

Practical Applications of Risk & Uncertainty Theory in Water Resources: Shortcuts Taken and Their Possible Effects

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Special thanks to Joe Countryman of MBK
for his thoughts on the topics

Basis of R&U Analysis in Water Resources

Paper considers:

1. Realities of using R&U Analysis evaluating water resources projects
2. Shortcuts taken to facility analysis and computations
3. Possible effects of those shortcuts

For flood risk reduction studies by US Army Corps of Engineers (COE), definitive guidance is in two pioneering 1996 documents:

- ER 1105-2-101, “*Risk Based Analysis for Evaluation of Hydrology/Hydraulics, Geotechnical Stability, and Economics in Flood Damage Reduction Studies*”
- EM 1110-2-1619, “*Risk-based Analysis of Flood Damage Reduction Studies.*”



Common Terms and Definitions

R&U Analysis

- Natural Uncertainty (Variability) - Inherent variability in physical world: also termed
 - process-model uncertainty
 - Aleatory uncertainty (bones or dice)
- Knowledge Uncertainty - Lack of scientific understanding of natural processes.
 - Statistical inference uncertainty
 - Statistical model uncertainty
 - Epistemic uncertainty



Terms Specific to R&U Analysis for Water Resources Studies

- **Deterministic Analysis** - Uses single values for key variables
- **Probabilistic Analysis** - Uses a probability distribution rather than single value for key variables
- **Annual Exceedance Probability (AEP)** - Measures “probability of getting flooded” in any given year, given uncertainties considering the full range of floods that can occur – *but generally uses only peak discharge for critical duration of each year*



Terms Specific to R&U Analysis for Water Resources Studies, cont.

- **Conditional Annual Non-Exceedance Prob., CNP (“Assurance”)** :
 - The probability that a project will provide protection from different combinations of factors for a specified event (i.e. 100 year flow); event often described by its exceedance/failure probability.
 - For levees, combinations of factors include chance of capacity exceedance and chance of failure at lesser stages, as well as discharge variability, and hydrologic uncertainty
 - Computed by determining 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)



Sources of Uncertainty in Water Resources Projects (adapted from USACE 1996)

- Uncertainty about future hydrologic events - includes future streamflow or rainfall (natural uncertainty)
- Simplified models - related to uncertainty that arises from the use of practical models to describe complex hydraulic phenomena
- Economic and social uncertainty - lack of information about relationship between depth and inundation damage, structure values and locations, and inability to predict how public will respond to a flood
- Structural and Geotechnical uncertainty - structural and geotechnical performance of water-control measures



Monte Carlo (MC) Techniques for R&U Analysis

- A comprehensive analysis combining variability and uncertainty in different variables often a formidable task
- For complex problems, analyses generally depend wholly or in part on MC simulation: a numerical technique for performing *with various levels of sophistication* the needed multivariate integration
- Statistical results for different reaches in large studies should be combined properly because they are generally interdependent, both statistically and physically: cannot just add quantiles of uncertainty distributions as was done (NRC, 2000).



A Simple MC Example for Flood Control

- Determine domain of possible inputs (e.g., average and standard deviation for h-hour rainfall) and develop a Probability Density Function (PDF) for inputs and transform into Cumulative Probability Distribution Functions (CDF) for a given design precipitation event
- Determine CDF of parameters affecting water surface elevations in hydraulic models given flow Q
- Use MC to develop a CDF of the water surface elevation versus discharge relationship, combining hydrologic and hydraulic distributions and generally assuming variation and uncertainty in different variables are independent and each has a single value over design life of project
- Results –probability for each water surface elevation for given design



