Are You Ready for Risk and Uncertainty Analysis?

Presented to:

Illinois Association for Floodplain And Stormwater Management

Presented by:

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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 paper presents 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 - Q*uantification 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 - A*ssociated 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 – probability (protection is attained) on top of a probability (should a 100 yr flood occur)!

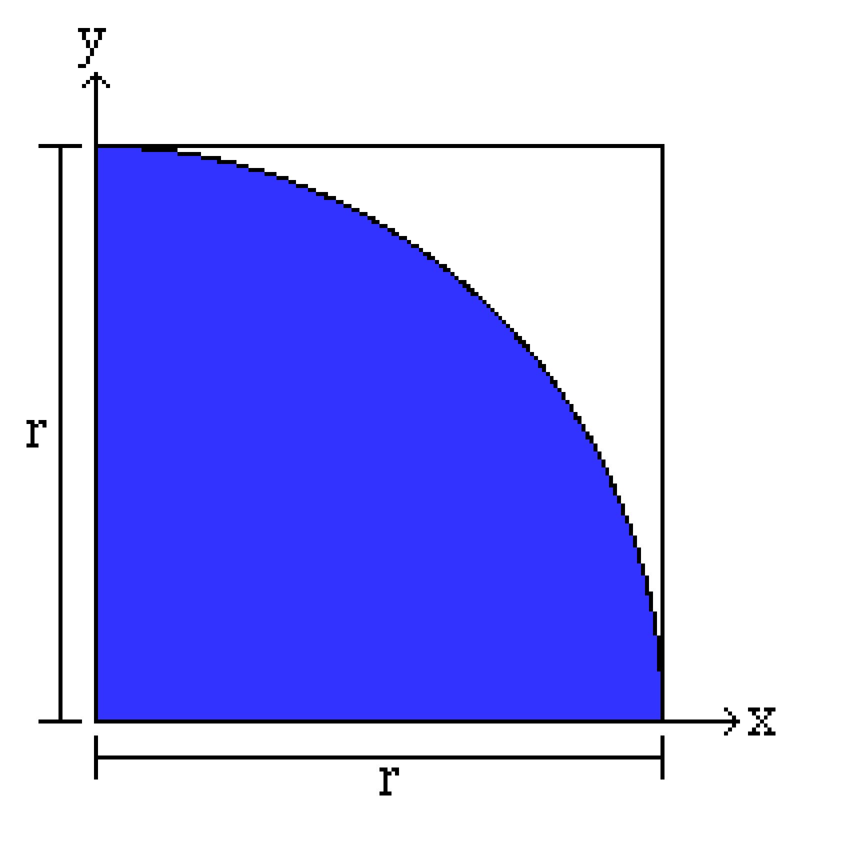
  – For levees, includes the chance of capacity exceedance <u>and</u> the chance of failure at lesser stages.

  – 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



$$\frac{\text{\# darts hitting shaded area}}{\text{\# darts hitting inside square}} = \frac{\frac{1}{4}\pi r^2}{r^2} = \frac{1}{4}\pi$$

or

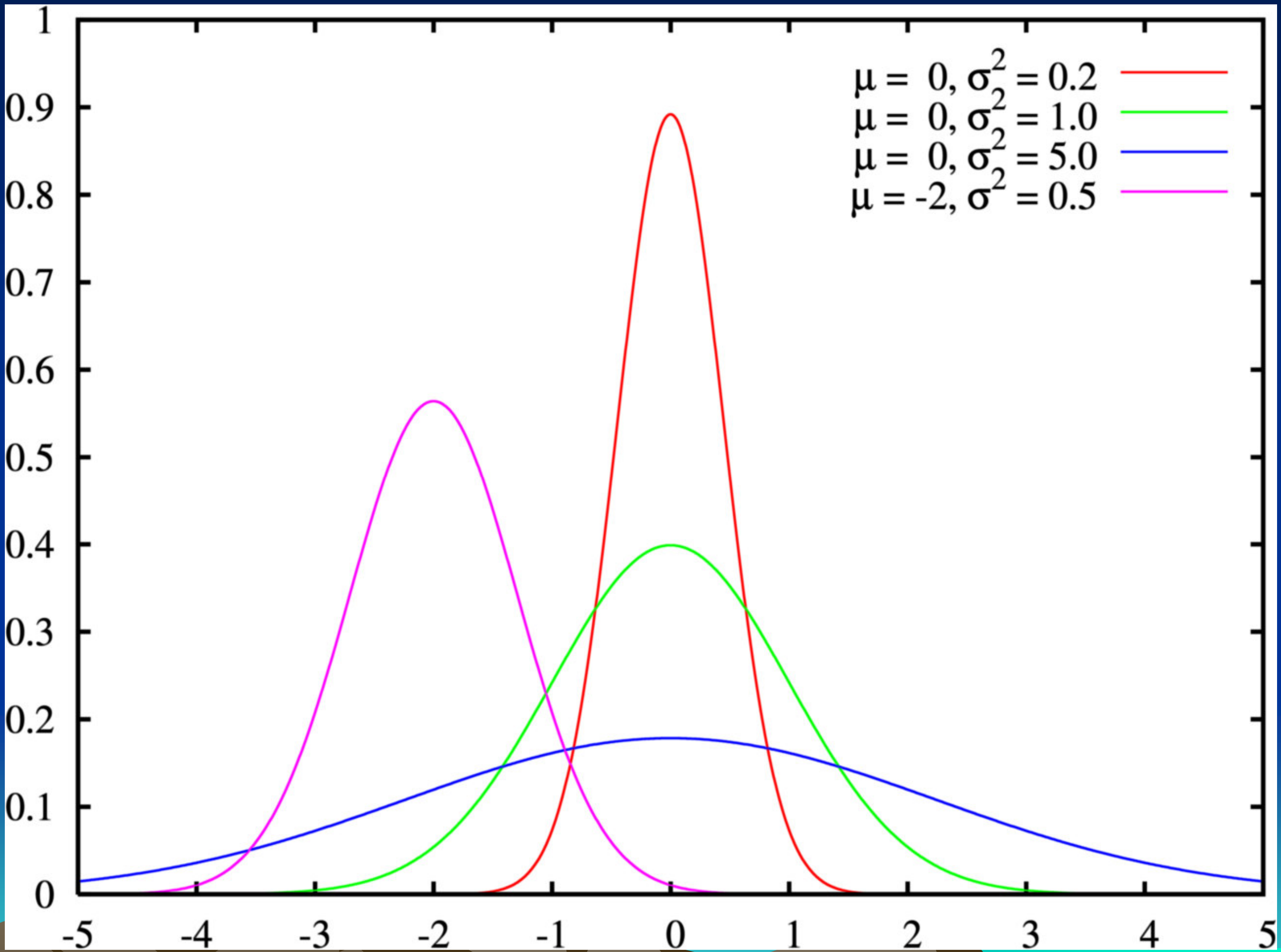
$$\pi = 4\,\frac{\text{\# darts hitting shaded area}}{\text{\# darts hitting inside square}}$$

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!

