Probabilistic Flood Hazard Assessment for a Small Watershed in Eastern Tennessee: Methodology and Lessons Learned

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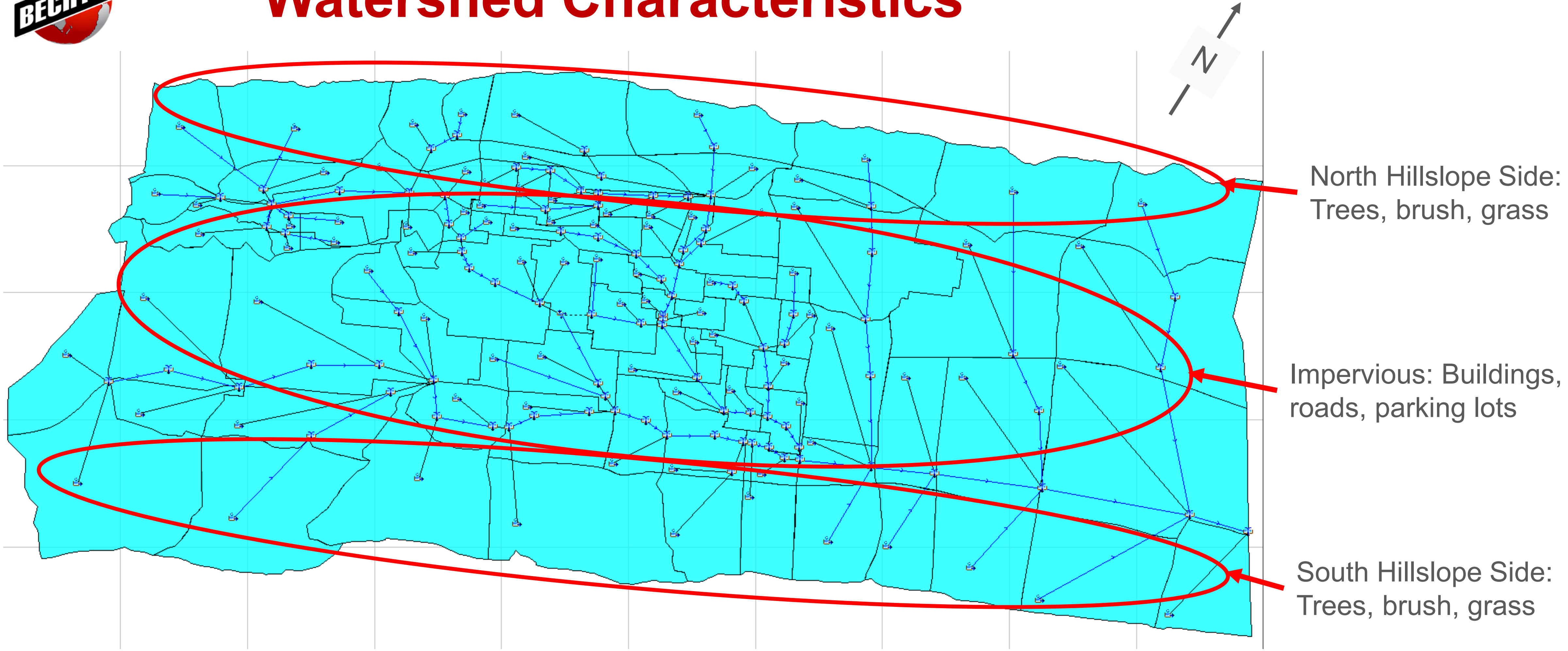
Presentation Outline

- Study Objectives
- Site Characteristics
- Regulatory Requirements
- Technical Approach
- Input Analysis
- Results
- Summary/Conclusions

Study Objectives

- Objectives of study:
  - Develop probabilistic flood hazard curves for locations within watershed
  - Determine design flood levels at buildings of interest within watershed
- Previously, a similar flood study was performed at the same watershed, which included some probabilistic elements.
  - Previous study was peer-reviewed
  - Peer-review team provided recommendations for additional probabilistic elements
- Three separate studies are prepared for determining design flood levels.
  - Precipitation (completed), Runoff (on-going), Hydraulic (on-going).

