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Introduction of David T. Williams

• BSCE and MSCE (Civil Engineering, Environmental), University of California, Davis
• Ph.D. (Civil Engineering, River Mechanics), Colorado State University

• Worked at:
  – Airborne Combat Engineer Officer, U.S. Army, 7th Special Forces Group
  – U.S. Army Corps of Engineers as a Civilian
    • Hydrologic Engineering Center, Nashville and Baltimore Districts, Engineer Research and Development Center (formally WES)
  – President/Co-founder of WEST Consultants
  – Taught various engineering courses at UC Davis, San Diego State University, and Colorado State University
  – National Director, Water Resources at PBS&J (Atkins) and HDR
Justin W. Griffiths, P.E., CFM, QSD/P

- BSCE – Cal Poly SLO
- MSCE– Villanova University (In progress)
  – Water Resources and Environmental Engineering Concentration
- Senior Water Resources Engineer at NV5 our San Diego office.
  – 13 years experience working on a variety of drainage projects

- Assisted David on the project R&U Analysis presented in this workshop
Learning Objectives for Part 1, Basics

• Determine the differences between the types of uncertainties

• Learn how R&U is used in water resources projects and specifically levee design

• Understand how PDFs are transformed to CDFs and how they are used in R&U analysis

• Comprehend how uncertainties in hydrology and hydraulics are interrelated
Course Outline, The Basics

• Definitions of Risk and Uncertainty
• Relationship Between Risk and Uncertainty
• Types of Uncertainty
• Definitions Used in Uncertainty analysis
• The Monte Carlo Method
• What are PDFs and CDFs?
• How is R&U used in Water Resources?
• Uncertainty in Hydrology
• Uncertainty in Hydraulics
• Applications of R&U to Levee Design and the Reasons
What is Risk and Uncertainty?
“As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know, we don't know.”
Some Definitions – Uncertainty (Wikipedia)

– **Uncertainty:**

  • The lack of complete certainty, that is, the existence of more than one possibility.

  • The "true" outcome/state/result/value is not known.

– **Measurement of uncertainty:**

  • A set of probabilities assigned to a set of possibilities.

  • Example: "There is a 60% chance this market will double in five years"
Some Definitions: Risk (Wikipedia)

• Risk:
  – A state of uncertainty where some of the possibilities involve a loss, catastrophe, or other undesirable outcome.

• Measurement of risk:
  – A set of possibilities each with quantified probabilities and quantified losses.
    – Example: "There is a 40% chance the proposed oil well will be dry with a loss of $12 million in exploratory drilling costs".
Relationships of Risk and Uncertainty
Based on Willows et al (2000)

<table>
<thead>
<tr>
<th>Good</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ambiguity about the risk</strong></td>
<td><strong>Ignorance about the risk</strong></td>
</tr>
<tr>
<td><em>Uncertain or unknown impacts</em></td>
<td><em>Changing climate</em></td>
</tr>
<tr>
<td><em>Uncertain how to value consequences</em></td>
<td><em>New/unknown processes</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Good knowledge of the risk</th>
<th>Uncertain probability</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Unchanging environment</em></td>
<td><em>Poor historical record</em></td>
</tr>
<tr>
<td><em>Good historical data</em></td>
<td><em>Limited evidence of frequency of extreme events</em></td>
</tr>
</tbody>
</table>
Whose idea was this to use Risk and Uncertainty Analysis in Water Resources?

• Many of the ideas presented have been around for many years

• This presentation shows the concepts of Risk and Uncertainty Analysis (affectionately termed as RU) as applicable to floodplain management and issues

• Also goes over some of the important aspects of RU analysis that should be understood by water resources engineers and floodplain managers

• The main proponent of this approach for use in water resources subjects is the U.S. Army Corps of Engineers (COE) and it use is mandated for COE flood control projects

• Within about 5 years, floodplain managers will be required to be knowledgeable on the subject of Risk and Uncertainty!
Types of Uncertainties
(from Pappenberger, et.al.)

• Natural Uncertainty (Variability) - Refers to inherent variability in the physical world
  – Uncertainties that stem from the assumed inherent randomness and basic unpredictability in the natural world
  – Characterized by the variability in known or observable populations
Types of Uncertainties (from Pappenberger, et.al.)

• Knowledge Uncertainty - Lack of scientific understanding of natural processes and events in a physical system.
  
  – *Process model uncertainty* – Models (e.g., HEC-RAS and HEC-HMS) are an abstraction of reality and can never be considered true. Measured data versus modeled data gives an insight into the extent of model uncertainty.

  – *Statistical inference uncertainty* - Quantification of the uncertainty of estimating the population from a sample. The uncertainty is related to the extent of data and variability of the data that make up the sample.

  – *Statistical model uncertainty* - Associated with the data fitting of a statistical model. If two different models fit a set of data equally well but have different extrapolations/interpolations, then it is not valid - statistical model uncertainty.
Some Definitions used in Uncertainty Analysis

• Deterministic Analysis
  - Uses single values for key variables, e.g., use of an expected flow to determine a single water surface elevation.

• Probabilistic Analysis
  - Uses a probability distribution rather than a single value for key variables - captures and describes uncertainty of the variable, e.g., expected flow including a range of possible flows to determine a range of possible water surface elevations.

• Annual Exceedance Probability (AEP)
  - Measures “the probability of getting flooded” in any given year, considering the full range of floods that can occur – uses only the peak discharge of each year.
Some Definitions used in Uncertainty Analysis

• Conditional Annual Non-Exceedence Probability - CNP (Assurance)
  – The probability that a project will provide protection from a possible distribution of a specified event.
  – For levees, includes the chance of capacity exceedance and the chance of failure at lesser stages.
  – CNP is computed by determining the expected exceedance/failures at top of levee (levee will not fail before overtopping); or application of levee elevation failure probability curve (chance of failure prior to overtopping)
Who is Monte Carlo and why are we afraid of him?