Assumptions and Shortcuts in Hydrology

- Frequency Analysis Using Gage Flood or Rain Data
 - The standard error of parameters and estimated quantiles for flood discharges from gaging station data can be determined as described by Kite (1988) for distributions used in hydrology
 - For the Log-Pearson III (LP3) distribution, approaches by Kite (1988) or Chowdhury & Stedinger (1991) are favored - they consider uncertainty in the skew coefficient which the Bulletin 17B approach ignores.
 - Fitting a simple 2- or 3-parameter distribution to rainfall/floodflow annual maxima and evaluating the uncertainty in estimated parameters can overestimate uncertainty in extreme quantile estimators (100- or 500- year flood values) because it does not recognize the physical limitations of a watershed (PMP, PMF, etc). Therefore, assurance level calculations based on Confidence Interval (CI) formulas can be misleading and overly conservative with CIs that are much too wide



Assumptions and Shortcuts in Hydrology

- Regional Analysis
 - Standard errors of estimate or prediction of USGS regression equations can be obtained from regional flood frequency reports (e.g., Dillow 1996; for theory, also Tasker & Stedinger, 1989)
 - The standard error for rainfall-runoff modeling is not usually known
 - IACWD (1981) suggested that it is larger than 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 but are often calibrated to small storms in absence of data
 - Although there can be adjustments for site specific characteristics, this is still a regional analysis and uncertainties for a specific location within a region are often not quantified in real studies.



Assumptions and Shortcuts in Hydrology

- Hydrologic Modeling with precipitation
 - Variations in storm centering, travel paths and precipitation distribution are rarely modeled to develop a CDF of discharges
 - Common practice is to assume worst case storm centering and use median precipitation intensities for defining the design event used to develop design discharge
 - If this is the case, no design discharge CDFs are developed and a singular deterministic value is used for design



Assumptions and Shortcuts in Hydrology

- Hydrologic Modeling, cont.
 - True R&U analysis would also include possible variations in such variables as infiltration (initial, constant or decay) rates, routing parameters, and other hydrologic parameters
 - CDFs are hard to determine for these variables, though importance of all of these simplifications is unclear.
 - Confidence limits or standard errors of flood discharges from rainfall-runoff models can be estimated if an equivalent years of record is assumed for flood discharges (USACE 1996)
 - No established practice of estimating uncertainty of derived flood estimates or even rainfall-runoff models in general; some attempts to do so (GLUE) are statistically naïve (Stedinger et al. 2008)



Reservoir Operation (Dunn & Deering 2009)

Reservoir operations, which are governed by operating rule curves (which are just guidelines), can vary from those rules so that distribution of peak outflow depends upon many factors; consider

- Inflow is different from design value
- Reservoir operation is different from nominal operation
- Other factors do not have nominal or implicit values

Rules curves can be relatively simplistic and operators will strive to make use of precipitation and inflow forecasts while considering real-time information on hydrologic conditions in the watershed and status of water control structures



Assumptions and Shortcuts in Hydraulics

- Hydraulic modeling
 - Present R&U practice generally assumes that the hydraulic model used for project is best available model or that there is no difference from use of alternative models
 - Manning's "n" value is estimated for a mean condition and is rarely adjusted for changes in season in relation to possible times of design flood. Also, shape of the "n" distribution is not known and a common assumption is to assume that the standard deviation is $\frac{1}{4}$ of the possible range of the "n".
 - Current R&U modeling practices ignore uncertainties in expansion and contraction coefficients and even ignore changes in coefficients under varying discharges and stages. This is of particular importance when doing unsteady flow modeling



Assumptions and Shortcuts in Hydraulics

- Hydraulic modeling, cont.
 - For unsteady flow analysis, various parameters (physically and numerically based) can have uncertainties but are generally kept static because it is hard to define their uncertainty distribution
- Coastal areas
 - For coastal areas, coincidence frequency analysis of sea level (perhaps with storm surge if correlated) and downstream starting depth for design flow is required. This needs to be performed for life of the project which includes sea level rise scenarios.
 - Common practice is to use highest projected sea level rise and does not define distribution of possible rise as a computational part of coincidence frequency analysis with design flow. This would result in a conservative (higher) estimate of downstream boundary conditions.