Watershed Characteristics



North Hillslope Side: Trees, brush, grass

Impervious: Buildings, roads, parking lots

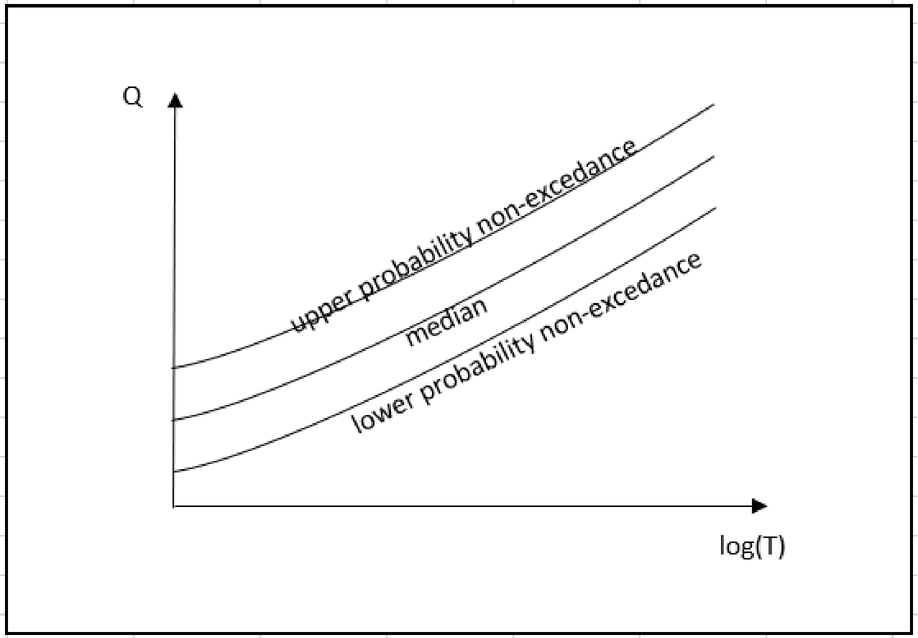
South Hillslope Side: Trees, brush, grass

- Urban land use
- 1.126 mi^2 drainage area
- Humid climate

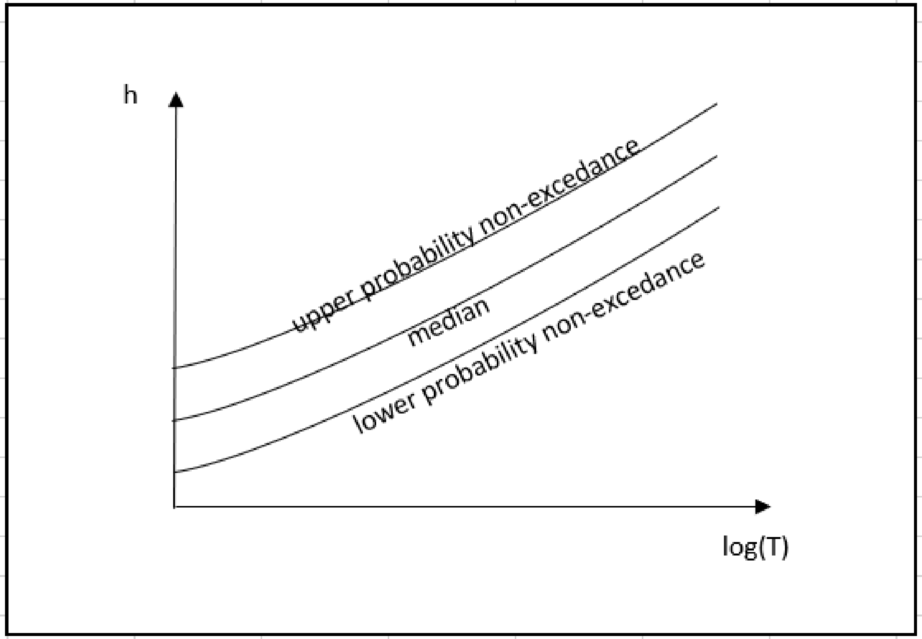
Regulatory Requirements

- Satisfy DOE-STD-1020-2016 “Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities” requirements:
  - Probabilistic approach that represents the flood/precipitation hazard as a function of the return period
  - Considers and propagates the uncertainties in the parameters used to estimate the flood levels