- Monte Carlo methods are a class of computational algorithms that iteratively evaluates deterministic model results using input of random numbers.

- Monte Carlo methods are used when it is infeasible or impossible to compute an exact result with a deterministic algorithm.

- There is no single Monte Carlo method; instead, the term describes a large and widely-used class of approaches. These approaches tend to follow a particular pattern:
  
  - Define a domain of possible inputs (e.g., average and standard deviation).
  - Generate inputs randomly from the domain, and perform a deterministic computation on them.
  - Aggregate the results of the individual computations into the final result.
Example: Determine Pi by Random Darts

But to get decent results, you need to throw a lot of darts!

We also need to do a lot of trials using Monte Carlo to get a decent answer!
## Example: Determine Pi by Random Darts

<table>
<thead>
<tr>
<th>Throw Number</th>
<th>Hit in shaded area</th>
<th>Hit inside square</th>
<th>Ratio of Shaded/in Sq.</th>
<th>Pi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>infinity</td>
<td>infinity</td>
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<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
<td>2.0</td>
</tr>
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<td>.</td>
<td>.</td>
</tr>
<tr>
<td>200</td>
<td>85</td>
<td>115</td>
<td>0.739</td>
<td>2.957</td>
</tr>
<tr>
<td>201</td>
<td>86</td>
<td>115</td>
<td>0.748</td>
<td>2.991</td>
</tr>
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<td>.</td>
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<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>2000</td>
<td>879</td>
<td>1121</td>
<td>0.784</td>
<td>3.136</td>
</tr>
<tr>
<td>2001</td>
<td>880</td>
<td>1121</td>
<td>0.785</td>
<td>3.140</td>
</tr>
</tbody>
</table>
Parameter Estimation and its Variation
(Probability Distribution Function, PDF)

![Graph showing different normal distributions with varying parameters](image-url)

- $\mu = 0, \sigma^2 = 0.2$ (Red line)
- $\mu = 0, \sigma^2 = 1.0$ (Green line)
- $\mu = 0, \sigma^2 = 5.0$ (Blue line)
- $\mu = -2, \sigma^2 = 0.5$ (Pink line)
Transform Parameter and its variation
Cumulative Probability Distribution Function (CDF)
Relationship Between Parameter and Results

Randomly sample the parameter

Determine results for the same probability

Parameter Value

Results with Input Parameter
Other Methods Used in Uncertainty Analyses

- Markov Chain Monte Carlo (MCMC) methods
- Bayesian Probability
- Bayesian Approximation using Monte Carlo
- Generalized Likelihood Uncertainty Estimation (GLUE) method
How is Risk and Uncertainty Applied to Hydrology and Hydraulics?
Some Comments on Uncertainty in Hydrology

• There are two basic attitudes in hydrology and water resources research regarding uncertainty

• The world is considered being basically non-deterministic (i.e., should be modeled in terms of stochastic systems)

• The stochastic process is a necessary factor and cannot be avoided at the present when our understanding is poor

• Stochastic becomes more deterministic as our understanding of the processes improves
Some Comments on Uncertainty in Hydrology, cont.

• It is not only uncertainty about inaccuracy in measurement but also the uncertainty in hydrology is much deeper and pertains to the governing mechanisms and understanding of the processes.

• The theory of chaotic systems states that the time-series of hydrological variables are unpredictable over a long time period, and therefore is inherently uncertain.

• The uncertainty in hydrology results from natural complexity, variability of hydrological systems and processes, and from deficiency in our knowledge.
General Comments on Uncertainty in Hydrology

- In flood control, the greatest uncertainty lies in the estimation of the flow frequency curve and/or stage frequency function.
- Many have relied upon confidence interval calculations found in Bulletin 17B to estimate this uncertainty.
- It has been shown that this procedure can vastly overestimate the uncertainty because it does not recognize physical limitations of a watershed (PMF, etc).
- Therefore, the assurance level calculations based on Bulletin 17B Confidence Interval calculation can be extremely misleading.
Determination of Trends in Seemingly Random Information

• It is important to know if streamflow data is a “static” condition in that the statistical parameters has not been moving over the time of the data record

• The Spearman-Conley test (McCuen, 1998) can be used to determine if these conditions exists and is used to test for serial correlation where values of independent variables are incomplete

• This can help determine if the changes in the hydrologic records are due to external non-random hydrologic phenomenon (e.g., global climate and watershed urbanization)
Uncertainty in Reservoir Regulation (Dunn)

Reservoir Operation Rule Curve with Uncertainty

If estimate of Inflow is off
Uncertainty in Reservoir Regulation (Dunn)

Reservoir Operation Rule Curve with Uncertainty

If estimate of Regulation is off

Outflow $Q_o$

Inflow $Q_i$ 0.005
Uncertainty in Reservoir Regulation (Dunn)

If estimate of Inflow and Regulation are off

Reservoir Operation Rule Curve with Uncertainty
Typical Determination of Uncertainty in Hydrology

- For hydrologic uncertainty, we often use frequency analysis of discharges from gage data.
Uncertainties in Hydraulics

• There are several sources of uncertainty in hydraulics

• As pointed out before, there is uncertainty in the accuracy of hydraulic models in relation to if they are correctly emulating the hydraulic phenomena and if the computation scheme is stable and accurate

• Model input of the geometry is one of the most important sources of errors (is the LIDAR info accurate? Did it pick up the ground below the water level? Did vegetation affect the results?)