Assumptions and Shortcuts in Hydraulics

- Hydraulic Effects of Levee Failures
 - If there are levees upstream from project, a true R&U analysis generally should consider possibility that upstream levees will fail so as to decrease maximum surface water levels downstream.
 - Upstream levee failure risk affects stage frequency function at a downstream project location.
 - A deterministic design may assume upstream levees do not fail and this assumption becomes just another of the “worse case” assumptions associated with deterministic design.
 - An absolute no-levee-failure assumption destroys basic assumption of R&U analysis: vastly overestimate flood risk.



Assumptions and Shortcuts in Hydraulics

- Hydraulic Effects of Levee Failures
 - There is a requirement to determine when and how a levee will fail. A levee that fails before the peak flows and stages have occurred has a much different impact on flood stages than a levee that fails at peak flow and stage condition or after.
 - The “How” assumption is also significant. A 25 foot wide levee break has a different impact than a 1,000 foot wide break.
 - Rate of levee breach, vertically & laterally, must be assessed.
 - At this time, models are limited in their capability to simulate varying assumptions of this type. Only a few select scenarios are usually analyzed and those selected are usually the most conservative (i.e., results in the most discharge downstream).



Assumptions and Shortcuts Made in Levees, Floodwalls, and Closure Structures

- There are numerous failure mechanisms associated with levees and floodwalls
- The mechanisms are generally well understood, but distributions of model input variables associated with failure mechanisms are not well defined and gross assumptions are often made, if any, of these mechanisms are analyzed at all
- A common practice, for new or rehabilitated levees and floodwalls, is to assume no failure would occur until they are overtopped, then only a few failure mechanisms are applied for higher water depths
- The authors do not know of any projects that have considered more than 2 or 3 failure mechanisms at once.



Assumptions and Shortcuts Made in Levees, Floodwalls, and Closure Structures

- Another consideration that is not fully integrated into many R&U analyses is change in capabilities of the levee, floodwall, and closure structure systems over time.
- The capabilities change due to deterioration, stresses on systems (e.g., life cycle analysis of the impacts of large flood events, seismic activities, subsidence and differential settlement, etc.), how rehabilitation is conducted, and how system recovers from rehabilitation.
- A maintenance plan is mandatory for accredited levees, but effective implementation is another issue.

