Technical Basis for Probabilistic Flood Hazard Assessment (PFHA) for Riverine Flooding

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PFHA Definition

- PFHA is defined as a site-specific, systematic evaluation of the probabilities and frequencies of exceedance of hazards generated by applicable flood mechanisms to which SSCs could be exposed during specified exposure times at an NPP site
  - PFHA is site-specific – from meteorologic conditions to watershed and riverine characteristics to site layout
  - Systematic – covers the full range of exceedance probabilities
  - Flood mechanisms – phenomena producing a flood
    - Addressing precipitation-generated flooding here
  - A flood can result in multiple hazards (e.g., hydrodynamic load, accumulation of water in structures)
    - Flood hazards are functions of the characteristics of the flow field (flood parameters)
  - Multiple SSCs may be affected
    - At the site scale, flow field is significantly affected by buildings and obstructions

Flood Hazards

Flood Hazard	Flood Parameters	Potential Effects on SSCs	Relevant Scale
Hydrostatic load	Water-surface elevation	Loss of functionality from exceeding the design basis	Site scale
Hydrodynamic load	Water-surface elevation, flow velocity, flow density	Loss of functionality from exceeding the design basis	Site scale
Inundation area	Water-surface elevation	Loss in accessibility leading to loss of functionality	Site scale
Accumulation volume of water in SSCs	Water-surface elevation, time of inundation of openings	Loss of functionality	Site scale
Erosion	Flow velocity, discharge, turbulence, and duration	Loss of functionality	Site scale
Deposition	Flow velocity, discharge, turbulence, and duration	Loss in accessibility leading to loss of functionality	Site scale
Debris impact load	Water-surface elevation, flow velocity, duration	Loss of functionality from exceeding the design basis	Site scale
Warning and lead times	Discharge hydrograph	Loss in accessibility leading to loss of functionality	Drainage area to site scale
Inundation duration	Discharge hydrograph, water-surface elevation	Loss in accessibility leading to loss of functionality, loss of functionality from exceeding the design basis	Drainage area to site scale

PFHA Components

- Data collection and analysis
- Model selection
- Model parameter estimation
- Evaluation of variability and uncertainty
- Quantification of probabilistically-defined hazard, including uncertainties

Potentially Applicable Data

- Streamflow data
- Physical data
  - Topography, watershed area, subwatersheds, drainage connectivity, land use and cover, soil types, channel lengths, connectivity, cross sections
- Hydrometeorologic input data
  - Precipitation, air temperature, solar radiation, wind speeds and direction
- Snow cover and water content
- Soil Moisture
- Data types, temporal resolution, and spatial coverage are dictated by model requirements