• Manning’s “n” values (the most important), expansion and contraction coefficients, effective and ineffective flow areas, variation in seasonal vegetation are some examples of sources of errors
Stage Uncertainty vs. Discharge (Dunn)
Applications to Hydrology and Hydraulics

• Determine the CDF for a given discharge

• Determine the CDF of the parameters affecting the water surface elevations in a hydraulic model

• Use Monte Carlo to develop a CDF of the water surface elevation versus discharge relationship, combining the hydrologic and hydraulic CDFs

• Results are associated probability for each water surface elevations for the given discharge

• Results can be used for a variety of floodplain management strategies
What does this all look like? (Deering, 2007)
What do the results look like for stage for a range of probabilities? (Davis, 2006)
What do the results look like for stage for a single probability? (Deering, 2007)
Hydrologic and Hydraulic Model Linkages and Stochastic Modeling

• The Corps of Engineers’ Engineering and Research and Development Center (ERDC) sponsors the development of WMS 7.0, which is an interface of various hydrologic models.

• The ability to link an HEC-1 hydrologic analysis to a HEC-RAS model have been developed. HEC-HMS will come later.

• User defines certain modeling parameters for both models within a range of probable values and then runs the linked simulations.

• Only CN and Precipitation are currently the possible parameters for HEC-1 models and Mannings roughness for HEC-RAS models.

• Additional parameters will be added to both models.
Levees, Corp of Engineers and FEMA
What a Mixed Bag!
What are Some Applications of RU to Levees?

• The traditional design for top of levees include freeboard (to account for uncertainties) added to the design water surface elevations.

• If the uncertainties can be quantified as a range of probabilities, the freeboard can be determined if a certain CNP can be agreed upon (say 90 or 95% CNP).

• The lower the acceptable risk (want less risk of failure), the higher the CNP and the higher the top of levee above the traditional deterministic water surface elevation.
What is the Corps Policy on This and Levees?

- The US Army Corps of Engineers (COE) has guidelines for computing an aggregated annual exceedance probability (AEP) in the floodplain for levee certification (see USACE, 1996a and 1996b and NRC, 2000).

- The COE (since 1996a) does not use “freeboard” but uses the concept of the CNP elevation above the deterministic elevation.

- NRC (2000) report - USACE approach to levee certification is well thought out, but is still lacking in certain areas.

- Two recommendations for improving the current methods (NRC 2000): (1) consider spatial variability in flood studies and (2) use the AEP more widely as the measure of levee performance for both COE and FEMA.
What about FEMA, Corps, Levees and RU?

• In 1996, FEMA and the Corps proposal combined FEMA’s old criteria with the Corps RU methodology - Supplements 44 CFR 65.10

• The Corps and FEMA agreed to certify a levee if its elevation was at least:
  – (1) at the 90 percent CNP elevation if it is greater than 3 feet above the 100 year DWSE.
  – (2) at the 95 percent CNP elevation if it is greater than 2 feet above the DWSE.
  – (3) at 3 feet above the DWSE if it is between the CNP elevations of 90 percent and 95 percent.

• See Engineer Technical Letter (ETL) 1110-2-570, “Certification of Levee Systems for the National Flood Insurance Program (NFIP),” September 2007
Why Bother with RU for Levees? (Davis, 2007)

• Remember how uncertainty is used to determine CNP elevations:
  
  – Discharge vs. Frequency with Discharge Uncertainty
  
  – Stage vs. Discharge with Stage Uncertainty
  
  – Surge, Wind Wave and Wave Period with Surge Uncertainty (coastal)
Why bother with RU for levees? (Davis, 2007)

• Situation 1. Flat gradient, flow/stage variability low, long flow/stage record, high integrity existing levee.

• Situation 2. Steep gradient, flow/stage variability high, short record, uncertain integrity existing levee

• Traditional methods would give one value for freeboard, but risk analysis explicitly quantifies difference between these situations and reflects residual risk.
Levee Fragility Curves

- Levee fragility curves embody all the analysis of the levee design and the stresses on it such as, seepage (of water beneath and through the levees), stability, overtopping, erosion, etc.

- From the curves, the engineer determines out how the reliability of a levee changes as water rises and then overtops it – see slide for example

- This curve is integrated into the overall Monte Carlo simulations for RU analysis of the levee system
Fragility Curve Concept (E. Link, IPET)
Example of non-overtopping levee failure (Ref. Ed Link, IPET)
Levees and FEMA Standards
HEC’s Study on Levees, FEMA standards, and AEP

• From an HEC study of 13 levee systems, the following observations were made:

  – FEMA standard of 3 feet of freeboard provides a median expected level of protection of approximately 230 years, range of <100 years to >10,000 years

  – Corps – FEMA 90% - 3ft - 95% criterion provides an average of 3.3 feet of freeboard and yields a median expected level of protection of approximately 250 years, range of 190 to 10,000 years

  – The 90 percent CNP provides an average of 3.0 feet of freeboard and a median expected level of protection of approximately 230 years, range of 170 to 5,000 years

  – The 95 percent CNP provides an average of 4.0 feet of freeboard and a median expected level of protection of approximately 370 years, range of 210 to 10,000 years.
## Levee Elevations, RU and FEMA Methods, from Davis (2007)