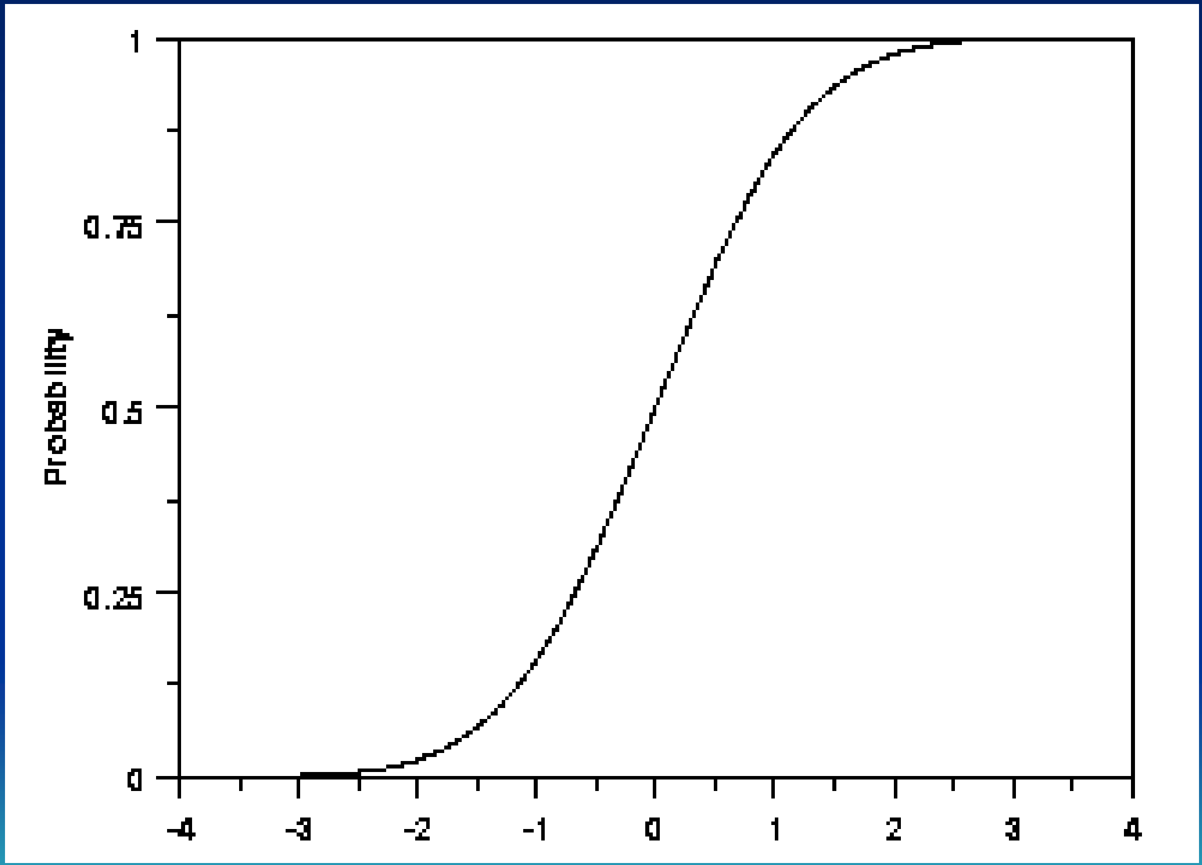
Parameter Estimation and its Variation (Probability Distribution Function, PDF)

Probability of Occurrence



Parameter Value and Possible Range

Transform Parameter and its variation to a Cumulative Probability Distribution Function (CDF)