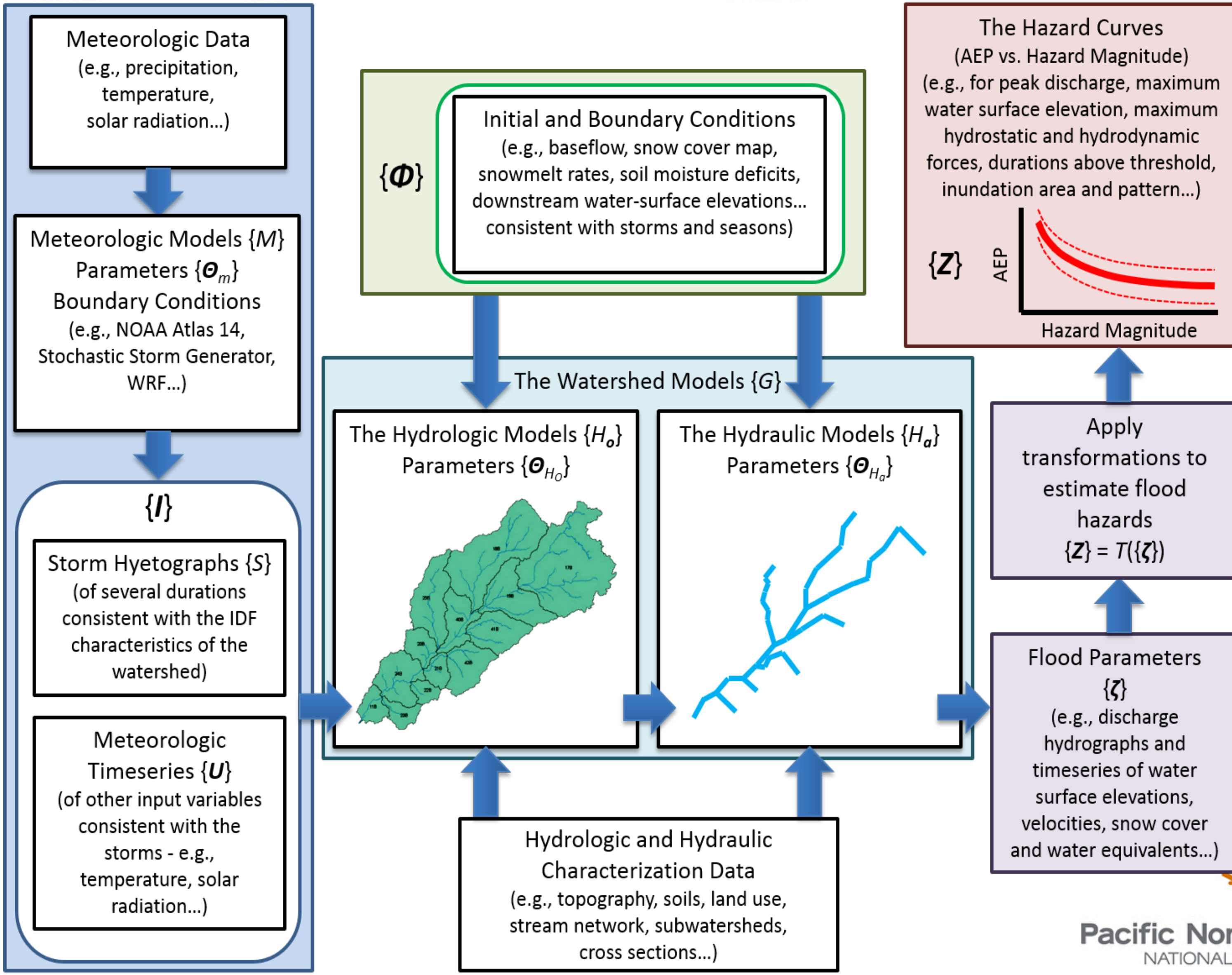
Potentially Applicable Models

- Statistical models (flood frequency analysis)
- Meteorologic models
  - Provides meteorologic input (e.g., a regional precipitation IDF curve)
- Watershed models
  - Hydrologic Model
    - Set up using physical watershed data (e.g., topography, subwatersheds, channel network, soils, land use and cover…)
    - Given input meteorologic data and initial conditions, predicts streamflow discharge hydrographs
  - Hydraulic Model
    - Set up using physical watershed data (e.g., topography, channel network, cross sections…)
    - Given initial conditions (baseflow) and streamflow discharge hydrographs, predicts flood characteristics (e.g., water-surface elevations, velocities…)

Multiple Model Alternatives

- Hydrologic Models
  - Lumped-parameter conceptual models (e.g., unit hydrograph)
  - Physically-based process models (e.g., Stanford Watershed Model, Sacramento Model, HSPF, IHDM, PRMS, HBV, TOPMODEL)
  - “Fully-distributed” physically-based models (e.g., SHE, DHSVM)
  - Semi-distributed, lumped-parameter models (e.g., HEC-HMS)
- Hydraulic Models
  - One-dimensional approximation (e.g., kinematic wave, diffusive wave)
  - Full one-dimensional dynamic wave models (e.g., NWS DWOPER, NWS DAMBRK, NWS FLDWAV, USACE HEC-RAS)
  - Two-dimensional hydraulic models (e.g., TUFLOW, Mike 21, TELEMAC)
- Varying data requirements
- Need calibration and validation