Flood Flow Hazard Curve



Flood Level Hazard Curve



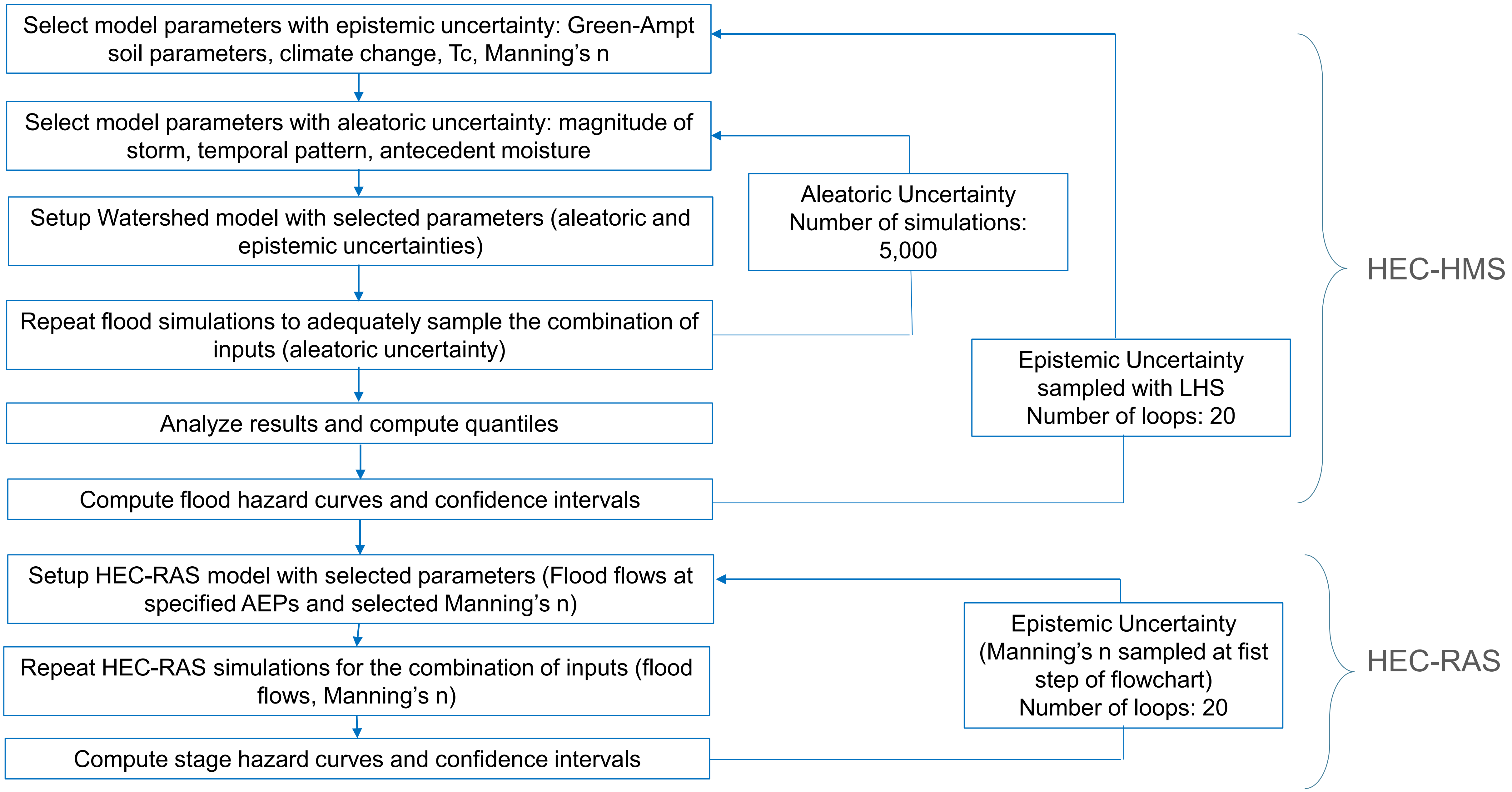
Uncertainty in Input Variables

- Aleatoric uncertainty: due to chance

    1. Rainfall duration
    2. Total rainfall depth
    3. Temporal pattern (hyetograph) of rainfall
    4. Day of occurrence of rainfall, which sets the initial water content of the soil

- Epistemic uncertainty: due to lack of knowledge

    1. Climate change adjustment factor for rainfall
    2. Sheet flow length
    3. Manning’s n for calculating travel time of sheet flow
    4. Peaking factor for adjusting lag time
    5. Soil hydraulic parameters for Green-Ampt (hydraulic conductivity, wetting front suction head, porosity)
    6. Manning’s n for the hydraulic analysis and M-C routing



Select model parameters with epistemic uncertainty: Green-Ampt soil parameters, climate change, Tc, Manning’s n

