Synthetic Weather Simulation for Characterization of Uncertainty in Extension of Stage-Frequency Curves in a System of Flood Control Dams

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Abstract

Extreme floods which overwhelm the capacity of a system of flood control dams may result in overtopping one or more of those structures. Traditional US Army Corps of Engineers analysis of hydrologic hazards isolates the study area to a single dam. However, in watersheds where flood hazard is managed by several dams, the estimate for the annual probability of overtopping a dam may be influenced by the operation of one or more other dams in that system. Evaluation and prioritization of modifications for dam safety in a portfolio of structures requires a sound estimate of overtopping probability for every structure. In an effort to properly characterize the hydrologic hazard for five dams in the Trinity River Basin above Dallas, Texas, synthetic weather generation coupled with hydrologic and reservoir models is applied to extend the stage-frequency curve for each dam beyond the observed record. The synthetic weather model is comprised of processes which typify floods most likely to result in overtopping the study dams: 1) continuous, local-scale precipitation and temperature sampling to characterize antecedent hydrologic conditions, 2) intermittent (inhomogenous Poisson), synoptic-scale precipitation sampling based on regional precipitation-frequency analysis to generate hazardous floods, 3) k-nearest-neighbor resampling of precipitation and temperature spatiotemporal patterns and 4) temporal disaggregation of daily precipitation to hourly using correlated Brownian processes. Interrelations between local-scale precipitation, synoptic-scale precipitation and temperature are preserved using a Gaussian copula. Natural variability in annual maximum reservoir stage is described using a stratified sampling scheme used to disproportionately represent extreme floods in a fixed sample of 1,000 events, resulting in fewer model events required to span the probability space from 0.5 to 10-8 annual exceedance probability. Knowledge uncertainty in model components is estimated using a parametric bootstrap, resulting in multiple realizations of synthetic weather. Each weather realization of 1,000 events generated using varying parameters is routed using hydrologic and reservoir models for the system which produce a posterior distribution of annual overtopping probability for each structure.