PFHA Framework: Model-based



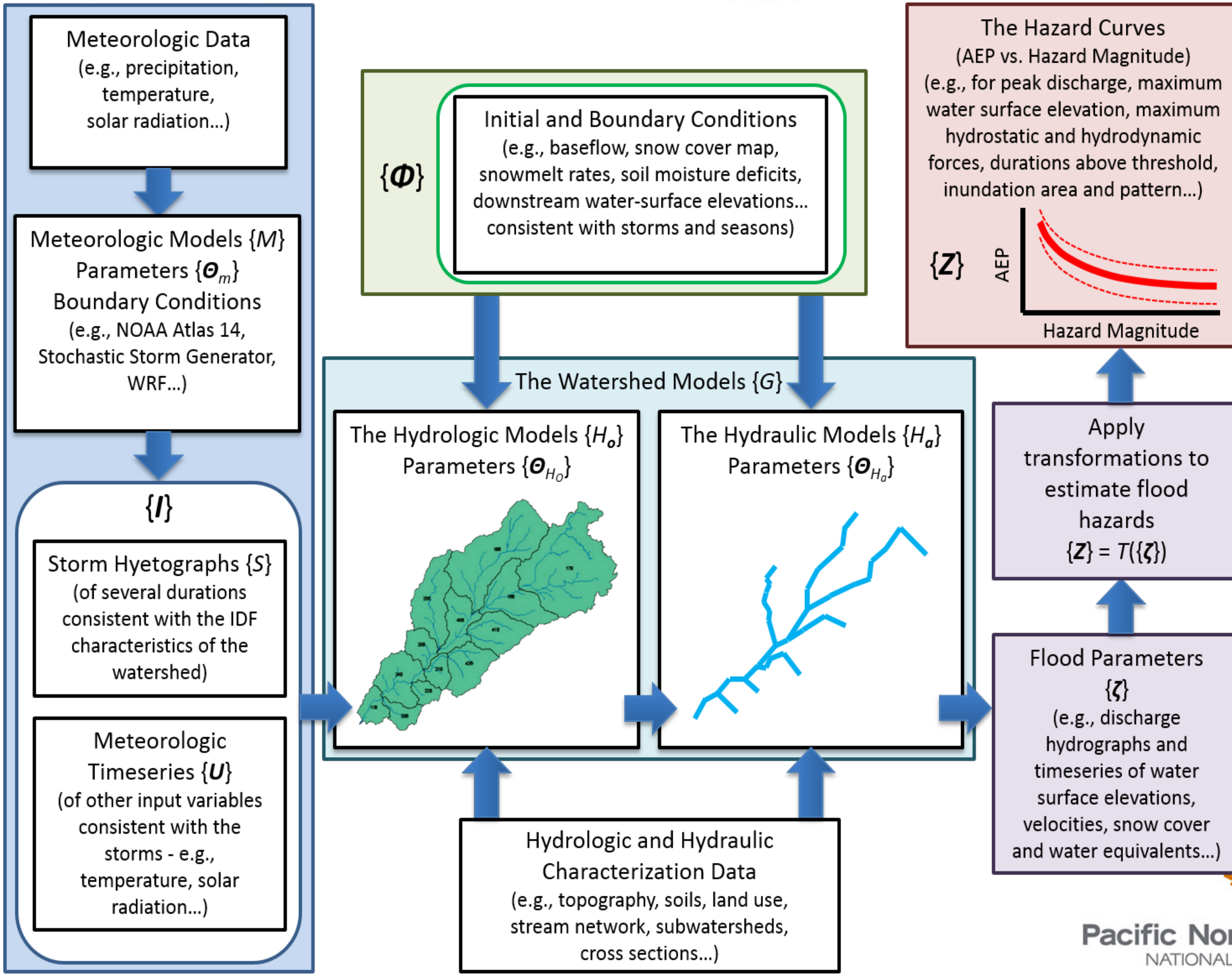
Model Parameter Estimation

- Evolution of methods
  - Trial and error → automated calibration
  - Single objective → multi-objective
  - Local → global search
  - Classical (least-squares, maximum likelihood) → Bayesian (prior parameter information)
- Extrapolation likely required even with best effort
  - Observed data record on the order of 100 years – may not include low-probability events
  - Best observations for parameter estimation may not include those for extreme floods

