Defining Flood Risk on Alluvial Fans

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Topics

• Flood hazard uncertainty vs complexity
• Possibility vs probability
• Flood risk ≠ flood hazard
• Stochastic vs deterministic flood hazard analyses
• Linking stochastic and deterministic methods
• Integrating hazard mapping and damage assessment
• Managing risk
Fan Flooding Considerations

Fans may have a large drainage area

Fan rainfall and infiltration are important
Fan Flooding Considerations

• Large flood events - but small apex channel capacity (2-5 yr return event capacity)

• Fan apex avulsions at the fan apex – are not the dominant process for the 100-year flood
Fan Flooding Considerations

Flooding hazard and risk is not always predispositioned by fan morphology, existing conditions or rainfall frequency.
Fan Sedimentation Issues

- Scour and deposition – flow paths: Issue for frequent events, but not for the 100-year flood
- For arid fans (not mudflows) assume 10% to 20% sediment concentration by volume – increases flood volume
- Loss of channel conveyance – causes avulsion
Fan Flooding - Important Factors

• Flood Volume = flood hydrographs + rainfall
• Floodwave attenuation
• Losses – infiltration = 40%
• Sediment concentration (increases flood volume)
• Topography
• Obstructions

Minor Factors: avulsion, apex channels, roughness
Key Words

- Uncertainty
- Risk
- Hazard
- Probability
• “Risk analysis and uncertainty in flood damage reduction studies”

• “Extreme storms create serious flood hazards in the Colorado Front Range, making flood risk an important aspect of state and local planning. However, in areas of steep topography such as Colorado, estimates of flood risk are highly uncertain because of the sparsity of data and the high spatial and temporal variability in precipitation.”

• “Sources of uncertainty in flood inundation maps”
Fan Flooding - Uncertainty

Flood path uncertainty occurs with:

• Variable topography – unconfined flow
• Sediment load – incision and avulsion
• Hydrology - deviate from design storm
• Floodwave attenuation
Is it possible to flood this site?

Anything is possible. Is it probable? What is the likelihood that this location will be flooded during the 100-year rainfall?
Flood Probability

100-yr design storm – 1% chance in any given year with roughly a 63% chance in a 100 yr period

• Water only flood?

• Hyperconcentrated sediment flow (mudflood, mud flow, debris flow) $C_v > 20\%$
Hazard ≠ Risk

Hazard
• An event that poses a danger

Vulnerability
• Susceptibility to specific hazard

Risk
• Probability of suffering harm or loss
Hazard

“...a potentially damaging physical event...that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation.”   UN-ISDR (2004)

Flood hazard is defined as exposure to flooding.
Risk

“...the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions.” UN-ISDR (2004)

When people discuss risk, they typically mean hazard.
Hazard ≠ Risk

Risk = Hazard ∩ Vulnerability
For specific event
Assume 3 ft of flood hazard on each side of the river. Similar hazard but significantly different risk.
Stochastic vs Deterministic Models

Stochastic (probabilistic) models:

- Assumes flood hazard is a random process. Uses random variables that have assumed or known probability distributions.
- Generates repeated output that may not be the same, but will follow statistical patterns.
- Displays flood hazard as a probability of inundation.
- Cannot predict flood intensity or vulnerability
Stochastic vs Deterministic Models

Deterministic models:

• Based on physical relationships. Predicts solutions/outcomes based on existing fan conditions.

• Always produces the same output from the same set of input data.

• Cannot establish the probability of flood inundation for varying future conditions.
FEMA FAN Model - Stochastic?
Stochastic vs Deterministic Models

Best of Both Worlds:

• Stochastic model establishes the range of variability in future conditions through a stochastic process.

• Deterministic model predicts the flood intensity for the range of variability or worse case scenario.
Conceptual Model: Linking Stochastic and Deterministic Approaches to Alluvial Fan Flooding
Flood hazards are primarily controlled by the project hydrology - establishes the flood volume and the overall area of inundation.