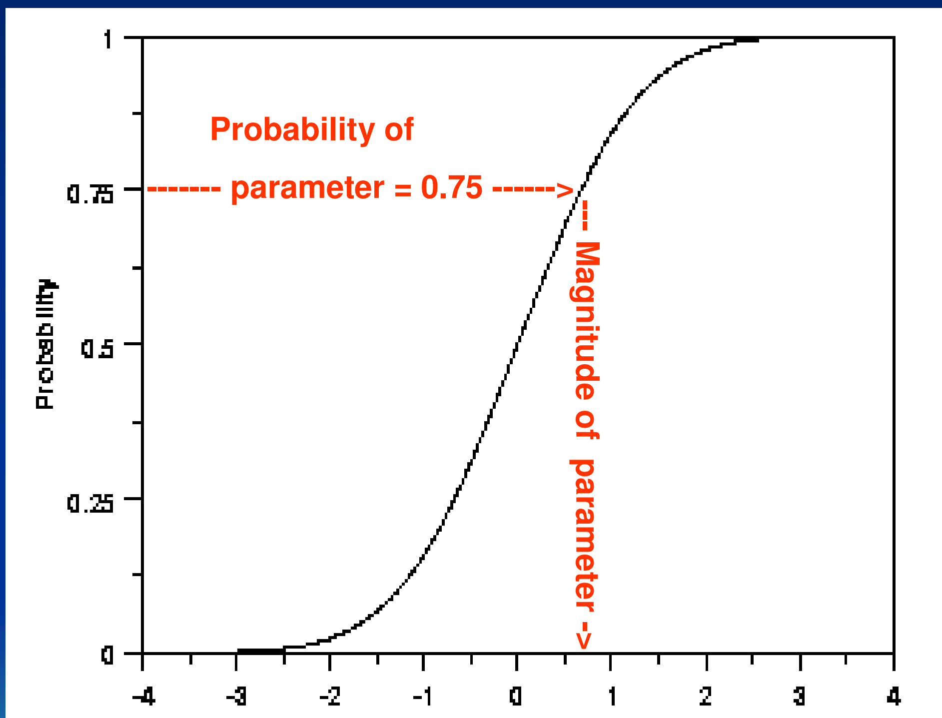


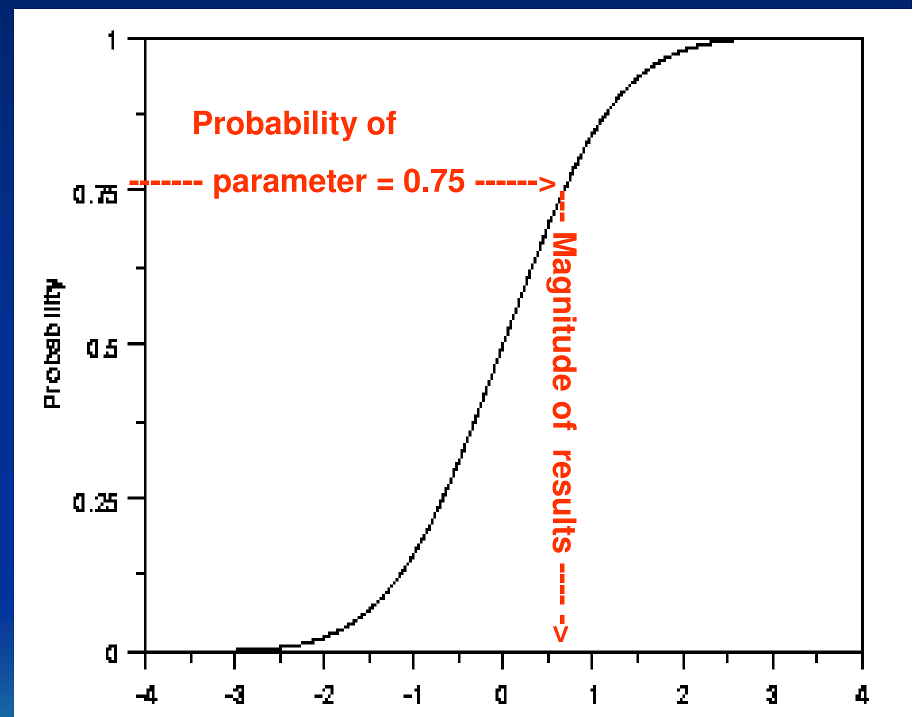
Parameter Magnitude

Relationship Between Parameter and Results

Randomly sample the parameter

Determine results for the same probability





Parameter Value

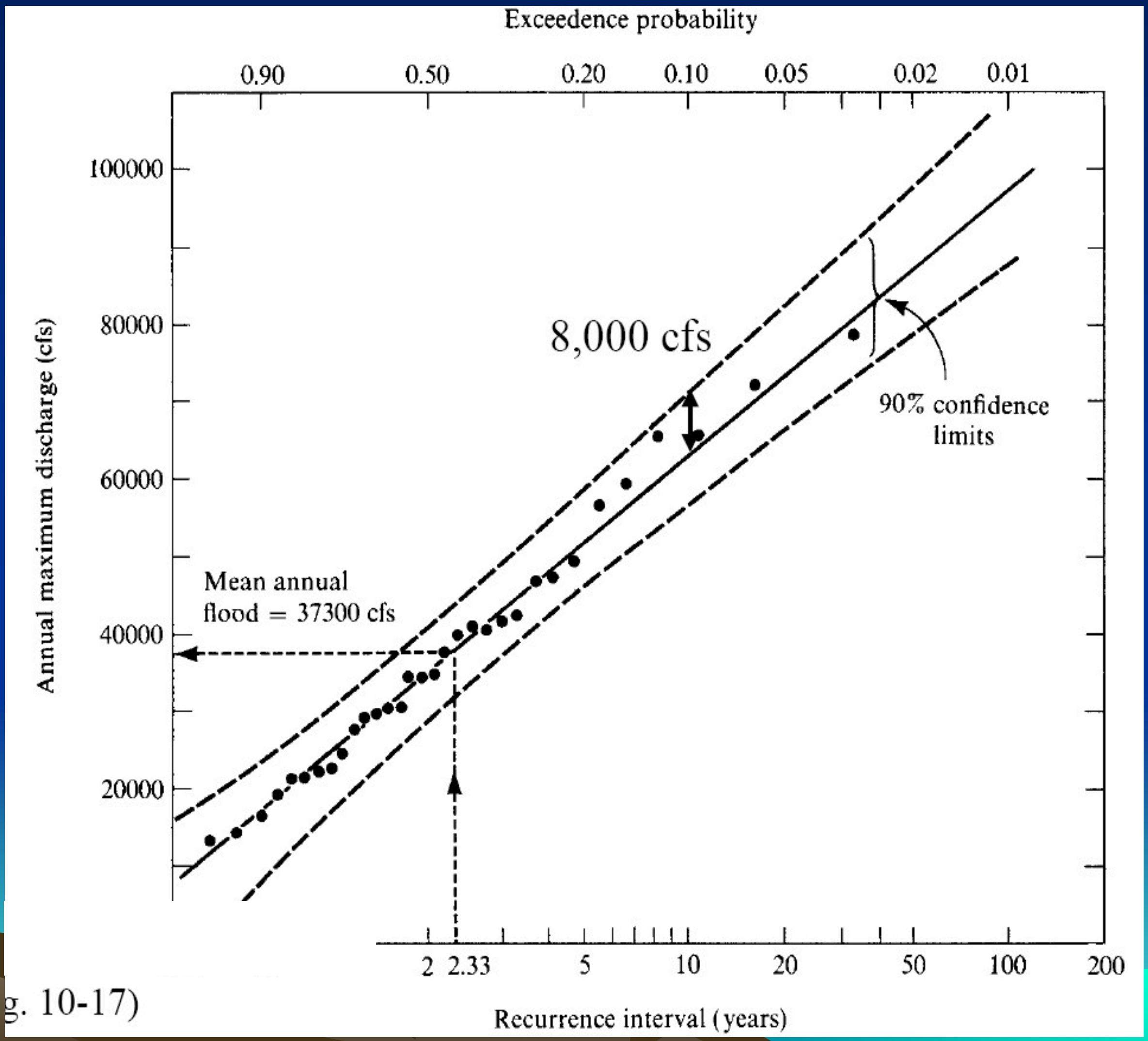
Results with Input Parameter

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

How do we determine the hydrologic parameters and their variations?

- For hydrology, we can use frequency analysis of discharges from gage data



g. 10-17)

How do we determine the hydrologic parameters and their variations?

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

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 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 on 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).

- No established practice of estimating the uncertainty of flood estimates from rainfall-runoff models.

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:

$$S = [0.07208 + 0.04936\ I_{Bed} - 2.2626x10^{-7} A_{Basin} + 0.02164\ H_{Range} + 1.4194 \times 10^{-5} Q_{100}]^2$$

