific breaches
- Can further break down into specific return period run
- Random numbers used for assigning are stored to allow for the reproduction of the analysis
  - Hyetograph decile
  - AMS condition
  - Confidence limits
  - Etc

xkcd #242 “The Difference”
Risk Assessment

- The full flood risk greater than the 2 year flood is captured by modeling 100 events.
- The percent chance of each event occurring is calculated and used as a weight for the potential damages caused by that event.
Reasons for a New Approach

*Institutional & Policy Drivers*

**Learning from the Past**

- >25% NFIP claims are structures outside SFHA (about 60% of losses)
  *This moves away from SFHA zones*
- Current insurance rating system doesn’t reflect risk (NFIP deficit)
  *This reflects potential loss (frequency, value, damage)*
- Technical & catastrophic modeling improvements
Reasons for a New Approach

**Technical Advances**

- To account for uncertainty
- Model future & varied conditions
- Information on wide range of events, (2-3000 yr)

**In Data Use**

- Show graduated risk within floodplain
- Include full risk profile
  - *Fluvial (riverine)*
  - *Residual (behind levees)*
  - *Pluvial (localized rainfall)*
  - *Coastal (in pilot phase)*
- Structure-specific risk information
- Gridded data for nearly any return period
FEMA Flood Map
Concept of Probabilistic Modeling

Existing Approach Comparison

1D or 2D Hydraulic Modeling
Concept of Probabilistic Modeling
Random Sampling Methodology

Concept behind event sampling

Hydraulics
- discharge vs. elevation
- loss vs. elevation

Hydrology
- discharge vs. probability
- loss vs. probability

Loss Calculations (at a single structure)

Damage Curves
Concept of Probabilistic Modeling

Risk Assessment

- Individual model results plotted out to produce various curves
Crash Course of Probabilistic Approach

Fluvial Hydrology

![Discharge-Probability Curve & Uncertainty Cloud](image)
**Crash Course of Probabilistic Approach**

*Hydraulics – Land Cover*

**Uncertainty in Manning’s n-values**

<table>
<thead>
<tr>
<th>NLCD Classification</th>
<th>Assigned Manning’s Roughness</th>
<th>Minimum</th>
<th>Normal</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Water</td>
<td></td>
<td>0.025</td>
<td>0.03</td>
<td>0.033</td>
</tr>
<tr>
<td>Developed, Open Space</td>
<td></td>
<td>0.035</td>
<td>0.055</td>
<td>0.095</td>
</tr>
<tr>
<td>Developed, Low Intensity</td>
<td></td>
<td>0.085</td>
<td>0.095</td>
<td>0.11</td>
</tr>
<tr>
<td>Developed, Medium Intensity</td>
<td></td>
<td>0.09</td>
<td>0.115</td>
<td>0.13</td>
</tr>
<tr>
<td>Developed, High Intensity</td>
<td></td>
<td>0.1</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>Barren Land</td>
<td></td>
<td>0.03</td>
<td>0.033</td>
<td>0.036</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td></td>
<td>0.1</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td></td>
<td>0.085</td>
<td>0.115</td>
<td>0.14</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td></td>
<td>0.09</td>
<td>0.115</td>
<td>0.15</td>
</tr>
<tr>
<td>Scrub/Shrub</td>
<td></td>
<td>0.05</td>
<td>0.075</td>
<td>0.09</td>
</tr>
<tr>
<td>Grassland Herbaceous</td>
<td></td>
<td>0.028</td>
<td>0.03</td>
<td>0.035</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td></td>
<td>0.038</td>
<td>0.045</td>
<td>0.055</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td></td>
<td>0.035</td>
<td>0.042</td>
<td>0.048</td>
</tr>
<tr>
<td>Woody Wetlands</td>
<td></td>
<td>0.08</td>
<td>0.095</td>
<td>0.12</td>
</tr>
<tr>
<td>Emergent Wetland</td>
<td></td>
<td>0.04</td>
<td>0.065</td>
<td>0.1</td>
</tr>
<tr>
<td>River Channel</td>
<td></td>
<td>0.026</td>
<td>0.028</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Depth-Damage Functions used in Risk Assessments

• Composite Depth-Damage curves for each structure type were used based on available curves from Hazus
Hot Spot Map of AAL Ratio (Combined Fluvial and Pluvial)

AAL Ratio = \frac{AAL}{Structure Value}

High AALs were primarily due to pluvial flooding within low-lying topographic areas
Next Steps

- Additional pilots studies
- Methodology being refined based on lessons learned
- Development of guidelines and best practices
- Results to inform insurance premium adjustments
1D Flood Modeling
2D Flood Modeling
Conservation of Mass

\[
\frac{\partial H}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = \text{Sources} - \text{Sinks} \quad (1a)
\]