Evaluation of Variability and Uncertainty

- Aleatory Uncertainty
  - Arises from the natural variability in a system; irreducible
  - For PFHA, the primary irreducible uncertainties affecting the occurrence of future flooding at a site are:
    - the depth and intensity of rainfall events in the future, and the
    - watershed conditions at the time of those events
    - associated with the hydrometeorologic inputs, $\boldsymbol{I}$, and with the watershed initial and boundary conditions, $\boldsymbol{\Phi}$
  - Aleatory uncertainties result in a distribution of each flood hazard (a hazard curve)

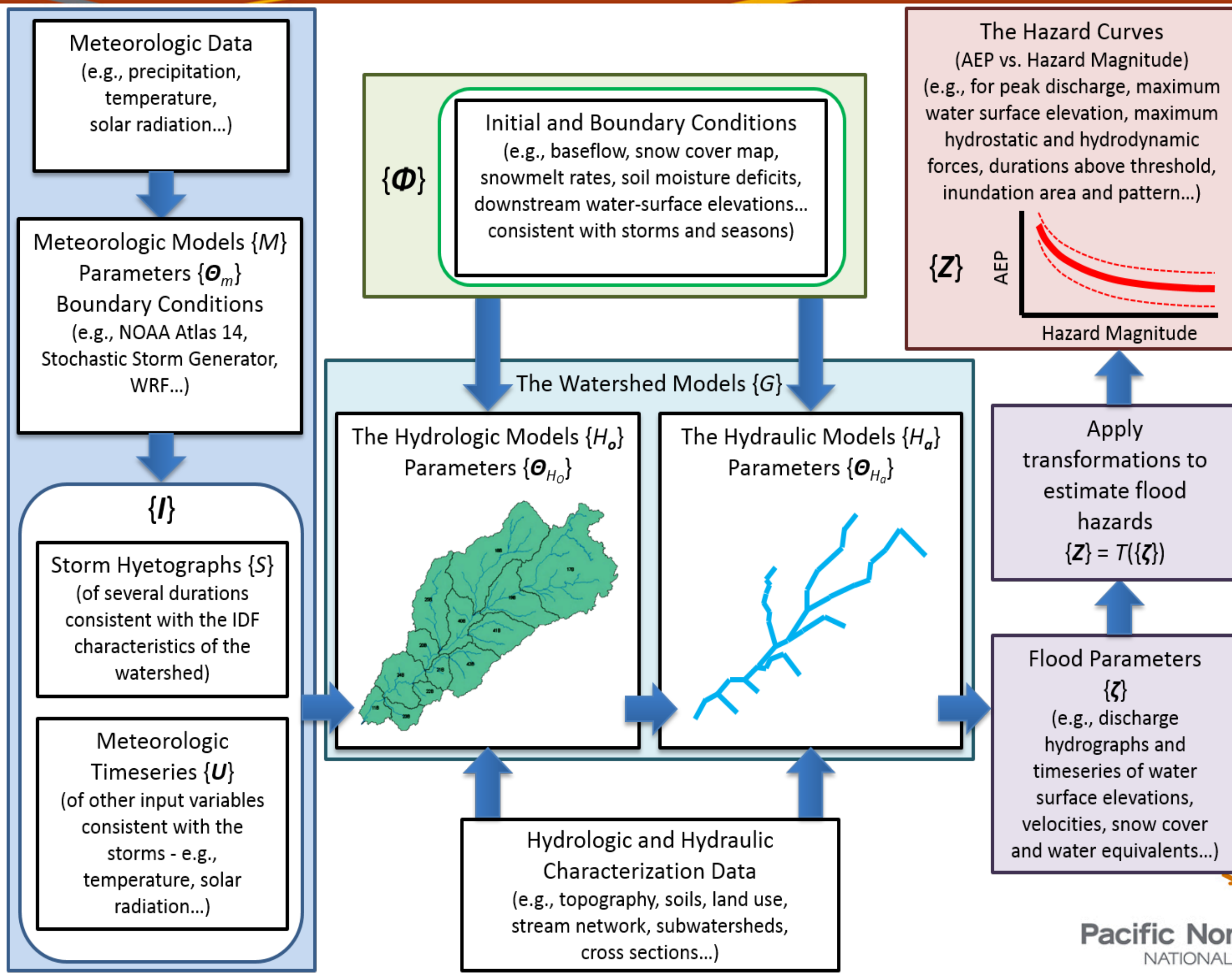
PFHA Framework: Model-based



Evaluation of Variability and Uncertainty

- Epistemic Uncertainty
  - Represents our lack of knowledge about a system; may be reducible with collection of additional data
  - For PFHA, the primary epistemic uncertainties are in:
    - modeling the precipitation-runoff processes
    - characterizing the watershed
    - determining appropriate parameter values for the models.
    - May be represented as parameter probability distributions, alternative process representations, and alternative model structures (a discrete set of choices), all collected in the model parameters, $\boldsymbol{\Theta}$
  - Epistemic uncertainties contribute to the uncertainty in the quantiles of the hazard distribution (e.g., the uncertainty in the exceedance probability of a given flood hazard value)

PFHA Framework: Model-based



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Quantifying the Hazard

- Consistent with the model-based PFHA framework, for a flood hazard $\boldsymbol{Z}$
  - $\boldsymbol{Z} = T[G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})]$
    - where
      - $\boldsymbol{Z}$ = the flood hazard
      - G = the watershed model
      - $\boldsymbol{I}$ = the hydrometeorologic input variables
      - $\boldsymbol{\Phi}$ = the initial and boundary conditions in the watershed
      - $\boldsymbol{\Theta} = \{\boldsymbol{\Theta}_{H_o}, \boldsymbol{\Theta}_{H_a}\}$ = the model parameters
      - T = any further transformation or analysis needed to estimate the flood hazard from primary flood parameters simulated by the watershed model
  - with