Select model parameters with aleatoric uncertainty: magnitude of storm, temporal pattern, antecedent moisture

Setup Watershed model with selected parameters (aleatoric and epistemic uncertainties)

Repeat flood simulations to adequately sample the combination of inputs (aleatoric uncertainty)

Analyze results and compute quantiles

Compute flood hazard curves and confidence intervals

Setup HEC-RAS model with selected parameters (Flood flows at specified AEPs and selected Manning’s n)

Repeat HEC-RAS simulations for the combination of inputs (flood flows, Manning’s n)

Compute stage hazard curves and confidence intervals

Aleatoric Uncertainty
Number of simulations:
5,000

Epistemic Uncertainty
sampled with LHS
Number of loops: 20

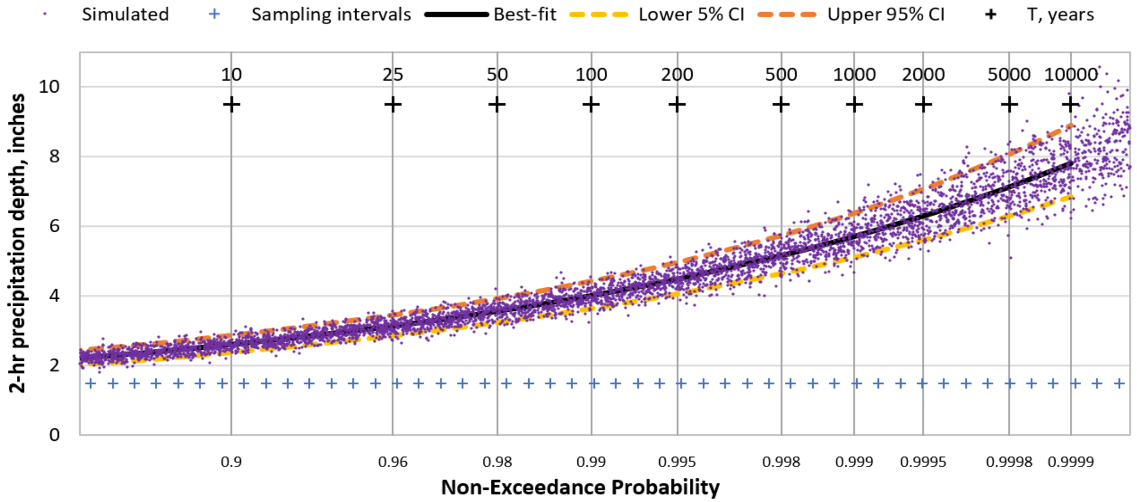
Epistemic Uncertainty
(Manning’s n sampled at fist step of flowchart)
Number of loops: 20