Table 5-1
Bed Identifiers

Material	Identifier
Rock/Resistant Clay	0
Boulders	1
Cobbles	2
Gravels	3
Sands	4

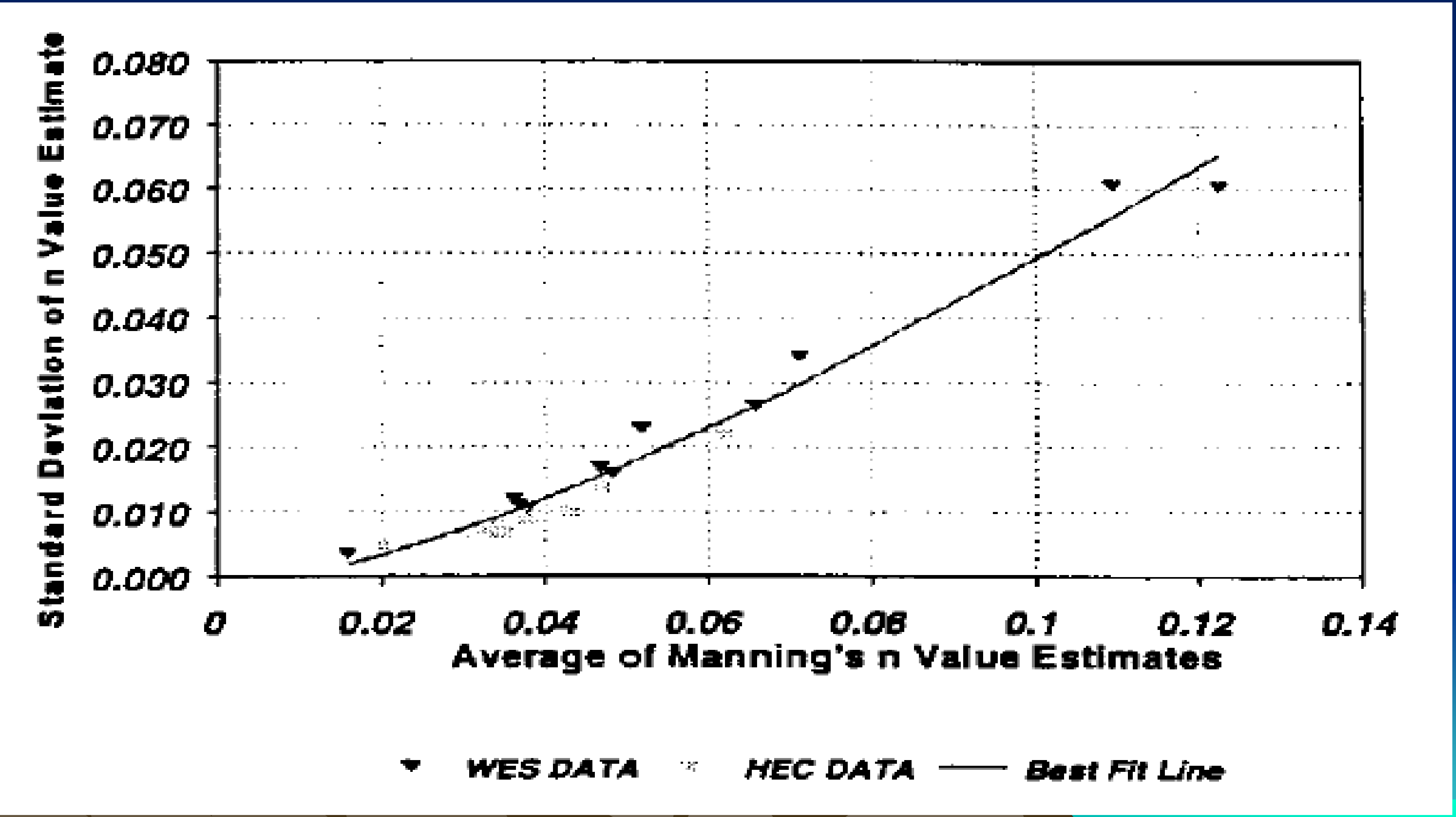
Where: S = standard deviation in meters, H = maximum expected stage

A = basin area in sq km, Q = 100 year discharge, I = from Table 5-1

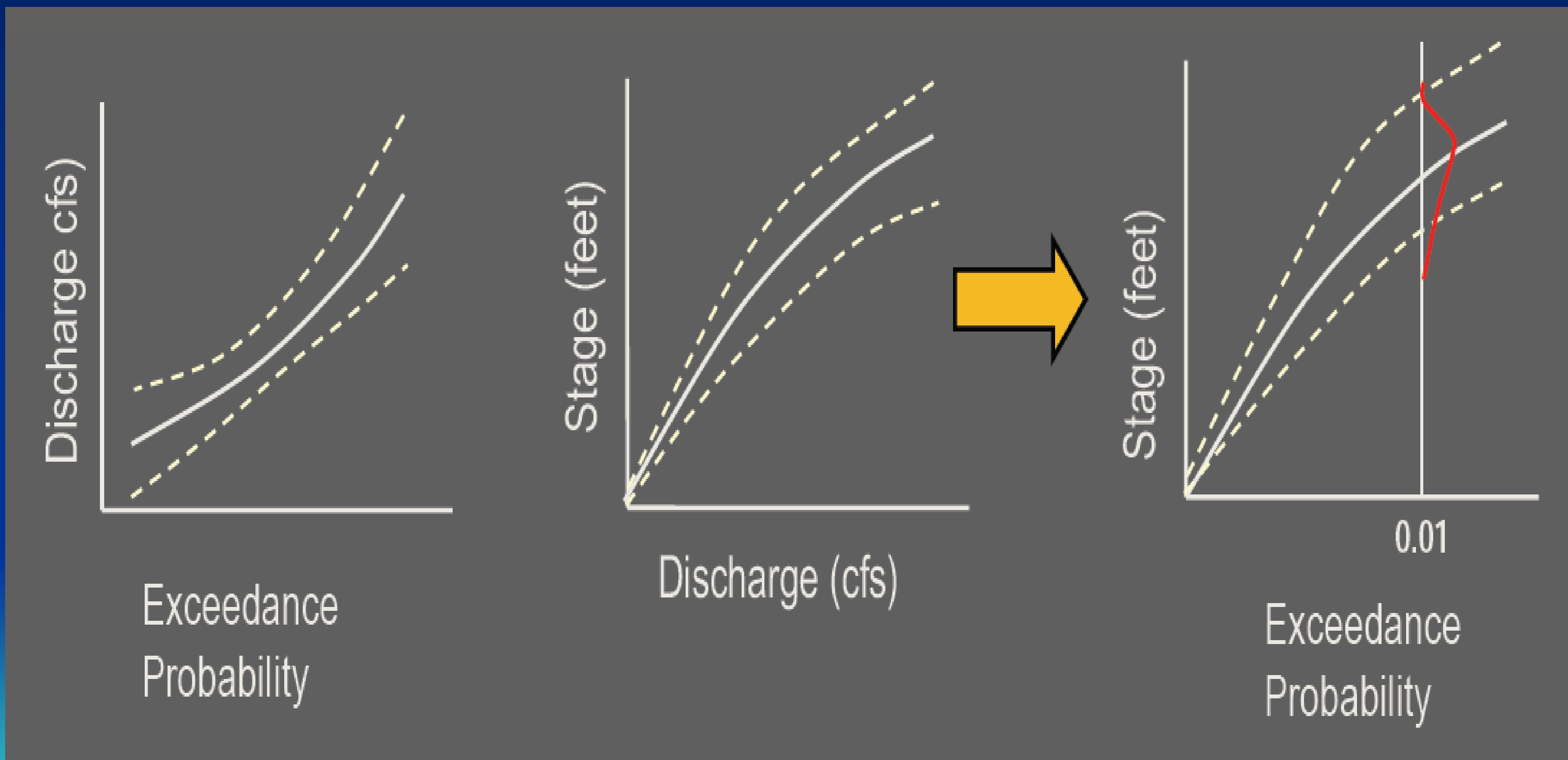
How do we determine the hydraulic parameters and their variation?