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<thead>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl R., Jackson, MS</td>
<td>44.6</td>
<td>47.0</td>
<td>1/770</td>
<td>97.6</td>
<td>99.8</td>
<td>43.4</td>
<td>44.0</td>
</tr>
<tr>
<td>American R, Sacramento, CA</td>
<td>49.1</td>
<td>52.0</td>
<td>1/230</td>
<td>91.9</td>
<td>94.4</td>
<td>48.5</td>
<td>52.3</td>
</tr>
<tr>
<td>Portage, WS</td>
<td>798.3</td>
<td>797.0</td>
<td>1/10000</td>
<td>99.9</td>
<td>99.6</td>
<td>796.6</td>
<td>797.3</td>
</tr>
<tr>
<td>Hamburg, IA</td>
<td>912.2</td>
<td>911.5</td>
<td>1/910</td>
<td>99.9</td>
<td>99.2</td>
<td>910.7</td>
<td>910.8</td>
</tr>
<tr>
<td>Pender, NE</td>
<td>1329.3</td>
<td>1330.0</td>
<td>1/380</td>
<td>76.3</td>
<td>83.6</td>
<td>1330.9</td>
<td>1331.5</td>
</tr>
<tr>
<td>Muscatine, IA</td>
<td>560.8</td>
<td>561.5</td>
<td>1/330</td>
<td>90.1</td>
<td>94.4</td>
<td>560.8</td>
<td>561.7</td>
</tr>
<tr>
<td>E Peoria, IL</td>
<td>458.1</td>
<td>462.6</td>
<td>1/10000</td>
<td>45.3</td>
<td>99.5</td>
<td>468.7</td>
<td>461.2</td>
</tr>
<tr>
<td>Cedar Falls, IA</td>
<td>864.7</td>
<td>866.0</td>
<td>1/360</td>
<td>90.0</td>
<td>94.0</td>
<td>866.8</td>
<td>866.3</td>
</tr>
<tr>
<td>Guadalupe, TX</td>
<td>57.9</td>
<td>56.8</td>
<td>1/110</td>
<td>87.2</td>
<td>76.9</td>
<td>58.4</td>
<td>59.5</td>
</tr>
<tr>
<td>White River, IN</td>
<td>715.0</td>
<td>713.2</td>
<td>1/250</td>
<td>98.0</td>
<td>86.0</td>
<td>713.5</td>
<td>713.9</td>
</tr>
</tbody>
</table>
What Are Some Issues Related to the Use of Risk and Uncertainty in Water Resources?
Issues Related to RU Analysis

• Much of the uncertainty is impossible to define with any accuracy
  – Standard deviation of the water surface elevation for a given flow
  – Coincident probabilities of stage and wind for a wave calculation
  – Coincident timing of flood peaks for two different size drainage areas upstream from your project
  – CNP is a concept, not a reality

• Consequently, deterministic “worst case” assumptions are made about these items and therefore establish “Base” case or most likely conditions that are far more extreme than the most likely

• RU therefore begins with a significant bias that is often not recognized
Levee Related Issues

- A levee project designed with R&U has a design top of levee but no design water surface elevation. This makes operation and maintenance requirements for the channel unknowable.

- If there are many miles of levee upstream from a project, a true RU analysis must consider the possibility that upstream levees will fail.

- Upstream levee failure will impact the stage frequency function at the project location.

- A deterministic design may assume upstream levees do not fail, which becomes just another of the “worse case” assumptions associated with deterministic design.
More Levee Related Issues

• A no failure assumption destroys the basic assumption of RU analysis and would vastly overestimate the flood risk

• In RU analysis, there is a requirement to determine “when” and “how” a levee will fail

• A levee that fails after the peak flows and stages have occurred has a much different impact on flood stages than a levee that fails before or at the peak flow and stage condition

• The “How” assumption is significant; e.g., a 25 foot wide break has a different impact than a 1000 foot wide break
General Comments

• Hydraulic model must be able to execute the desired failure scenarios; at this time the models are quite limited in their capability to simulate varying assumptions efficiently

• An RU Analysis that incorporates “Worse” case assumptions as the \textit{base} case will significantly overstate the risks and could lead to bad decision making

• A requirement to use RU procedures when correcting project defects has been stated as a Corps 408 permit requirement but no definitive guidance provided

• What does it mean and how to implement it is a very significant policy issue
Risk and Uncertainty, Part 2: Getting the Numbers and Applying to Projects

Learning Objectives

• Learn the difference types of uncertainties in hydrology and hydraulics

• Determine the relative importance of parameters in relation to uncertainty

• Find how to define the uncertainties of various hydrologic and hydraulic parameters

• Understand the important steps in performing a R&U analysis for a project
Course Outline, Part 2: Getting the Numbers and Applying to Projects

• HEC-SSP (Statistical Software Package)

• How do we determine hydrologic parameters and their variations?

• What if we do not have gage information?

• How do we determine the hydraulic parameters and their variation

• Hydrologic and hydraulic model linkages and stochastic modeling

• Goals for HEC-FRM Flood Risk Management

• Example Project
HEC-SSP (Statistical Software Package)


- **Generalized Frequency Analysis** – Allows the user to perform annual peak flow frequency analyses by various methods, the user can perform frequency analysis of variables other than peak flows, such as stage and precipitation data.

- **Volume-Duration Frequency Analysis** – Allows the user to perform a volume-duration frequency analyses on daily flow data.
How do we determine the hydrologic parameters and their variations?

• The standard error of flood discharges from river gaging station data - use procedures described by Kite (1988).

• The standard error of river gaging station estimates – also use 84-percent one-sided confidence limits as described in Bulletin 17B (WRC, 1981).