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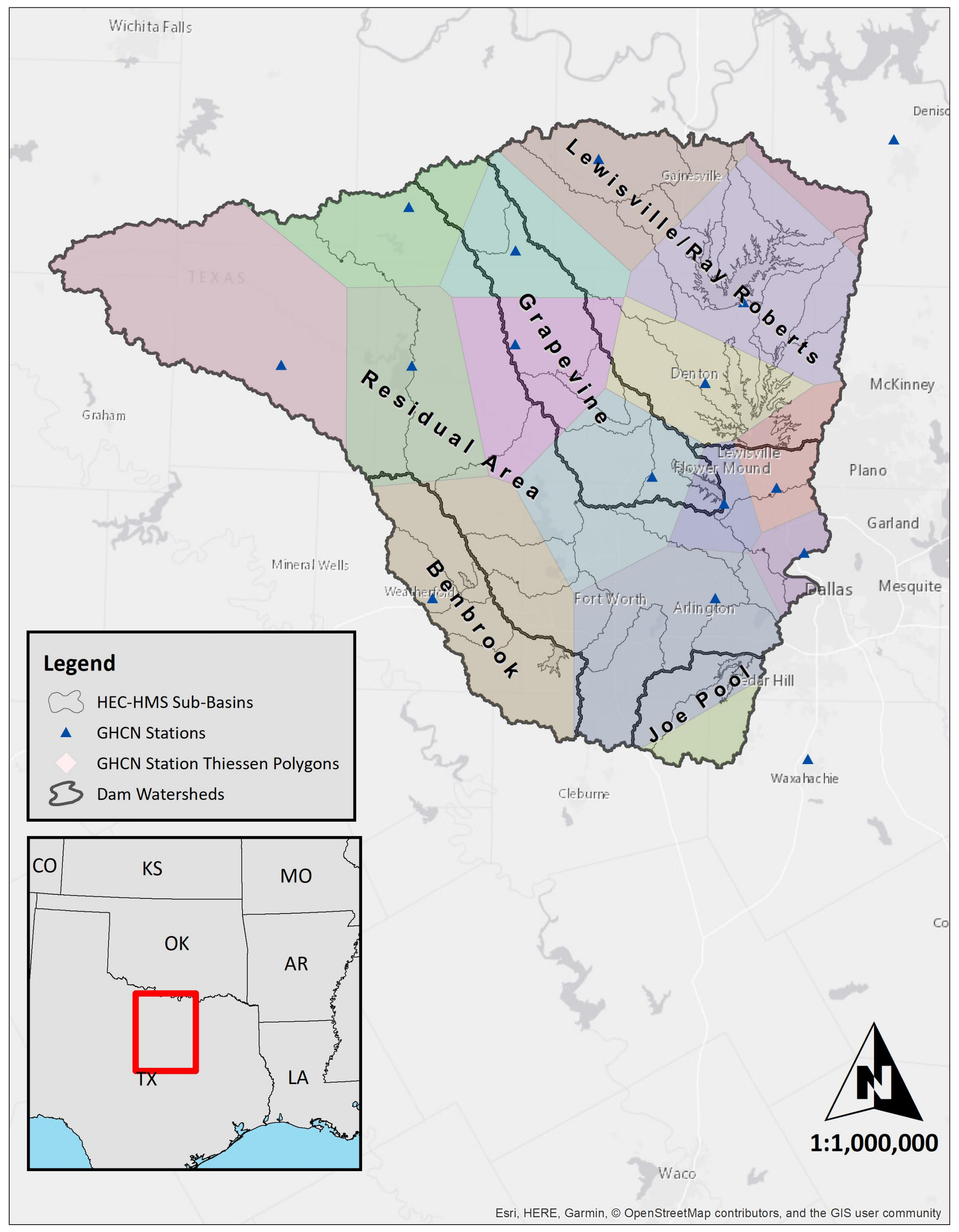
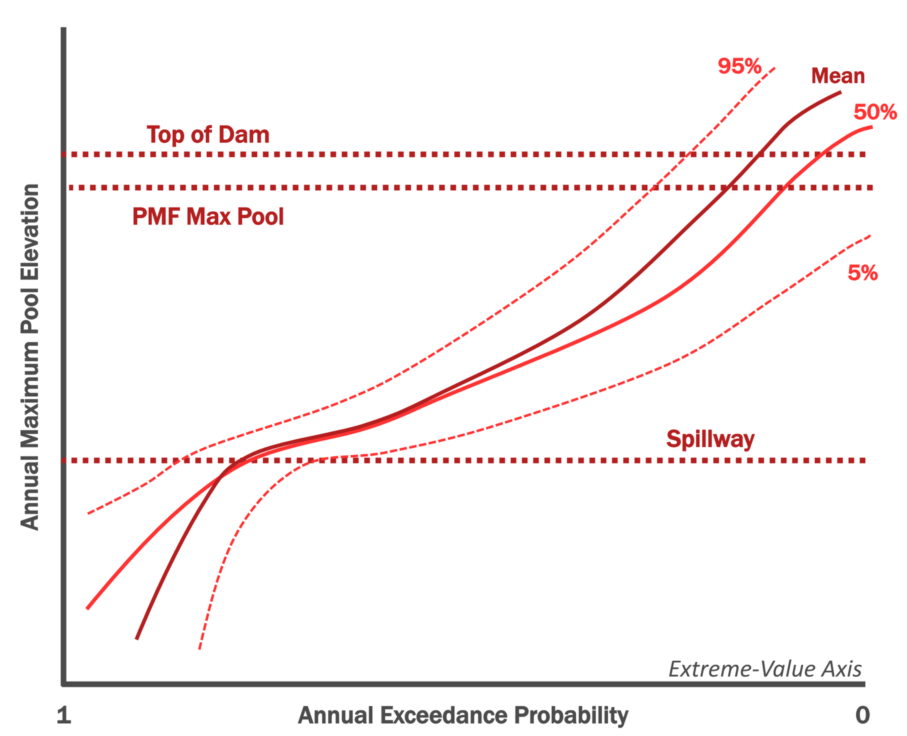
Project Overview

Project goal:
Estimate hydrologic hazard curves which consider parameter uncertainty for five co-operated USACE flood control dams in the Trinity River Basin above Dallas, TX for use in dam safety risk assessments.



The Trinity River Basin above Dallas, TX including the five dam drainage areas, hydrologic model sub-basins and precipitation discretization



Schematic of a typical hydrologic hazard curve used for dam safety studies illustrating typical key reservoir characteristics for a risk assessment, as well as parameter uncertainty bounds.