Hydraulic routing plays a secondary role - distributes the flood to define the local inundation details.
General Approach Concepts

Methods for conducting uncertainty analyses for hydrologic or hydraulic models:

• First-order, second moment approximation methods
• Probabilistic point methods
• Monte Carlo simulations
• Integral transformation methods
Alluvial Fan Flooding as a Stochastic Process

The number of variables affecting the flood depth may exceed the capabilities of deterministic models.

Stochastic models define the flood by treating the physical system as an indexed collection of random variables.
Monte Carlo Simulations

Hydrologic/hydraulic parameters vary randomly but follow known/assumed probability distributions

Requires repeated simulations using prescribed values of the random variables generated from the probability distribution

Results are statistically significant if the sample results reflect the observed results
Monte Carlo (MC) Simulations

Critical task is generating the parameter probability distribution

Alluvial fans Monte Carlo studies:
- Calvo and Savi, 2008
- Wichmann and Becht, 2003
- Price, 1974

Applying MC is problematic because the hydraulic models take hour(s) to complete one simulation

Required number of MC simulations ~ 10,000
Possible New Alluvial Hazard Delineation Method

Random Walk Model: MC method that doesn’t require repeated flood simulations (Price, 1974; Wichmann and Becht, 2003).
Random Walk Model*

Start with inflow node:
Method selects the potential flow path (random walk) from the directions that have a lower elevation.

*Patterned after Gamma (2000)
Alluvial Fan Parameters

Uncertainty parameters:

- Topography, slope
- Roughness value
- Momentum change
- Obstructions (levees, buildings)
- Flow path preference or persistence (channels, streets, distributary channels)
- Sediment concentration (optional)
- Scour and deposition (channel avulsion)
Probability Distribution Functions

Probability distribution for a random variable $H$ at a discrete location on the alluvial fan is:

$$P_{(H|X)} = \int_{x_0}^{\infty} P_{(H|X)} f_X(x) \, dx$$

where $x$ is a second random variable (e.g. discharge), $P_{(H|X)}$ is the probability that the point on the fan will be inundated, and $f_X(x)$ is the probability density function PDF.
Probability Distribution Function

\[ \phi_{\mu, \sigma^2}(x) \]

- \( \mu = 0, \quad \sigma^2 = 0.2, \)
- \( \mu = 0, \quad \sigma^2 = 1.0, \)
- \( \mu = 0, \quad \sigma^2 = 5.0, \)
- \( \mu = -2, \quad \sigma^2 = 0.5, \)
Simple Example PDF: Avulsion Function*

Avulsion (av) or obstruction (ob):

• No opportunity for avulsion or obstruction:
  \[ av = 0. \text{ or } ob = 0. \]
  probability (P = 1.0) for the given flow direction

• For an occurrence of avulsion or obstruction
  \[ av = 1. \text{ or } ob = 1. \]
  no probability for flow (P = 0.0) in that direction

*From Heggen (1994)
Price (1974) computes the probability for the slope (s) as:

\[ P = 0.25 + 0.75s \]

If the slope is 0.0, there is a 25% probability for a typical four paths uniform grid system (or 0.125 probability for the 8-direction FLO-2D model)
Probability Assignment

Probabilities based on a random estimate within a given range of the prescribed probability function.

Generate uniformly distributed random numbers between 0 and 1 to assign a probability for:

- Potential scour and deposition
- Variation in flow roughness
- Changes in flow path direction
- Obstructions, flow path preference and avulsion are assigned probabilities = switch (on or off).
Random Number Generation within the Range

![Graph showing probability density vs. length. The graph is a bell curve with a shaded area indicating the probability density for a specific range of lengths.]
Random Walk Model

The probability for each grid element to be selected from the set of potential path elements is given by:

\[
p_i = \begin{cases} 
\frac{\tan \beta_i \ p}{\tan \beta_j}, & \text{if } k \in N \\
\frac{\sum_j \tan \beta_i}{\sum_j \tan \beta_j}, & \text{if } k \notin N 
\end{cases}
\]

where \( N \) is the set of potential flow directions for the given element, \( \beta_i \) is the bed slope to neighbor element \( i \), \( p \) is a persistence factor and \( k \) is the previous flow direction.