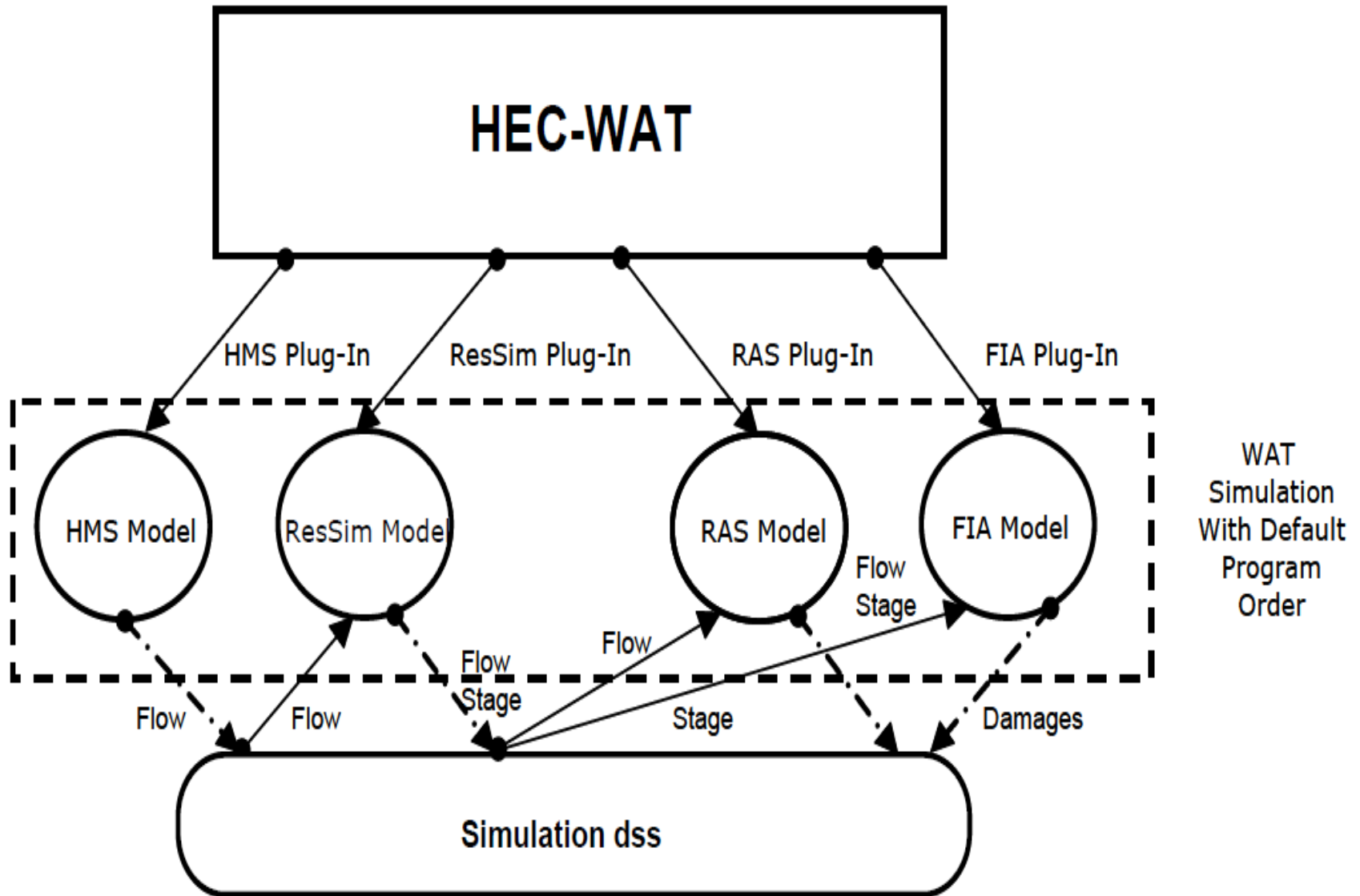


HEC-WAT and HEC-FRM

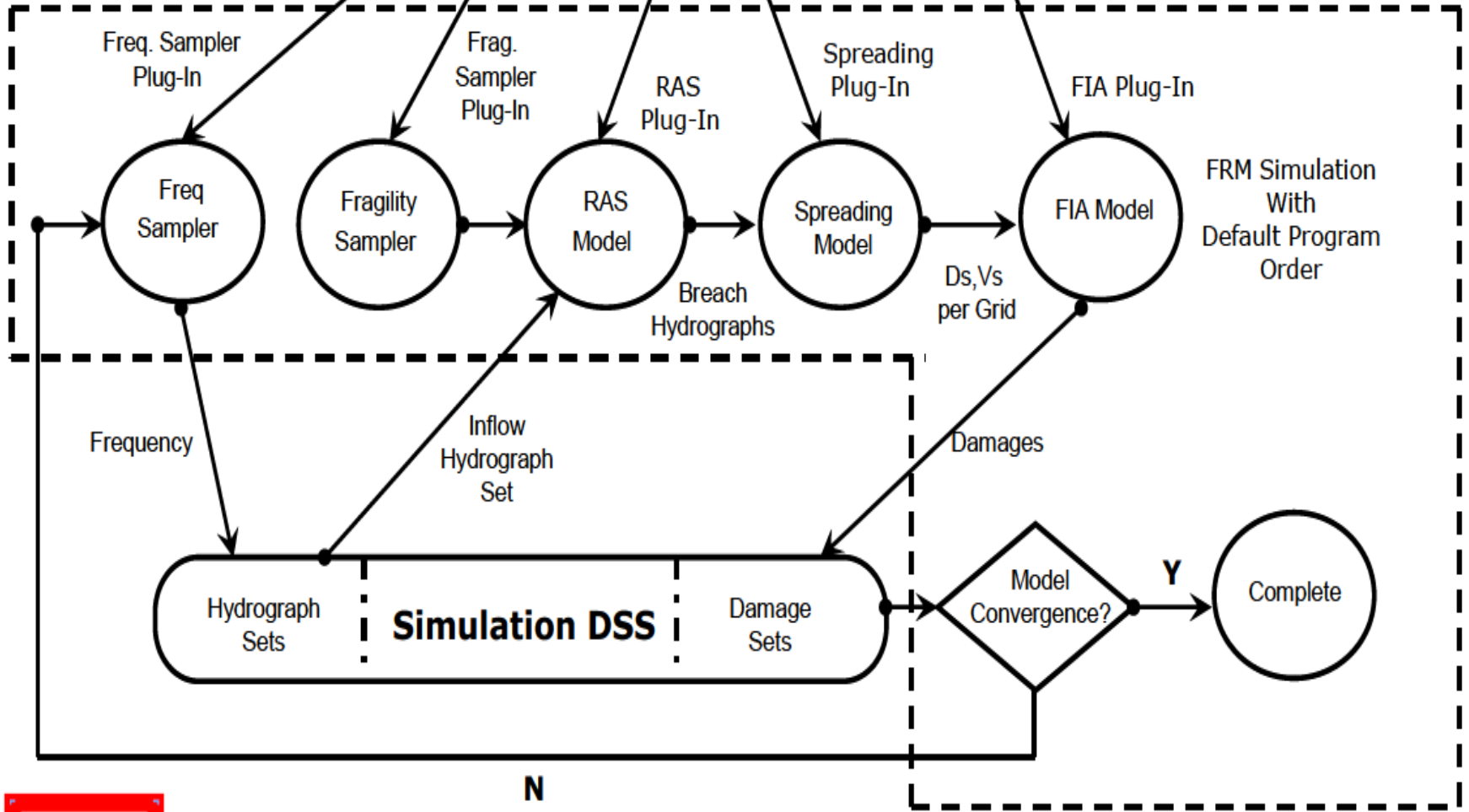
- The Hydrologic Engineering Center (HEC) has long recognized that an integrated approach utilizing all components of hydrology, hydraulics, levee fragility, reservoir operation, project life cycle etc. is needed to perform comprehensive and accurate Risk & Uncertainty analyses.
- HEC has developed HEC-WAT and HEC-FRM as a first step for meeting this goal.
- It is in its infancy and much work needs to be done to address the topics presented in this paper and in other publications such as NRC (2000).



HEC-WAT



HEC-FRM



HEC-WAT and HEC-FRM Challenges

- How to generate flood events?
 - Discharge Frequency Based, OR,
 - Synthetic ApproachBoth have pros and cons
- How to automate 1000s of hydrodynamic simulations?
(e.g., unsteady HEC-RAS runs)
- How to model multiple failure modes?
- How to evaluate consequences?
- How to reduce computational burden?



Summary

- Much of the quantification of uncertainty required for R&U Analysis is difficult to resolve accurately. Many are neglected.
- Deterministic assumptions are often adopted for some processes, and because designers have been trained to analyze “worse” case conditions, they adopt “Base” case or most likely conditions that are more extreme than the “actual” most likely outcome. Thus R&U Analysis begins with a significant conservative bias.
- A Risk Analysis methodology that incorporates “Worse” case assumptions as “Base” case can significantly overstate probability of damages associated with a project; that could potentially lead to bad economic risk-based decisions.



Summary

- R. W. Hamming said

“The purpose of computing is insight, not numbers.”

- Does use of Risk & Uncertainty Analysis result in development and selection of better projects from economic and public policy/safety perspectives?
- A critical product of R&U analyses should be
 1. understanding of critical sources of variability impacting project performance,
 2. which knowledge uncertainties are the most important
 3. where largest errors from computational methods occur.
- Such understanding should help engineers focus their efforts to improve such analyses where it will have the greatest benefit.



Questions
and
Comments?