    - aleatory uncertainties, $\boldsymbol{I}$ and $\boldsymbol{\Phi}$
    - epistemic uncertainties, $\boldsymbol{\Theta}$ (possibly including discrete model process/structural uncertainties)

Probabilistically-defined Hazard

- Given the joint distribution of the aleatory and epistemic uncertainties, the hazard exceedance probability is
  - $P(\boldsymbol{Z} > z) = \int_{-\infty}^{\infty} P(\boldsymbol{Z} > z|\, \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}\, \boldsymbol{d\Theta}$
    - which would generally be solved numerically
    - e.g., estimate $P(\boldsymbol{Z} > z)$ using $\hat{P}(z) = \frac{1}{N}\sum_{i=1}^{N} H(z_i - z)$
      - where $z_i = T[G(\boldsymbol{I}_i, \boldsymbol{\Phi}_i, \boldsymbol{\Theta}_i)]$ for $i = 1 \ldots, N$ samples from $f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})$
      - and $H(z_i - z)$ is the Heaviside function
  - Reduce computational effort by
    - efficient sampling (e.g., latin hypercube, importance sampling)
    - simplifying the form of $G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})$ (e.g., reduce model dimensions, simplify process representation, use surrogate model)
    - adopt a conservative approach for certain aspects of the analysis

PRA Integration

Annual Frequency of Exceedance

- If $\boldsymbol{Z}$ is a partial duration series for a flood parameter with flood events exceeding a threshold, z_0, and an arrival rate λ (mean number of yearly flood events exceeding z_0), then mean annual frequency of flood events exceeding $z > z_0$ is
  - $\lambda^* = \lambda \int_{-\infty}^{\infty} P(\boldsymbol{Z} > z | \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}\, \boldsymbol{d\Theta}$
- For an annual maximum series ($\boldsymbol{Z}_a$), the equivalent (assuming flood events occur as a Poisson process) is
  - $\lambda^* = -\ln[1 - \int_{-\infty}^{\infty} P(\boldsymbol{Z}_a > z | \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}\, \boldsymbol{d\Theta}]$
  - $\lambda^* \approx P(\boldsymbol{Z}_a > z)$ when λ^* is less than about 0.1
- The probability of a flood hazard, $\boldsymbol{Z}$, exceeding z over a period of t years is
  - $P_t(Z > z) = 1 - e^{-\lambda^* t}$, or
  - $\approx 1 - (1 - \lambda^*)^t$ (when t is small)
  - $\approx \lambda^* t$ (when $\lambda^* t$ is small)