• The approach by Kite (1988) is favored - considers the uncertainty in the skew coefficient while the Bulletin 17B approach does not.
Example of Precipitation Data:
Cities in Pennsylvania

<table>
<thead>
<tr>
<th></th>
<th>Allentown</th>
<th>Erie</th>
<th>Harrisburg</th>
<th>Philadelphia</th>
<th>Pittsburgh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (inches):</td>
<td>3.171</td>
<td>2.483</td>
<td>2.899</td>
<td>3.165</td>
<td>2.791</td>
</tr>
<tr>
<td>Median (inches):</td>
<td>2.900</td>
<td>2.315</td>
<td>2.630</td>
<td>2.900</td>
<td>2.340</td>
</tr>
<tr>
<td>Mode (inches):</td>
<td>3.660</td>
<td>4.400</td>
<td>2.650</td>
<td>1.670</td>
<td>2.550</td>
</tr>
<tr>
<td>Standard Deviation (inches):</td>
<td>1.720</td>
<td>1.111</td>
<td>1.463</td>
<td>1.627</td>
<td>1.259</td>
</tr>
</tbody>
</table>
NOAA Atlas 2 Site to Obtain Precip. Data

1. DATA DESCRIPTION:
   - Data type: Precipitation depth
   - Units: English
   - Time series type: Partial duration

2. SELECT LOCATION:
   - Select site from list:
   - Enter location:
     - Latitude (decimal degrees): lat
     - Longitude (decimal degrees): lon
   - Click on map to select location information:
     - Latitude: 39.168
     - Longitude: -114.727
     - Elevation (feet): 7286
What if we do not have gage information?

- The standard errors of estimate or prediction of the USGS regression equations - regional flood frequency reports (e.g., Dillow, 1996).

- The standard error of rainfall-runoff model estimates (such as HEC-HMS) is not usually known. WRC report(1981) suggested that it is larger then the standard error of regression estimates, in part because rainfall-runoff models based upon calibration to a single-event design storm are not usually calibrated to regional data.

- Confidence limits or standard errors of flood discharges from rainfall-runoff models can be estimated if an equivalent years of record is assumed for the flood discharges - USACE (1996b). The equivalent years of record is the number of years of streamflow record necessary to provide an estimate equal in accuracy to the regression equation.

- No established practice of estimating the uncertainty of flood estimates from rainfall-runoff models.
Streamstats Website to obtain flow frequency information
Streamstats Website to obtain flow frequency information at any location within a Watershed

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Flow ($\text{ft}^3/\text{s}$)</th>
<th>Prediction Error (percent)</th>
<th>Equivalent years of record</th>
<th>90-Percent Prediction Interval Minimum</th>
<th>90-Percent Prediction Interval Maximum</th>
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</thead>
<tbody>
<tr>
<td>PK2</td>
<td>420</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK5</td>
<td>964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK10</td>
<td>1470</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK25</td>
<td>2440</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK50</td>
<td>3260</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK100</td>
<td>4400</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK200</td>
<td>5490</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PK500</td>
<td>7460</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Frequency Equations and Associated Errors
(Analysis of the Magnitude and Frequency of Flood on Colorado, USGS WRIR 99-4190)

<table>
<thead>
<tr>
<th>Recurrence interval, in years</th>
<th>Regression equation</th>
<th>Standard error of the model, in percent</th>
<th>Average standard error of prediction, in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( Q = 11.0 (A)^{0.663} (S + 1.0)^{3.465} )</td>
<td>58.5</td>
<td>59.6</td>
</tr>
<tr>
<td>5</td>
<td>( Q = 17.9 (A)^{0.677} (S + 1.0)^{2.739} )</td>
<td>47.7</td>
<td>48.6</td>
</tr>
<tr>
<td>10</td>
<td>( Q = 23.0 (A)^{0.685} (S + 1.0)^{2.364} )</td>
<td>43.7</td>
<td>44.6</td>
</tr>
<tr>
<td>25</td>
<td>( Q = 29.4 (A)^{0.695} (S + 1.0)^{2.004} )</td>
<td>41.4</td>
<td>42.3</td>
</tr>
<tr>
<td>50</td>
<td>( Q = 34.5 (A)^{0.700} (S + 1.0)^{1.768} )</td>
<td>41.4</td>
<td>42.3</td>
</tr>
<tr>
<td>100</td>
<td>( Q = 39.5 (A)^{0.706} (S + 1.0)^{1.577} )</td>
<td>42.4</td>
<td>43.4</td>
</tr>
<tr>
<td>200</td>
<td>( Q = 44.6 (A)^{0.710} (S + 1.0)^{1.408} )</td>
<td>44.2</td>
<td>45.2</td>
</tr>
<tr>
<td>500</td>
<td>( Q = 51.5 (A)^{0.715} (S + 1.0)^{1.209} )</td>
<td>47.5</td>
<td>48.6</td>
</tr>
</tbody>
</table>

\( Q \), discharge, in cubic feet per second; \( A \), drainage area, in square miles; \( P \), mean annual precipitation, in inches; \( S \), mean drainage-basin slope, in foot per foot.
How do we determine the hydraulic parameters and their variation (COE, 1996)?

- It can be done by observation of the stage vs. discharge relationship.
- The uncertainty in stage for ungaged locations can be estimated by:

\[
S = \left[ 0.07208 + 0.04936 I_{Bed} - 2.2626 \times 10^{-7} A_{Basin} + 0.02164 H_{Range} + 1.4194 \times 10^{-5} Q_{100} \right]^2
\]

Where: \( S \) = standard deviation in meters, \( H \) = maximum expected stage, \( A \) = basin area in sq km, \( Q \) = 100 year discharge, \( I \) = from Table 5-1

Table 5-1
<table>
<thead>
<tr>
<th>Bed Identifiers</th>
<th>Identifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock/Resistant Clay</td>
<td>0</td>
</tr>
<tr>
<td>Boulders</td>
<td>1</td>
</tr>
<tr>
<td>Cobbles</td>
<td>2</td>
</tr>
<tr>
<td>Gravels</td>
<td>3</td>
</tr>
<tr>
<td>Sands</td>
<td>4</td>
</tr>
</tbody>
</table>
How do we determine the hydraulic parameters and their variation?