- 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

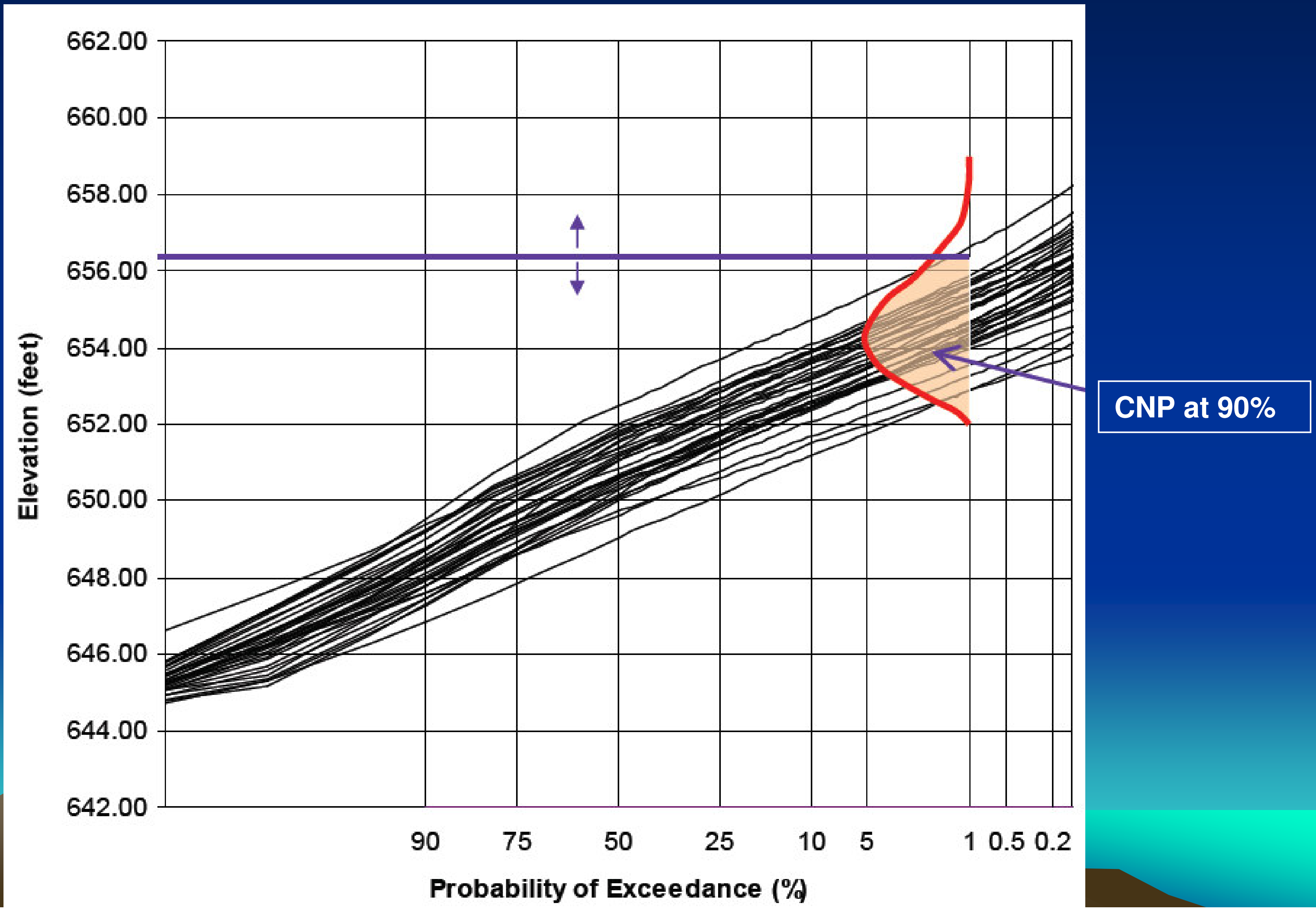
Estimation of the Variation in Manning's "n" (COE, 1996)



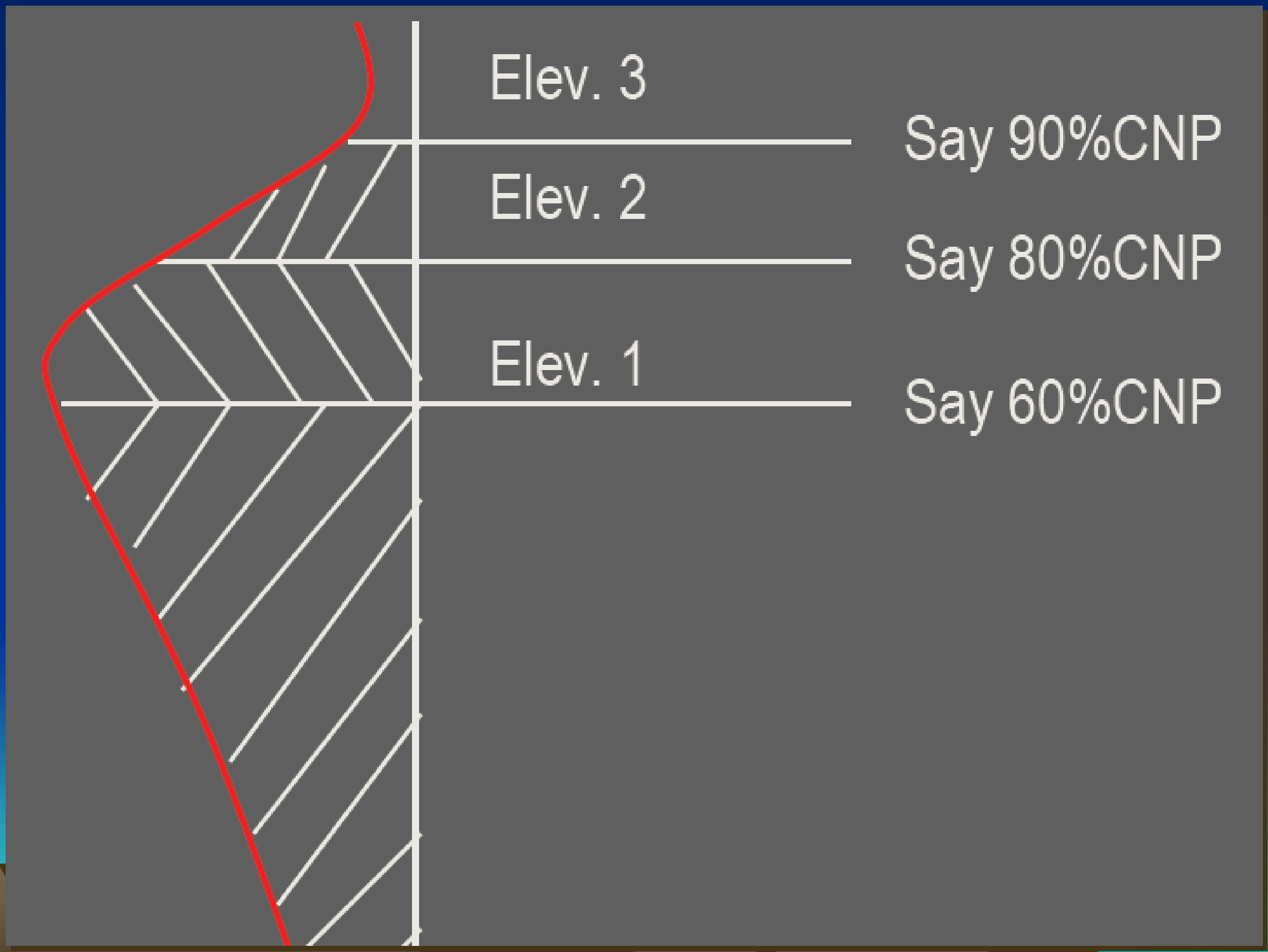
What doe this all look like? (Deering, 2007)



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.