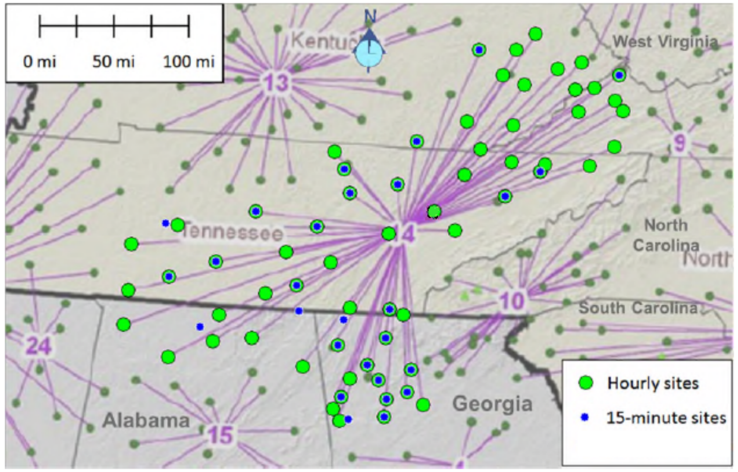
HEC-HMS

HEC-RAS

Precipitation Input - Aleatoric Uncertainty

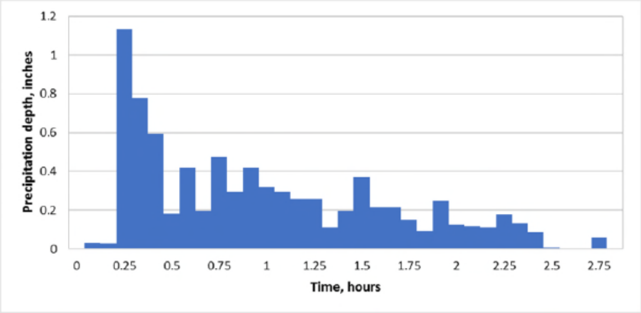
- GEV distribution parameters estimated using L-moments.
- 64 stations with hourly precipitation records and 28 stations with 15-minute records are used.
- Example of 2-hr precipitation-frequency curve.
- Probability space is divided into 50 equal width intervals. 100 values are simulated within each interval.





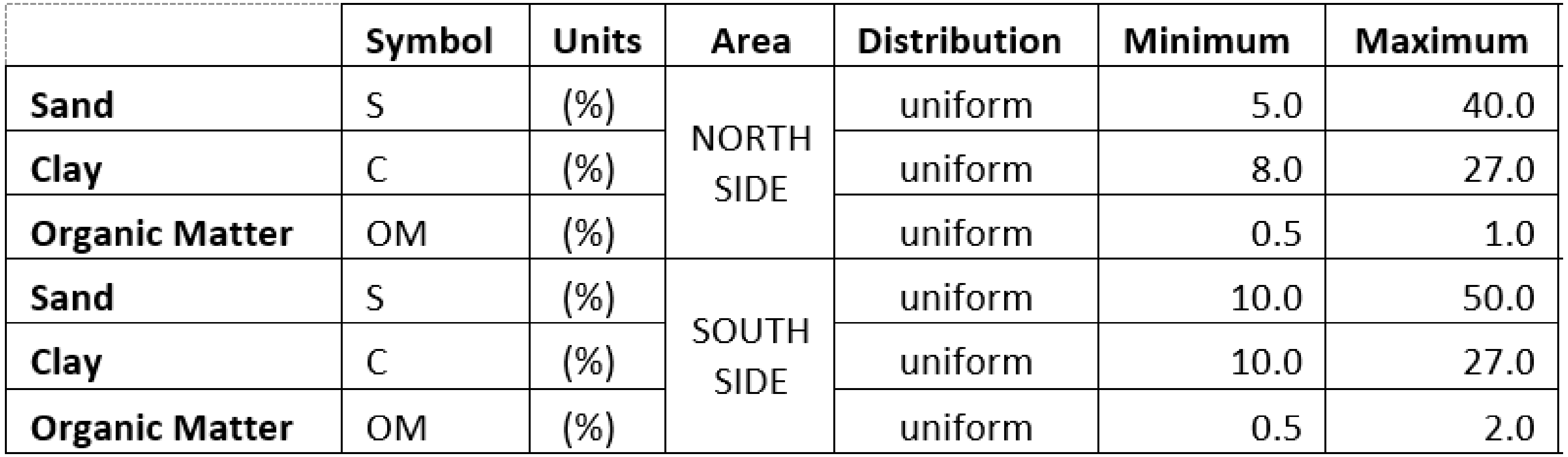
Sites selected for the regional frequency analysis (background shows regional groupings of hourly stations from NOAA (2006) Atlas 14 Volume 2).