- Hydraulic models can be used and the parameters that could be varied are:
  - Expansion and contraction ratios (usually important only at bridges and culverts)
  - There are others, but their influence on the stage vs. discharge relationship is very small
  - Manning’s “n” values – requires a mean value, maximum and minimum, and an assumed distribution (usually a normal “Gaussian” distribution): this is the most common parameter to be varied
Estimation of the Variation in Manning's “n” (COE, 1996)
### Estimating Manning’s n and Statistics

Source: EM 1110-2-1601

<table>
<thead>
<tr>
<th>Reference</th>
<th>m</th>
<th>$n_b$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$n_3$</th>
<th>$n_4$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>USDT (Arcement and Schneider 1989), pp 4 &amp; 7</td>
<td>1.0</td>
<td>0.024</td>
<td>0.002</td>
<td>0.002</td>
<td>0.001</td>
<td>0.005</td>
<td>0.034</td>
</tr>
<tr>
<td>Barnes (1967), p 78</td>
<td>-</td>
<td>0.037</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.034</td>
</tr>
<tr>
<td>Chow (1959), p 109, Table 5-5, Fine Gravel</td>
<td>1.0</td>
<td>0.024</td>
<td>0.005</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
<td>0.034</td>
</tr>
<tr>
<td>Chow (1959), p 112, Table 5-6, D-1a3</td>
<td>-</td>
<td>0.040</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.040</td>
</tr>
<tr>
<td>Chow (1959), p 120, Figure 5-5(14)</td>
<td>-</td>
<td>0.030</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.030</td>
</tr>
<tr>
<td>Brater and King (1976), p 7-17, Natural</td>
<td>-</td>
<td>0.035</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Mean                                                |      | \[0.035\]
Standard deviation                                  |      | 0.003

Note:

\[ n = (n_b + n_1 + n_2 + n_3 + n_4)m \]

where

- \( n_b \) = base n-value
- \( n_1 \) = addition for surface irregularities
- \( n_2 \) = addition for variation in channel cross section
- \( n_3 \) = addition for obstructions
- \( n_4 \) = addition for vegetation
- \( m \) = ratio for meandering
Hydrologic and Hydraulic Model Linkages and Stochastic Modeling

- The Corps of Engineers’ Engineering and Research and Development Center (ERDC) sponsors the development of WMS 7.0, which is an interface of various hydrologic models.

- The ability to link an HEC-1 hydrologic analysis to a HEC-RAS model have been developed. HEC-HMS will come later.

- User defines certain modeling parameters for both models within a range of probable values and then runs the linked simulations.

- Only CN and Precipitation are currently the possible parameters for HEC-1 models and Mannings roughness for HEC-RAS models.

- Additional parameters will be added to both models.
Goals for HEC-FRM
Flood Risk Management (Dunn)

• Systems approach for assessing risks in complex, interdependent systems

• Incorporation of social and environmental consequences

• Tools for levee assessment and certification

• Effective risk communication

• New computational methodology
Example Project

Project Manager - David T. Williams, DTW and Associates: Project Engineer – Justin Griffiths, NV5

• Location: Palm Canyon Wash at Araby Drive Crossing, Palm Canyon, CA

• Project Client: Riverside County Flood Control and Water Conservation District, CA (Stuart McKibbin and Deborah de Chambeau)

• Problem Statement:
  – A low level crossing of Palm Canyon Wash exists at Araby Drive
  – The “dip” in the levee at the crossing and other portions of the levee do not meet FEMA criteria of 3 feet of freeboard
  – Determine if the levee at Araby Drive Crossing would meet the 3 feet freeboard criteria using Risk and Uncertainty
Project Location

Riverside County Flood Control District

Hydraulic Model for Arenas-Palm Levee System

Araby Dr. Crossing
Example Project
Hydrology: Discharge Probability Curve

- A previous FEMA study, using analysis of nearby hydrologic data and some measured discharges, determined the 10-, 50-, 100- and 500-year floods for the project.

- HEC developed HEC-FDA (Flood Damage Reduction Analysis), that can do statistical analysis of peak annual flows, according to Bulletin 17B (Water Resources Council (1981b)), and was used in this analysis.

- To perform the analysis, a minimum of the 2-year, 10-year and 100-year discharges are required.

- Since the FEMA study did not have the 2-year flood, a power function was fitted to the other discharges to extrapolate to the 2–year discharge.