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.
  - (2) at the 95 percent CNP elevation if it is greater than 2 feet
  - (3) at 3 feet if it is between the CNP 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*

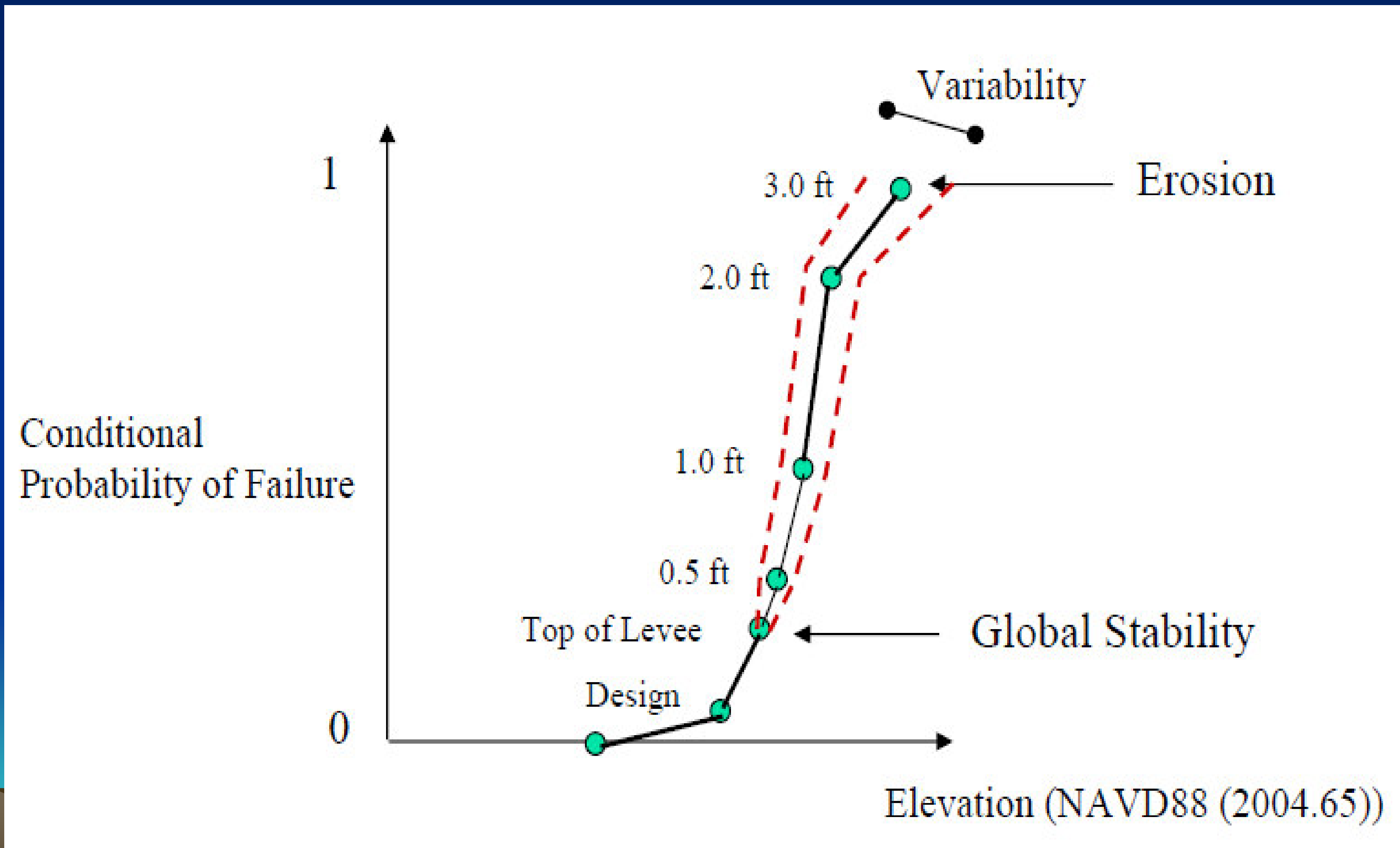
Levee Fragility Curves

- 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)



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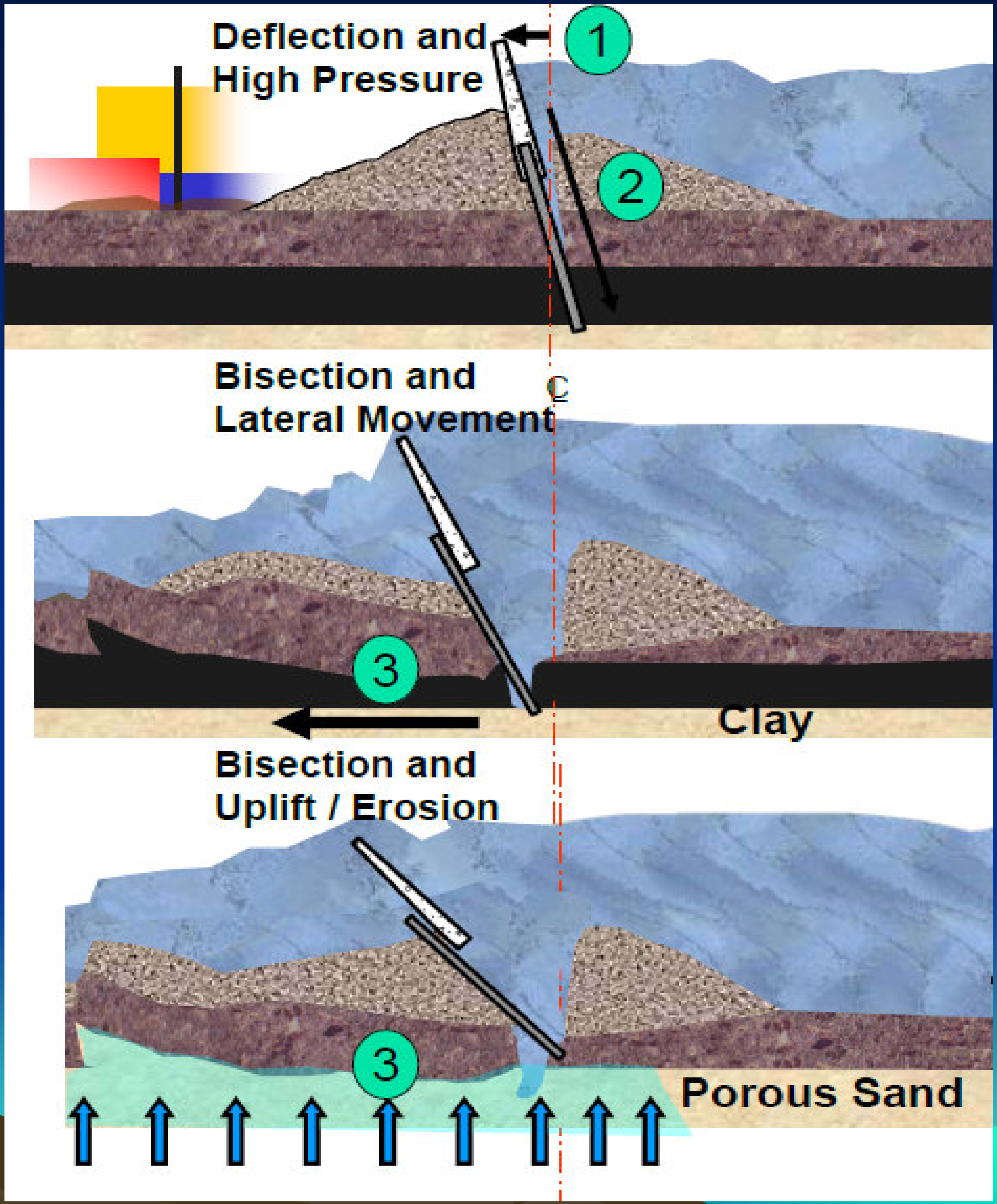
Factors for determining Levee Fragility Curves (Ref. URS, 2006)