- A group of scalable dimensionless hyetograph patterns was developed.
- The dimensionless hyetograph patterns were applied in a stochastic model that generated probabilistic storm sequences.



Run-off model: Green-Ampt

- Input parameters to G-A: Hydraulic conductivity, K, Water front suction head, S_f, Soil Porosity, φ
- Estimation of G-A parameters is based on regression equations (Saxton & Rawls, 2006).
- Regression equations use the composition of the soil in terms of percentage of sand, silt, clay and organic matter.
- USDA soil reports provide the composition of soils in sand, silt, clay, organic matter for the area.



	Symbol	Units	Area	Distribution	Minimum	Maximum
Sand	S	(%)	NORTH SIDE	uniform	5.0	40.0
Clay	C	(%)		uniform	8.0	27.0
Organic Matter	OM	(%)		uniform	0.5	1.0
Sand	S	(%)	SOUTH SIDE	uniform	10.0	50.0
Clay	C	(%)		uniform	10.0	27.0
Organic Matter	OM	(%)		uniform	0.5	2.0

- Soil composition is treated as epistemic uncertainty (LHS sampling).
- After the soil composition is selected for each epistemic loop, the regression equations are used to estimate the G-A parameters for the North and South Hillslope areas.
- Middle part of watershed is impervious.

Lesson Learned

- Green-Ampt Parameters selection.
- Hydraulic conductivity (K), Water front suction head (S_f) are inversely correlated.
- Different approaches:
    1. Used textbook values based on soil texture class to fit distributions and then sample. Correlation not preserved.
    2. USDA soil reports provide the composition of soils in sand, silt, clay, organic matter for the site. Stochastically sample the soil composition. Use regression equations to estimate Green-Ampt parameters. Fit distributions and then sample (LHS). Correlation not preserved.
    3. Same as No. 2 but first sample the soil composition as having epistemic uncertainty (LHS). Use regression equations to estimate Green-Ampt parameters. Correlation is preserved.