- Using the procedure in Appendix 5 of Bulletin 17B and the 2-year, 10-year and 100-year discharges, the statistics of the discharge probability curve were determined.
Projection to the 2-year Discharge

\[ y = 580.7 x^{-0.788} \]

\[ R^2 = 0.998 \]
Bulletin 17B Synthetic Statistics Equations

\[ G_s = -2.50 + 3.12 \frac{\log(Q_{0.01}/Q_{0.10})}{\log(Q_{0.10}/Q_{0.50})} \]  

(5-3)

\[ S_s = \frac{\log(Q_{0.01}/Q_{0.50})}{K_{0.01} - K_{0.50}} \]  

(5-4)

\[ \bar{X}_s = \log(Q_{0.50}) - K_{0.50}(S_s) \]  

(5-5)
Tabular Discharge Probability Data

![Exceedance Probability Functions with Uncertainty](image)

<table>
<thead>
<tr>
<th>Exceedance Probability</th>
<th>Discharge (cfs)</th>
<th>95%</th>
<th>75%</th>
<th>25%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9990</td>
<td>698</td>
<td>650</td>
<td>747</td>
<td>819</td>
<td></td>
</tr>
<tr>
<td>0.9900</td>
<td>699</td>
<td>651</td>
<td>748</td>
<td>819</td>
<td></td>
</tr>
<tr>
<td>0.9500</td>
<td>705</td>
<td>657</td>
<td>754</td>
<td>827</td>
<td></td>
</tr>
<tr>
<td>0.9000</td>
<td>718</td>
<td>669</td>
<td>768</td>
<td>841</td>
<td></td>
</tr>
<tr>
<td>0.8000</td>
<td>757</td>
<td>706</td>
<td>808</td>
<td>884</td>
<td></td>
</tr>
<tr>
<td>0.7000</td>
<td>813</td>
<td>760</td>
<td>866</td>
<td>946</td>
<td></td>
</tr>
<tr>
<td>0.5000</td>
<td>1,003</td>
<td>942</td>
<td>1,066</td>
<td>1,161</td>
<td></td>
</tr>
<tr>
<td>0.3000</td>
<td>1,441</td>
<td>1,358</td>
<td>1,531</td>
<td>1,674</td>
<td></td>
</tr>
<tr>
<td>0.2000</td>
<td>1,961</td>
<td>1,842</td>
<td>2,033</td>
<td>2,313</td>
<td></td>
</tr>
<tr>
<td>0.1000</td>
<td>3,395</td>
<td>3,142</td>
<td>3,680</td>
<td>4,216</td>
<td></td>
</tr>
<tr>
<td>0.0400</td>
<td>7,202</td>
<td>6,466</td>
<td>8,109</td>
<td>9,845</td>
<td></td>
</tr>
<tr>
<td>0.0200</td>
<td>12,880</td>
<td>11,254</td>
<td>14,555</td>
<td>19,127</td>
<td></td>
</tr>
<tr>
<td>0.0100</td>
<td>23,200</td>
<td>19,697</td>
<td>27,829</td>
<td>37,598</td>
<td></td>
</tr>
<tr>
<td>0.0040</td>
<td>51,290</td>
<td>41,842</td>
<td>64,366</td>
<td>93,789</td>
<td></td>
</tr>
<tr>
<td>0.0020</td>
<td>92,704</td>
<td>73,357</td>
<td>120,360</td>
<td>185,690</td>
<td></td>
</tr>
<tr>
<td>0.0010</td>
<td>169,318</td>
<td>128,871</td>
<td>227,658</td>
<td>372,401</td>
<td></td>
</tr>
<tr>
<td>0.0001</td>
<td>1,272,817</td>
<td>878,540</td>
<td>1,526,240</td>
<td>3,839,349</td>
<td></td>
</tr>
</tbody>
</table>
The Resulting Discharge Probability Curve
Stage - Discharge Curve

• Hydraulics: The existing conditions HEC-RAS hydraulic model was used to determine the water surface elevations for all the discharges.

• A “median” stage-discharge curve was generated (the deterministic results – usually around a CNP of 50%) at Araby Road crossing and supplemented by running HEC-RAS for a full range of flows.

• However, we need the possible range and associated statistics of the water surface elevations at the crossing due to uncertainties related to the hydraulics.
Stage - Discharge Curve: Standard Deviations

- According the USACE EM 1110-2-1619:

\[
SD_{\text{total}} = \left( SD_{\text{nat}}^2 + SD_{\text{mod}}^2 + SD_{\text{terrain}}^2 \right)^{0.5}
\]

- Where:
  - \(SD\) = standard deviation of the total uncertainty
  - \(SD_{\text{nat}}\) = standard deviation due to natural uncertainties related to hydraulics
  - \(SD_{\text{mod}}\) = standard deviation due to hydraulic modeling uncertainties
  - \(SD_{\text{terrain}}\) = standard deviation due to uncertainties in the geometry used in the hydraulic model
Stage - Discharge Curve: Standard Deviations

- $SD_{nat}$ is assumed to be $E_{mean}/4$ where $E_{mean}$ is the difference between the lowest and highest probable water elevations (USACE EM 1110-2-1619).

- The probable water surface elevations are assumed to be bounded within the 95 percent of the total stage uncertainty and therefore assumed to be the water surface elevations resulting from a range of low and high values Manning’s n values.
Stage - Discharge Curve: Standard Deviations

- The SD of the Manning’s n value is determined by the RD-26 (see references):

\[
SD_n = n^*\left(e^{(0.582+0.10\ln(n))^2-1}\right)^{0.5}
\]

- The average Manning’s n value of the wash in conjunction with the SD from the above equation to determine the high and low n values were run in the HEC-RAS hydraulic model to determine \(E_{\text{mean}}/4\) and thus \(SD_{\text{nat}}\)

- \(SD_{\text{nat}} = \) standard deviation due to natural uncertainties related to hydraulics is assumed to be equal to \(SD_{\text{mod}} = \) standard deviation due to hydraulic modeling uncertainties
Stage - Discharge Curve: Standard Deviations

- \( \text{SD}_{\text{terrain}} = \) standard deviation due to uncertainties in the geometry used in the hydraulic model was obtained using Table 3 of RD-26. The topographic data had an contour interval of 2 feet and therefore had a SD of 0.6 feet

<table>
<thead>
<tr>
<th>Contour Interval</th>
<th>Standard Deviation Aerial Spot Elevations</th>
<th>Standard Deviation Topographic Maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.30</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>0.60</td>
<td>1.50</td>
</tr>
<tr>
<td>10</td>
<td>1.50</td>
<td>3.00</td>
</tr>
</tbody>
</table>
Stage - Discharge Curve: Standard Deviations

- According to USACE EM 1110-2-1619, there is a minimum SD that can be adopted depending on geometry accuracy and confidence in the estimation of the Manning’s $n$ values.