The calculated transition probabilities are scaled to cumulative values in the \([0,1]\) interval and a random number generator selects one flow path element from the \( N \) set.
Creating the Linkage between the Stochastic and Deterministic Models

The inundation probability is established through a large number of random walk path simulations (e.g. 10,000 runs). The procedure is:

• Identify the primary parameters;
• Select PDF to represent the parameters;
• Perform the MC random number calculation and conduct the random walk path simulations;
• Calculate the inundation probability of the each grid element (based on the number of hits that each grid element received out of total number of path simulations).
Final Hazard and Risk Maps

Series of four overlaid maps consisting of:

- Predicted maximum flow depths/velocity for the existing conditions – Deterministic Model
- Hazard Map - High, moderate, low hazard - Deterministic Model
- Inundation probability – Stochastic Model
- Damage or Risk Map
Inundation, Hydraulic Intensity, and Hazard Maps
Hazard Maps

<table>
<thead>
<tr>
<th>INTENSITY</th>
<th>HIGH</th>
<th>MEDIUM</th>
<th>LOW</th>
<th>VERY LOW</th>
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<tr>
<td>HIGH</td>
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<td>LOW</td>
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PROBABILITY

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<th>RETURN PERIOD</th>
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<th>PROBABILITY OF EXCEEDENCE</th>
<th>10%</th>
<th>1%</th>
<th>0.2%</th>
<th>&lt;&lt;0.2%</th>
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- **High Hazard (red)**
- **Medium Hazard (orange)**
- **Low Hazard (yellow)**
<table>
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<tr>
<th>Hazard Level</th>
<th>Map color</th>
<th>Description</th>
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<tbody>
<tr>
<td>High</td>
<td>Red</td>
<td>People are in danger both inside and outside of structures. Buildings are in danger of being destroyed.</td>
</tr>
<tr>
<td>Medium</td>
<td>Orange</td>
<td>People are in danger outside or structures. Buildings may suffer damage or possible destruction depending on construction materials.</td>
</tr>
<tr>
<td>Low</td>
<td>Yellow</td>
<td>Danger to people is low. Buildings may suffer limited damage, but flooding or sedimentation may affect structures.</td>
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Hazard Map
Probability Map Based on the Random Walk Method
Integration of flood depths, building shape files, depth-damage $ table
Biggest Effort is Building the Damage Cost Table

Flooding Damage Estimation

Buildings shape file: HOUSES.SHP

Building Id field: HOUSES_ID

Import Damage Table: C:\Tracks\tests\Maricopall\Damage\DamageCode_06.tbl

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Integration Takes a Few Minutes
Managing Risk

Eliminate or manage risk by:

• Identify the potential area of inundation
• Review the high hazard areas
• Overlay the probability map with the damage map

Select mitigation where it will do the most good!
Managing Risk – Real World
Manage Risk Practical Application – Storm Drains
No Storm Drains
Manage Risk Practical Application – Storm Drains With Storm Drains
## Manage Risk Practical Application

<table>
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<tr>
<th>Storm Event</th>
<th>Number of Parcels</th>
<th>Number of Structures</th>
<th>Property Values ($M)</th>
<th>Land Values ($M)</th>
<th>Structure Values ($M)</th>
<th>Structure Value Ratio</th>
<th>Structure Damage Costs ($M)</th>
<th>Content Damage Costs ($M)</th>
<th>Agricultural Damage Costs ($M)</th>
<th>Damage Costs per Storm Event ($M)</th>
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<td>444</td>
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<td>$18.7</td>
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<td>$98.7</td>
<td>$47.8</td>
<td>$9.6</td>
<td>$156.1</td>
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</table>

**ANNUALIZED COSTS, $M (5-500YR)**

- $55.7
- $2.7
- $0.3
- $8.7

Mean Annual Costs ($/year) are based on the formula contained in FEMA's Benefit-Cost Analysis Tool V5.2.3
Save your comments/questions for the Panel Discussion