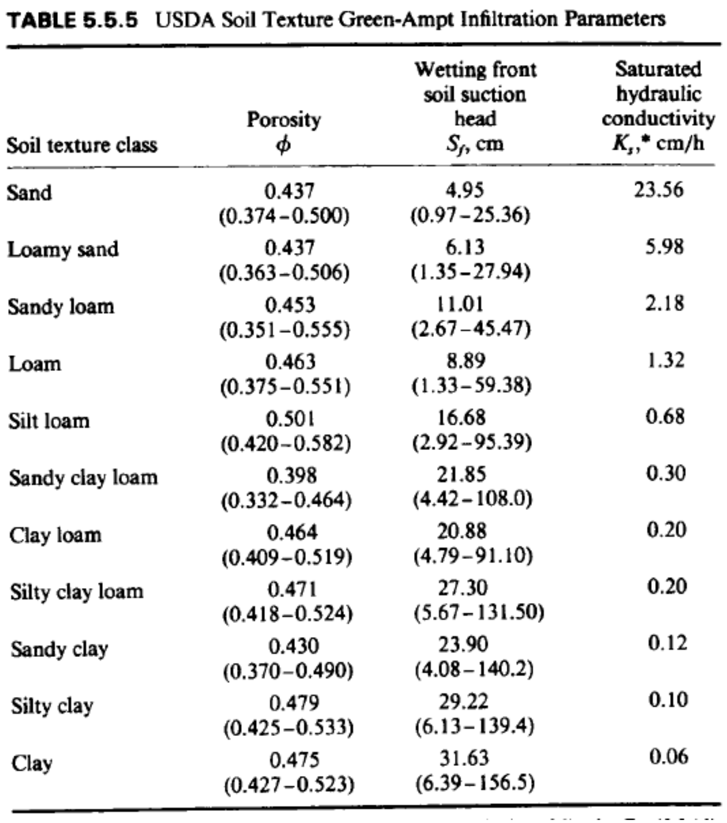


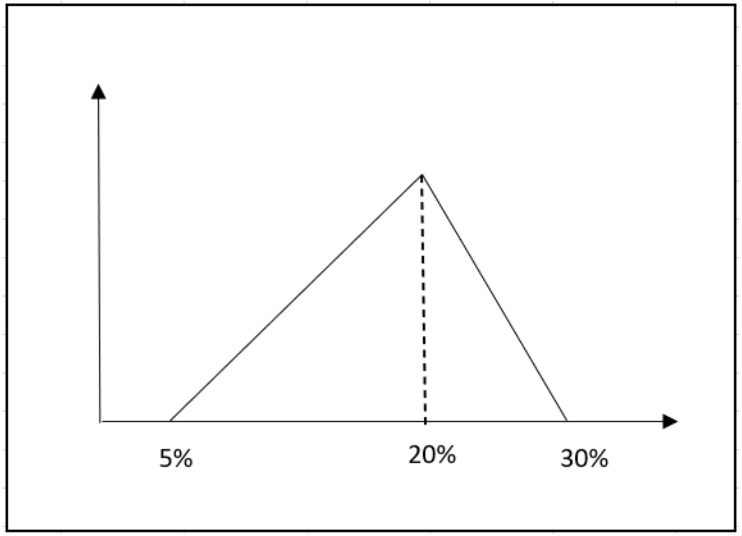
TABLE 5.5.5 USDA Soil Texture Green-Ampt Infiltration Parameters

Soil texture class	Porosity ϕ	Wetting front soil suction head S_f, cm	Saturated hydraulic conductivity K_s,* cm/h
Sand	0.437 (0.374–0.500)	4.95 (0.97–25.36)	23.56
Loamy sand	0.437 (0.363–0.506)	6.13 (1.35–27.94)	5.98
Sandy loam	0.453 (0.351–0.555)	11.01 (2.67–45.47)	2.18
Loam	0.463 (0.375–0.551)	8.89 (1.33–59.38)	1.32
Silt loam	0.501 (0.420–0.582)	16.68 (2.92–95.39)	0.68
Sandy clay loam	0.398 (0.332–0.464)	21.85 (4.42–108.0)	0.30
Clay loam	0.464 (0.409–0.519)	20.88 (4.79–91.10)	0.20
Silty clay loam	0.471 (0.418–0.524)	27.30 (5.67–131.50)	0.20
Sandy clay	0.430 (0.370–0.490)	23.90 (4.08–140.2)	0.12
Silty clay	0.479 (0.425–0.533)	29.22 (6.13–139.4)	0.10
Clay	0.475 (0.427–0.523)	31.63 (6.39–156.5)	0.06

Source: Rawls, W.J., L.R. Ahuja, D.L. Brakensiek, and A. Shirmohammadi, (1993). "Infiltration and soil water movement," Chapter 5 in Handbook of Hydrology McGraw-Hill.

Climate change adjustment factor

- From literature review: a range of different estimates of future changes to precipitation extremes as a result of climate change.
- Model the climate change adjustment factor using a triangular probability density function (pdf) having a lower bound of +5%, an upper bound of +30%, and a mode at +20%.