Uncertainty Representation

- Expert knowledge generally applied to specify uncertainty representation
  - e.g., it may be reasonable to assume that the hydrometeorologic inputs, the initial watershed conditions, and the parameters of the watershed model are statistically independent
    - $f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) = f(\boldsymbol{I})f(\boldsymbol{\Phi})f(\boldsymbol{\Theta})$
  - parameter calibration:
    - $f(\boldsymbol{\Theta}) = f(\boldsymbol{\Theta}|\hat{\boldsymbol{I}}, \hat{\boldsymbol{\Phi}}, \widehat{\boldsymbol{Q}_p})$, is the posterior parameter distribution of the watershed model parameters, conditioned on observations of the watershed response, $\widehat{\boldsymbol{Q}_p}$, to observed precipitation events, $\hat{\boldsymbol{I}}$, with observed initial watershed conditions, $\hat{\boldsymbol{\Phi}}$
  - expand epistemic uncertainty
    - $Z = T[G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})] + \boldsymbol{\epsilon}$
      - where $\boldsymbol{\epsilon}$ characterizes unmodeled uncertainties (e.g. errors in the transformation of the watershed model outputs to the flood hazard)

Evaluation of Hazard Curve Uncertainty

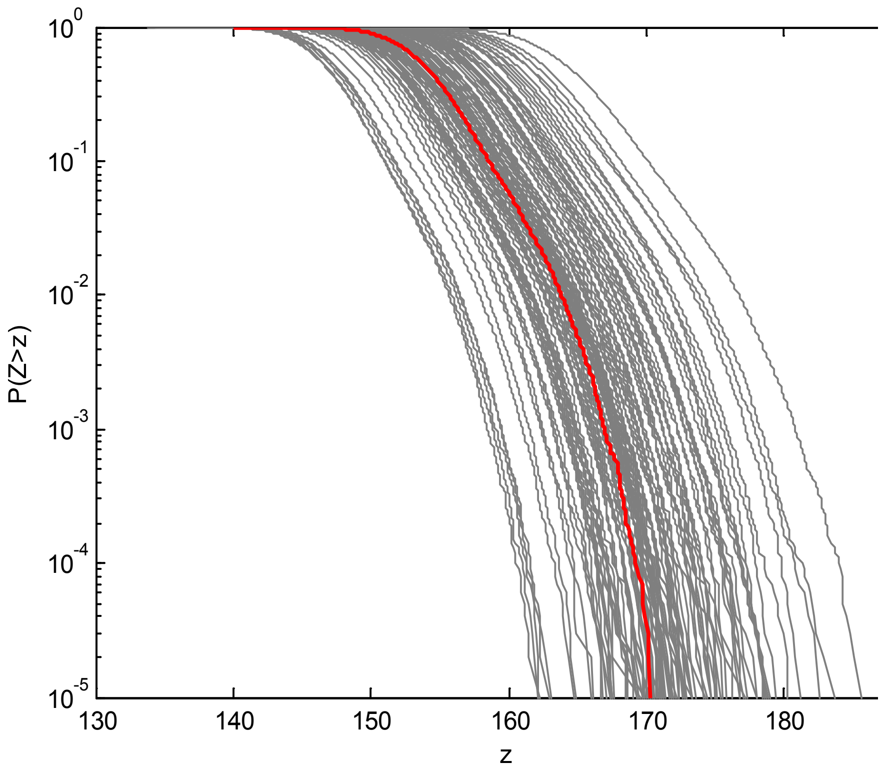
- A single hazard curve representing the aleatory uncertainties would arise from the solution of
  - $P(Z > z|\, \boldsymbol{\Theta}, \boldsymbol{\epsilon}) = \int_{(I,\Phi)} P(Z > z|\, \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}, \boldsymbol{\epsilon}) f(\boldsymbol{I}, \boldsymbol{\Phi}|\boldsymbol{\Theta}, \boldsymbol{\epsilon})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}$