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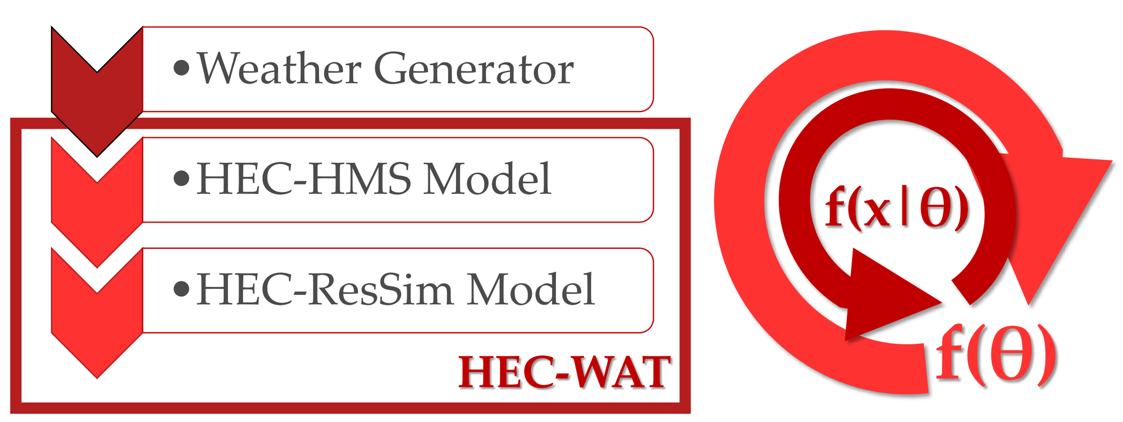
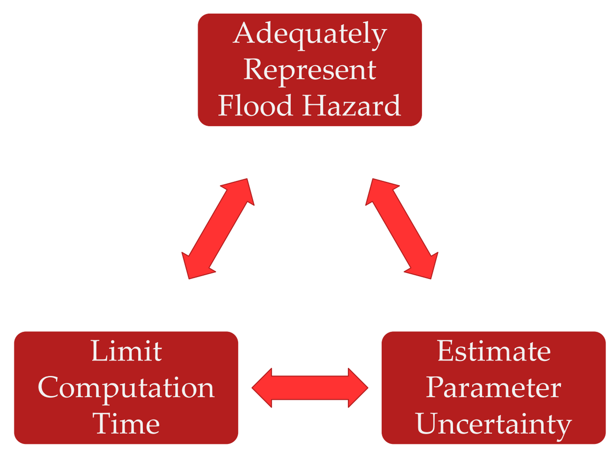
Hazard Modeling Framework



The hazard analysis framework is driven by a seasonally-continuous weather generator forcing an HEC-HMS hydrologic model for the watershed and an HEC-ResSim model for reservoir operations. HEC-WAT is used to couple the models, distribute simulations and organize outputs. Epistemic and aleatory uncertainty are modeled using a two-stage Monte Carlo approach.

Model	Parameter Uncertainty Method
Weather Generator	Parametric Bootstrap
HEC-HMS (Hydrology)	Bayesian Markov Chain Monte Carlo
HEC-ResSim (Reservoir Operations)	Deterministic

Model Design



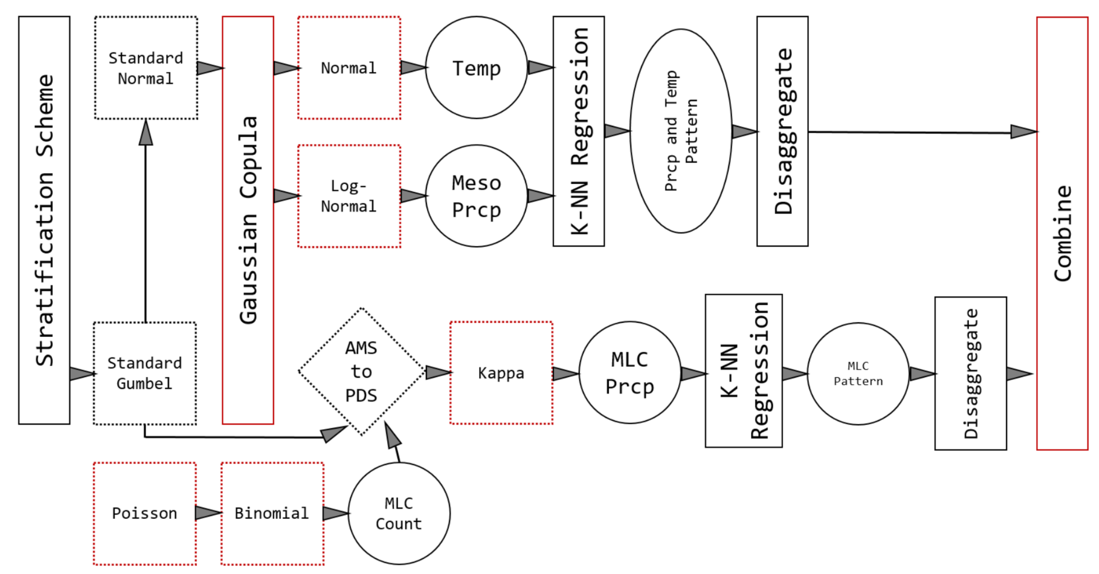
Designing the weather model required balancing computational and budgetary resources with the need for timely, decisionable information.