Summary of Engineering Models

Failure Modes	Basis of Prediction	Models and Parameters	Input from Others	Uncertainties (Aleatory and Epistemic)
Through and/or under seepage	Levee class, Maintenance, Height of water and duration	Seepage analysis numerical models (e.g., SEEP/W), gradients	Height of water and duration	Model, Geometry, Material properties
Wave-induced erosion	Levee class, Maintenance, Wave size, Riprap size	Wave height versus riprap, Weight or D_{50} for F.S. of ½,1, 2	Wave size, (hydrologists)	Model, Geometry, Levee fill, Riprap
Flood-induced overtopping	Levee class, Height of water, Duration, Width of levee, Paved?	Height of water and duration over crest	Height of water and duration	Model, Geometry, Material properties
Current-induced erosion	Levee class, Riprap, Velocity	Velocity, Riprap,	Velocity (hydrologists)	Model, Geometry, Material properties
Static instability	Levee class, Height of water	Slope stability analysis	Height of water	Model, geometry, Material properties
Levee instability due to sudden drawdown	Levee class, amount of drawdown	UTEXAS-3, Levee fill properties	Amount of drawdown (gulp)	Variation around the mean drawdown value ( )
Seismic-induced deformation or liquefaction	Estimate deformation	Deformation analysis (simplified and QUAD4M-Newmark)	PGA, Mw Acceleration time history, response spectra	Model, geometry, Dynamic material properties

Example of non-overtopping levee failure (Ref. Ed Link, IPET)



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

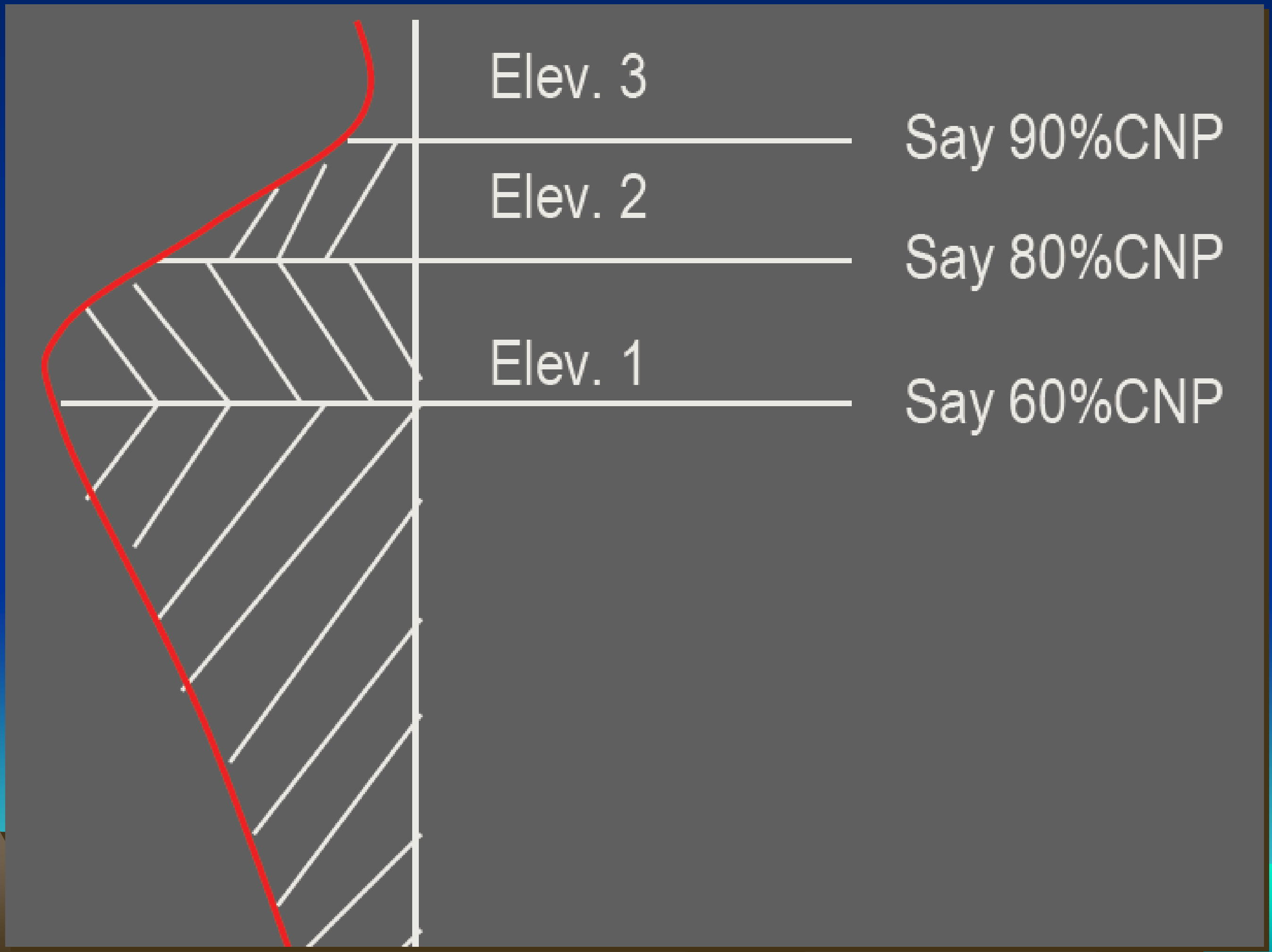
  – The 90 percent CNP provides an average of 3.0 feet of freeboard and a median expected level of protection of approximately 230 years, range of 170 to 5,000 years

  – 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)

Levee Projects	CFR Cert. Elev.	NED Plan Elev.	NED Elev. Exceedance	% CNP CFR Elev.	% CNP NED Elev.	Elev. - 90% CNP for 1%	Elev. – 95% CNP for 1%
Pearl R., Jackson, MS	44.6	47.0	1/770	97.6	99.8	43.4	*44.0*
American R, Sacramento, CA	*49.1*	52.0	1/230	91.9	94.4	48.5	52.3
Portage, WS	798.3	797.0	1/10000	99.9	99.6	796.6	*797.3*
Hamburg, IA	912.2	911.5	1/910	99.9	99.2	910.7	*910.8*
Pender, NE	1329.3	1330.0	1/380	76.3	83.6	*1330.9*	1331.5
Muscatine, IA	*560.8*	561.5	1/330	90.1	94.4	560.8	561.7
E Peoria, IL	458.1	462.6	1/10000	45.3	99.5	*460.7*	461.2
Cedar Falls, IA	864.7	866.0	1/360	90.0	94.0	*865.0*	866.3
Guadalupe, TX	57.9	56.8	1/110	87.2	76.9	*58.4*	59.5
White River, IN	715.0	713.2	1/250	98.0	86.0	713.5	*713.9*