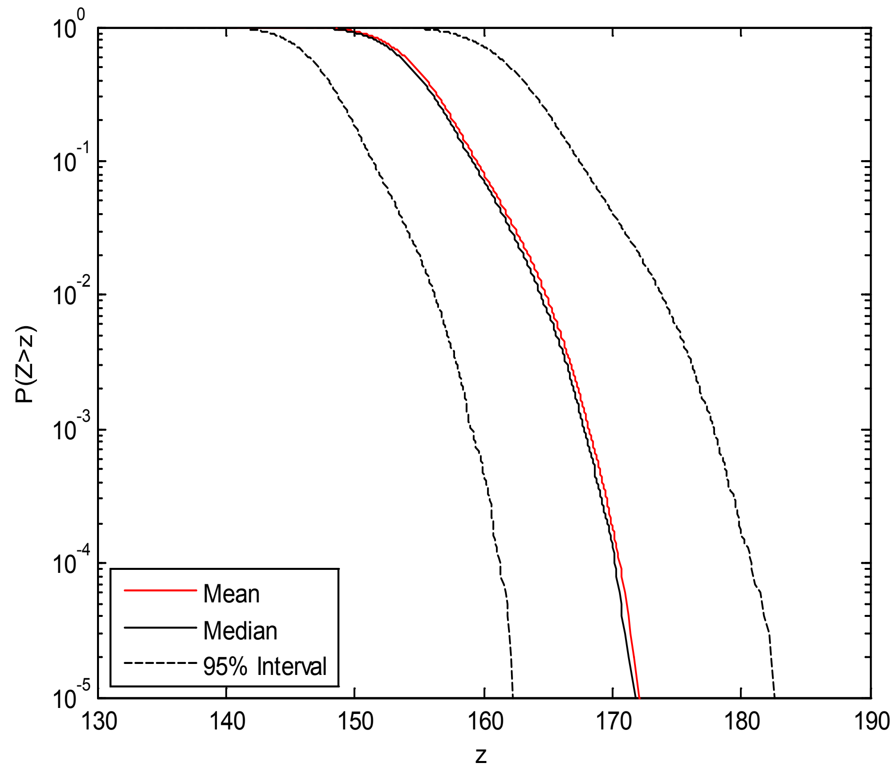
- A family of hazard curves representing the epistemic uncertainties would be calculated by sampling repeatedly from the distribution of the epistemic uncertainties, $f(\boldsymbol{\Theta}, \boldsymbol{\epsilon})$, and solving the above expression

Evaluation of Hazard Curve Uncertainty

- Small hypothetical watershed example
  - Aleatory uncertainties
    - $f(\boldsymbol{I})$, GEV distribution for the 1-hr annual maximum rainfall depth based on NOAA Atlas 14 results
    - $f(\boldsymbol{\Phi}|\boldsymbol{I})$, watershed initial condition, dependent on the rainfall depth
  - Epistemic uncertainties
    - $f(\boldsymbol{\Theta})$, independent watershed model parameters
    - $f(\epsilon|\boldsymbol{I},\boldsymbol{\Phi},\boldsymbol{\Theta})$, additional uncertainty dependent on the output of the watershed model
  - Aleatory hazard curve (in red on following figure) from constant $\boldsymbol{\Theta}$ at mean values and $\epsilon = 0$
  - Gray curves sampled from epistemic uncertainty, $f(\boldsymbol{\Theta},\epsilon|\boldsymbol{I},\boldsymbol{\Phi}) = f(\epsilon|\boldsymbol{I},\boldsymbol{\Phi},\boldsymbol{\Theta})f(\boldsymbol{\Theta})$

Evaluation of Hazard Curve Uncertainty





- Aleatory hazard curve (in red) from constant $\boldsymbol{\Theta}$ at mean values and $\epsilon = 0$
- Gray curves sampled from epistemic uncertainty,
$$f(\boldsymbol{\Theta}, \boldsymbol{\epsilon} | \boldsymbol{I}, \boldsymbol{\Phi}) = f(\boldsymbol{\epsilon} | \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{\Theta})$$
- Statistics (on right) computed from epistemic results

PFHA Framework – Next Steps

- Uncertainty representation
  - Valid generalizations
  - Valid simplifications
  - Integration of multiple sources of data/information
  - Treatment of nonstationarities
- Computational tools
  - Integration of applicable tools
  - Selective development
- Application/demonstration

Questions?

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