- Model individual and interdependent flood hazards at each dam
- Provide hydrometeorological context for extreme flood events
- Preserve spatiotemporal dependency of flooding
- Provide measure of parameter uncertainty

Flood Hazard Characterization

- Generate extreme hazard-driving floods
  - Large-scale heavy springtime rainfall caused by mid-latitude cyclones
  - More than one possible in a year
  - Flood volumes fill flood control pool
  - Flood peaks control peak stage
- Continuous meteorology for antecedent flood conditions
  - Captures smaller-scale storm events
  - Soil moisture deficit
  - Reservoir storage
- Events must span entire relevant probability range
  - Spillway flow initiation
  - Dam overtopping elevation
  - Computationally-expensive if using naïve Monte Carlo

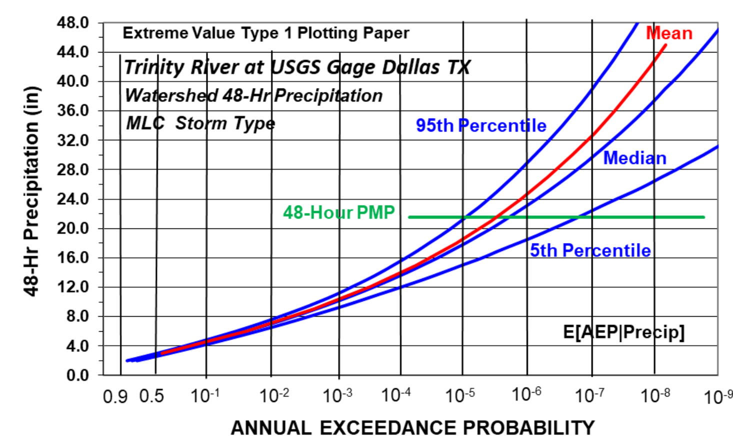
Model Structure



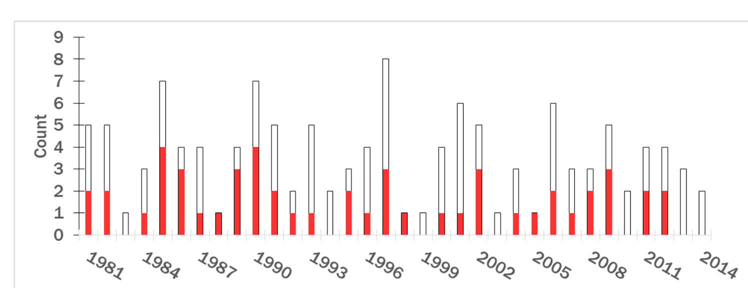
The weather generator structure represented as a flowchart. Elements outlined in red have parameters which are treated with uncertainty in the "outer loop" using a parametric bootstrap.

Model Input Development

- Regional precipitation frequency analysis with storm typing
  - Report to USACE (Martin et al., 2018)
  - Precipitation-frequency for MLC storm type
- MLC rate and timing properties for arrival model
  - Precipitation and temperature pattern templates
- Spatially-averaged PRISM daily climate data