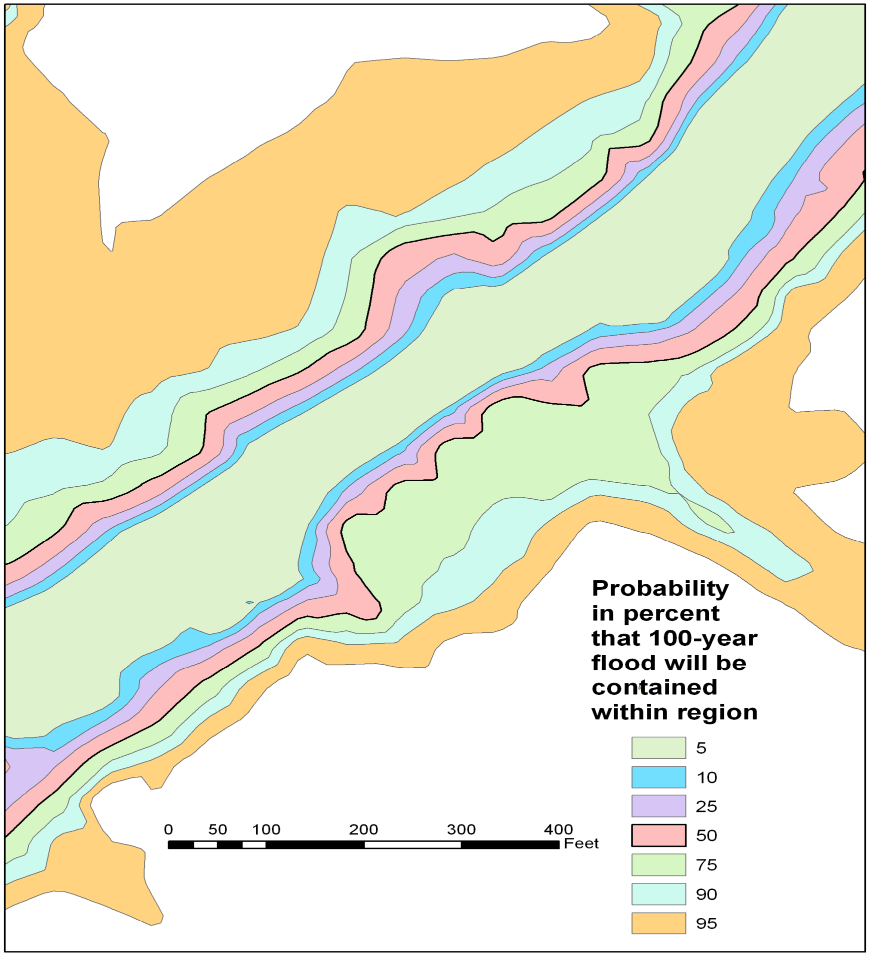
We can use the results of the RU analysis to determine inundation extents for any CNP



Application of CNP Floodplain Contours

- From the CNP elevations for a given AEP (say 100 year event), we can map the floodplain inundation areas for a given CNP
- Christopher Smemoe et. al. (2004) have proposed using uncertainty analysis for this purpose
- Aids the floodplain managers in regulation of the floodplain
- E.g., it may be helpful to know that the 100 year CNP of 90% may be at the deterministic 500 year floodplain.
- Flood insurance rates within contour intervals could be determined by a more realistic and physically based methodology

Example Floodplain Probability Contours



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 which establish a “Base case” that are far more extreme than the “most likely case” – results in a “conditional” RU
- RU therefore begins with a significant bias that is often not recognized

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 over estimate 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

Levee Related Issues

- A levee project designed with R&U has a design top of levee but no design water surface elevation; top of levee O&M requirements for the channel are unknown
- If there are many miles of levee upstream from a project, a true RU analysis must consider the possibility that upstream levees may fail
- Upstream levee failures (and sequences) 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 but is often neglected
- A levee that fails after the peak flows and maximum stages have occurred has a much different impact on flood stages than a levee that fails before or at the peak flow and stages
- The “How” assumption is particularly significant; e.g., a 25 foot wide break has a different impact than a 1,000 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

- An RU Analysis that incorporates "Worse" case assumptions as the **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

References

- Davis, Darryl (2006), "Risk Analysis and Levee Certification," FEMA Levee Policy Review Task Committee, Washington, DC
- Deering, Michael (2007), "Certification of Levee Systems for the National Flood Insurance Program Certification Program," USACE Infrastructure Conference, Detroit, MI
- Dillow, J. A. (1996), "Techniques for Estimating Magnitude and Frequency of Peak Flows in Maryland," U.S. Geological Survey Water-Resources Investigations Report 95-4154, p. 55

References

- Kite, G. W. (1988), “Frequency and Risk Analysis in Hydrology,” Water Resources Publications, Littleton, Colorado, p. 257

- National Research Council (2000), “Risk Analysis and Uncertainty in Flood Damage Reduction Studies,” National Academy Press

- Pappenberger, F., Harvey, H., Beven, K. J., Hall, J., Romanowicz, R., and Smith, P. J. (2006), “Risk and Uncertainty – Tools and Implementation,” UK Flood Risk Management Research Consortium, Lancaster University, Lancaster, UK

References

- Sehlke, Gerald, Hayes, D. F., Stevens, D. K. – Editors (2004), “Critical Transitions in Water and Environmental Resources Management,” World Water and Environmental Resources Congress, June 27 – July 1, 2004, Salt Lake City, Utah, USA

- Smemoe, Christopher, Nelson, J., and Zundel, A. (2004), “Risk Analysis Using Spatial Data in Flood Damage Reduction Studies,” World Water Congress, ASCE, 2004

- Thomas, Wilbur O., Grimm, M., and McCuen, R. (1999), “Evaluation of Flood Frequency Estimates for Ungaged Watersheds,” Hydrologic Frequency Analysis Work Group, Hydrology Subcommittee of the Advisory Committee on Water Information (ACWI)

References

- URS Corporation and Jack R. Benjamin Associates (2006), "Initial Technical Framework Paper, Levee Fragility," Prepared for the CA Dept. of Water Resources, September 2006

- U.S. Army Corps of Engineers (2007), Engineer Technical Letter (ETL) 1110-2-570, "Certification of Levee Systems for the National Flood Insurance Program (NFIP)," Washington, DC., September 2007

- U.S. Army Corps of Engineers (2000), ER 1105-22-100, "Guidance for Conducting Civil Works Planning Studies," Washington, DC., April 2000

- U.S. Army Corps of Engineers (1996a), ER 1105-22-101, "Risked-Based Analysis for Evaluation of Hydrology/Hydraulics, Geotechnical Stability, and Economics in Flood Damage Reduction Studies," Washington, DC., March 1996

References

- U.S. Army Corps of Engineers (1996b), EM 1110-2-1619, "Risk-Based Analysis for Flood Damage Reduction Studies," Washington, DC., 1996

- Water Resources Council (1981a), "Estimating Peak Flow Frequencies for Natural Ungaged Watersheds – A Proposed Nationwide Test," Hydrology Subcommittee, U.S. Water Resources Council, 346 p.

- Water Resources Council (1981b), "Guidelines for Determining Flood Flow Frequency, Bulletin 17B," Hydrology Subcommittee, U.S. Water Resources Council