- The table below shows the criteria. In our analysis, since Manning’s $n$ values are hard to determine for desert sand washes and the cross sections was based upon topographic maps, a minimum SD value of 1.5 feet was used.

### Table 5-2
Minimum Standard Deviation of Error in Stage

<table>
<thead>
<tr>
<th>Manning’s $n$ Value Reliability</th>
<th>Standard Deviation (in feet)</th>
<th>Cross Section Based on Field Survey or Aerial Spot Elevation</th>
<th>Cross Section Based on Topographic Map with 2-5’ Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Fair</td>
<td></td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Poor</td>
<td></td>
<td>1.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

1 Where good reliability of Manning’s $n$ value equates to excellent to very good model adjustment/validation to a stream gauge, a set of high water marks in the project effective size range, and other data. Fair reliability relates to fair to good model adjustment/validation for which some, but limited, high-water mark data are available. Poor reliability equates to poor model adjustment/validation or essentially no data for model adjustment/validation.
Stage - Discharge Curve: Standard Deviations

• The following is the results of the analysis of the standard deviations:

<table>
<thead>
<tr>
<th>Standard Deviation of Error</th>
<th>$^{1}\text{SD}_n$</th>
<th>$^{2}\text{SD}_{nat}$</th>
<th>$^{2}\text{SD}_{mod}$</th>
<th>$^{3}\text{SD}_{terrain}$</th>
<th>$^{4}\text{SD}_{total}$</th>
<th>$^{5}\text{SD}_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.009</td>
<td>0.11</td>
<td>0.11</td>
<td>0.6</td>
<td>0.62</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Notes:

1. $\text{SD}_n = n^* (e^{0.582 + 0.10\ln(n)} - 1)^{0.5}$ (Eqn. 5.2 of RD-26)
2. $\text{SD}_{nat} = \text{SD}_{mod} = \text{E}_{\text{mean}}/4$ (Eqn. 5-7 of EM 1110-2-1619)
3. $\text{SD}_{terrain}$ (Table 5.3 of RD-26)
4. $\text{SD}_{total} = (\text{SD}_{nat}^2 + \text{SD}_{mod}^2 + \text{SD}_{terrain}^2)^{0.5}$ (Eqn. 5-6 of EM 1110-2-1619)
5. $\text{SD}_{min}$ (Table 5-2 of EM 1110-2-1619)

• Note that the total SD was less than the minimum SD.
Stage - Discharge Curve: Results

• The “median” and standard deviations of the water surface elevations were determined and plotted as shown below.
Generating the Results

- HEC-FDA performed a Monte Carlo simulation integrating both the hydrology and hydraulics to determine the probability of the various water surface elevations for the 100 year flood – the conditional non-exceedence probability (CNP).
Overall Results

- Elevation 424.24 is at the deterministic water surface elevation (design WSE) for the 100-yr flood with a CNP of 43.1% and is 2.11 feet below the levee.

- Elevation 426.35 is at the top of the existing levee, has a CNP of 72.3% and is 2.11 feet above the DWSE.

- Elevation 427.24 is the Design WSE plus the FEMA required 3 feet and has a CNP of 80.4% and is 0.89 feet above the levee.

- Elevation 431.10 is at the 95% CNP and is 4.75 feet above the levee.

<table>
<thead>
<tr>
<th>Elevation (feet)</th>
<th>CNP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>431.10</td>
<td>95.0</td>
</tr>
<tr>
<td>429.00</td>
<td>90.0</td>
</tr>
<tr>
<td>427.24</td>
<td>80.4</td>
</tr>
<tr>
<td>426.35</td>
<td>72.3</td>
</tr>
<tr>
<td>424.24</td>
<td>43.1</td>
</tr>
</tbody>
</table>
Overall Results

• From Part 1:

The Corps and FEMA (U.S. Army Corps of Engineers (2007)), agreed to certify a levee if its elevation was at least:

(1) at the 90 percent CNP elevation if it is greater than 3 feet above the 100 year DWSE.

(2) at the 95 percent CNP elevation if it is greater than 2 feet above the DWSE.

(3) at 3 feet above the DWSE if it is between the CNP elevations of 90 percent and 95 percent.

• It fails (1) since the levee (426.35) is below the 90% CNP (429.00) and is only 2.11 feet above the DWSE.

• It fails (2) since the levee (426.35) is lower than the 95% CNP (431.10).

• It fails (3) since the levee (426.35) is not between the 90% CNP (429.00) and 95% CNP (431.10).
What Can Be Done To Improve the Results?

• Note that the minimum SD was set at 1.5 whereas the computed SD was 0.62.

• To reduce the SD minimum, a detailed cross section survey could be done.

• A well calibrated model based up high water marks would give more reliability to the estimation of Manning’s n, going from poor to fair or good. High water marks were not available.

• Long term gauge records would provide lower Standard Deviations.
References


References


References


• U.S. Army Corps of Engineers (2014), “HEC-FDA, Flood Damage Reduction Analysis,” Hydrologic Engineering Center, Davis, CA

References


References