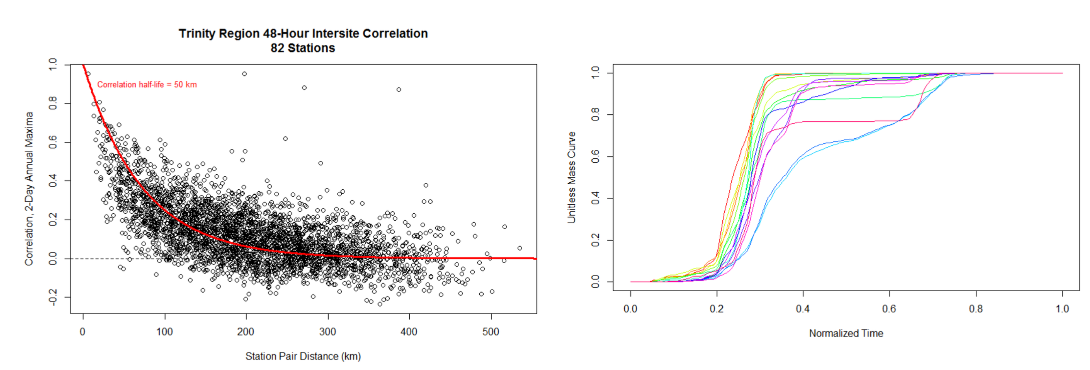
Annual maximum 48-hour precipitation for the mid-latitude cyclone (MLC) storm for the entire watershed above Dallas (from Martin et al. 2018)



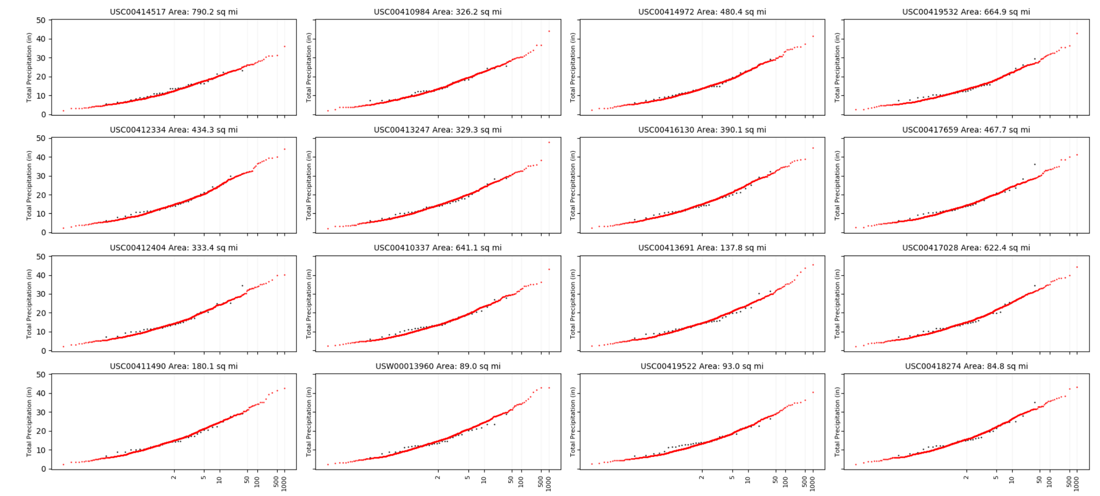
Annual and seasonal (red) counts of mid-latitude cyclones with 48-hour maximum basin-average precipitation exceeding the minimum annual maximum.

Research and Development Efforts

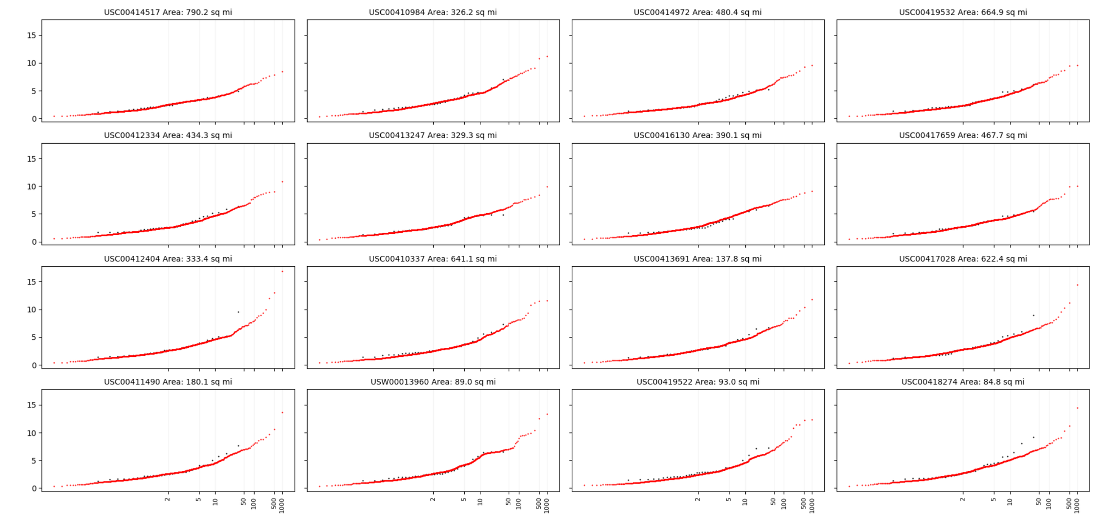
- Importance sampling to reduce computational burden
  - 50 samples from 20 strata
  - Strata evenly divide EV-1 space from 0.5 to 10^{-8} AEP
- Parametric bootstrap to estimate parameter uncertainty
  - 1,000 parameter realizations
- Correlated stochastic mass curve method for temporal precipitation disaggregation