- Where:
  - \( \frac{\partial H}{\partial t} \) is the rate of increase (or decrease) in water level, which for a fixed cell size is representative of the rate of change of volume of water contained in the cell.
  - \( \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} \) is the spatial variation in inflow (or outflow) across the cell in the \( x \) and \( y \) directions.
  - Sources = Rainfall, Stormwater Outlets, or Pump Outlets
  - Sinks = Pump Intakes, Infiltration, or Evaporation
Conservation of Momentum

\[
\frac{\partial u}{\partial t} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}\right) = -g \frac{\partial H}{\partial x} + v_t \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + f v
\tag{2a, x}
\]

\[
\frac{\partial v}{\partial t} + \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y}\right) = -g \frac{\partial H}{\partial y} + v_t \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v - f u
\tag{2a, y}
\]

Where:
- \(\frac{\partial u}{\partial t} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}\right)\) is the partial differential form of the flow acceleration
- \(g \frac{\partial H}{\partial x}\) is the hydrostatic pressure gradient term
- \(v_t \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\) is the viscosity (turbulence) term, \(v_t\) is the horizontal coeff. of eddy viscosity
- \(c_f u\) is the bed friction term
- \(f v\) is the Coriolis parameter

\[
c_f = \frac{n^2 g |V|}{R^{4/3}}
\]
2D Equations

- Where:
  - $H$ is the water surface elevation relative to a fixed datum.
  - $u$ is the depth-averaged velocity in the $x$ direction.
  - $v$ is the depth-averaged velocity in the $y$ direction.

- These are described as a function of the three main independent variables:
  - $x$ – Horizontal distance in the $x$ direction
  - $y$ – Horizontal distance in the $y$ direction
  - $t$ – Time

- Additionally, the time varying water depth at any location $h(x, y)$ can be expressed as $h = H - z$. 
# Basic Numerical Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Type of Computational Mesh</th>
<th>Advantages</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite Difference</td>
<td>Structured (Cartesian or Curvilinear)</td>
<td>Simple, Stable, Efficient</td>
<td>Terrain Representation</td>
</tr>
<tr>
<td>Finite Element</td>
<td>Structured or Unstructured</td>
<td>Terrain Representation</td>
<td>Issue with Mass Conservation/Stability/Less Efficient</td>
</tr>
<tr>
<td>Finite Volume</td>
<td>Structured or Unstructured</td>
<td>Terrain Representation, Stable, Flow Regime, Conservation of Mass/Volume</td>
<td>Less Efficient</td>
</tr>
</tbody>
</table>
# Numerical Solution Schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Description</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Explicit</strong></td>
<td>Water surface elevations and flow velocities at the new time step are computed directly (explicitly) as a function of the known values at the old time step</td>
<td>(1) Computationally Efficient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Stability Constraints - “Courant” Stability Criterion</td>
</tr>
<tr>
<td><strong>Implicit</strong></td>
<td>Water surface elevations and flow velocities at the new time step are expressed as a combination of both the known values at the old time step and adjacent unknown values at the new time step</td>
<td>(1) Courant stability criterion does not apply</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Time step based on accuracy and not stability</td>
</tr>
<tr>
<td><strong>Semi-implicit</strong></td>
<td>Water surface elevations and flow velocities at the new time step are expressed as a combination of adjacent values at the old and new time step</td>
<td>(1) Courant stability criterion theoretically does not apply</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Most accurate scheme</td>
</tr>
</tbody>
</table>
Diffusion Wave Approximation

Bottom Friction = Pressure Gradient

\[
\frac{\partial u}{\partial t} + \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -g \frac{\partial H}{\partial x} + v_t \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - c_f u + f v
\]

\[
g \frac{\partial H}{\partial x} + c_f u = 0
\]

Water surface slope is balanced by the friction slope
2.1.1.2 The Equations

The Saint-Venant equations are two coupled partial derivative equations. The first one is the mass conservation equation:

$$\frac{\partial A(x,t)}{\partial t} + \frac{\partial Q(x,t)}{\partial x} = 0,$$

(2.1)

2.1 Saint-Venant Equations for Open Channel Flow

and the second one is the momentum conservation equation:

$$\frac{\partial Q(x,t)}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{Q^2(x,t)}{A(x,t)} \right] + gA(x,t) \left( \frac{\partial Y(x,t)}{\partial x} + S_f(x,t) - S_b(x) \right) = 0.$$

(2.2)

The friction slope $S_f$ is modeled with the classical Manning formula [5]:

$$S_f = \frac{Q^2 n^2}{A^2 R^{4/3}},$$

(2.3)