Results – Weather Generator

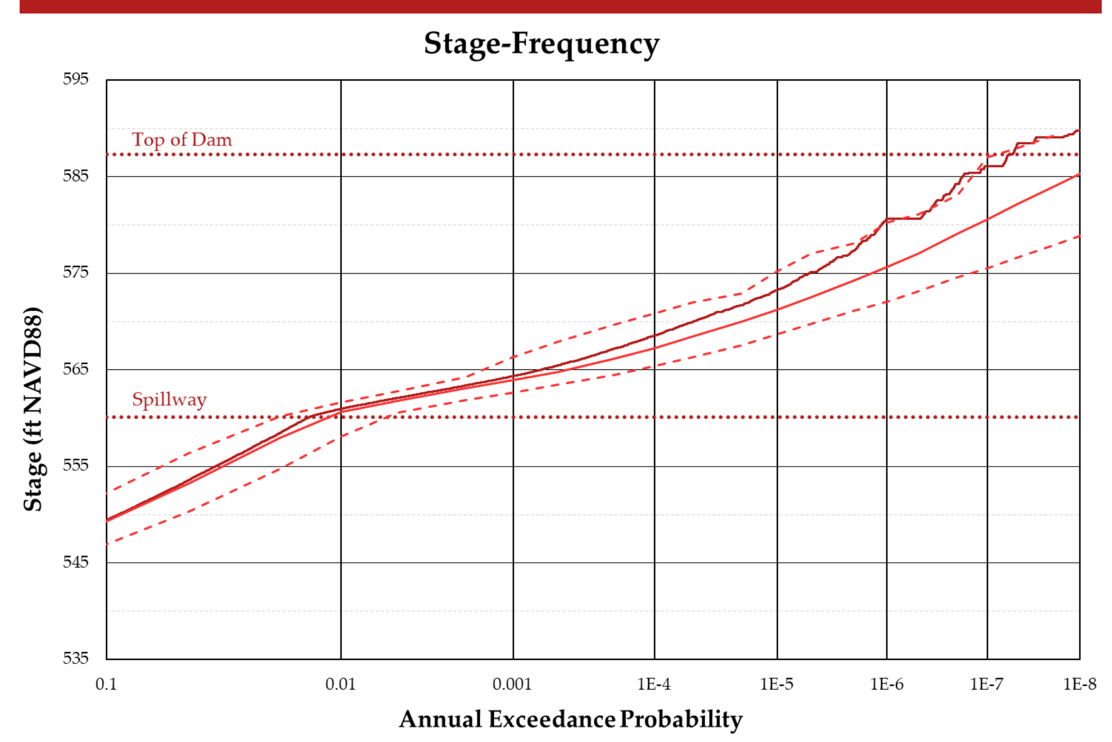


Sampled and observed season-total precipitation for the 16 weather polygons.



Sampled and observed 48-hour seasonal maximum precipitation for the 16 weather polygons.

Results – Coupled Models



Hydrologic hazard curve for one of the five dams in the study area. Despite the large stratified sample, uncertainty results have not converged at the right tail resulting in jaggedness of the mean and upper parameter uncertainty bound (95%).

References

Martin, D. L., Schaefer, M. G., Parzybok, T. W., Ward, K., Bahls, V., and Caldwell, R. J. (2018). Trinity River hydrologic hazards project task 3 report – regional extreme precipitation-frequency analysis for the Trinity River Basin. MetStat, Inc., Ft. Collins, CO.

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