Probability Density Function for Climate Change Adjustment Factor

Reach Routing / Time of Concentration

- Reach Routing:
  - Reach routing accounts for the effects of reach storage on the runoff hydrographs as the flood flow moves through a reach.
  - The Muskingum-Cunge (M-C) method is a more theoretically detailed routing method.
  - Uses physical characteristics of the reach (reach length, slope, Manning’s n and cross section shape) rather than empirical approaches.
  - Manning’s n is treated probabilistic (epistemic uncertainty).

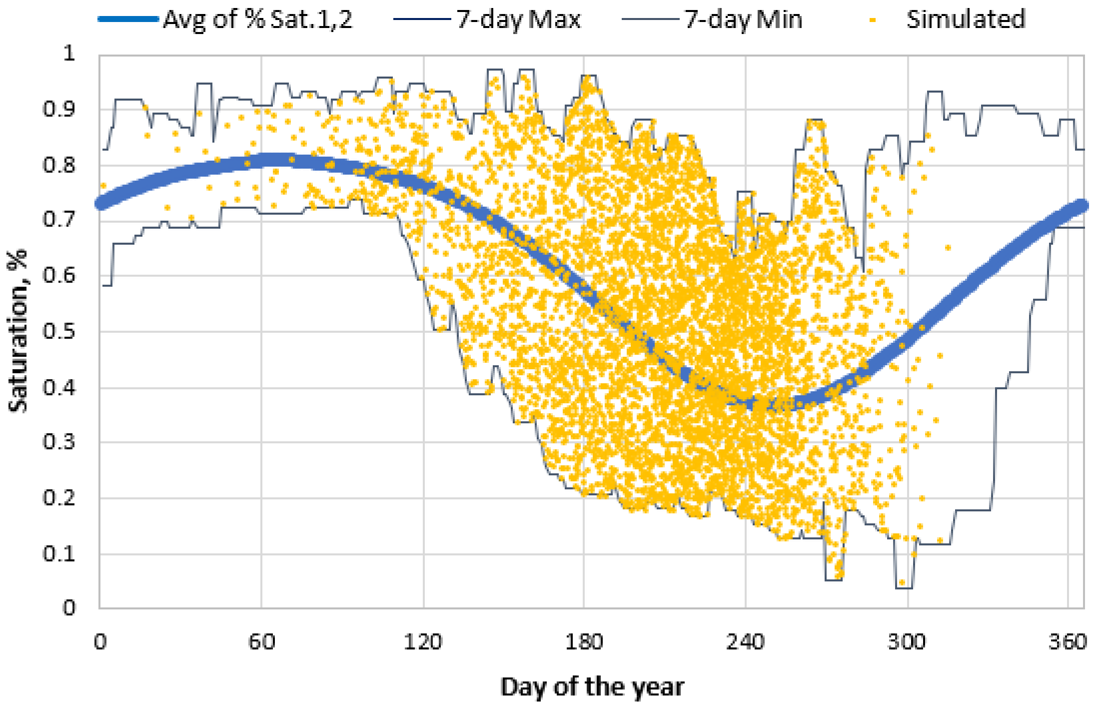
- Time of Concentration:
  - SCS unit hydrograph method is used.
  - Primary uncertainty is in the sheet flow portion:
    - Length of the sheet flow.
    - Sheet flow Manning’s n, (different from Manning’s n in M-C routing).
    - 2-year, 24-hour rainfall (climate change factor is incorporated).
  - These three parameters are varied within a certain range.
  - A range of minimum/maximum time of concentration is generated for each sub-basin.
  - Part of epistemic uncertainty (sample by LHS).

Antecedent Moisture Conditions

- Soil water content measurements at two depths (5 cm and 10 cm) from a nearby station, were converted to relative salutation with the following equation:

$$S_i = \frac{\theta_i - \theta_r}{\phi - \theta_r}$$

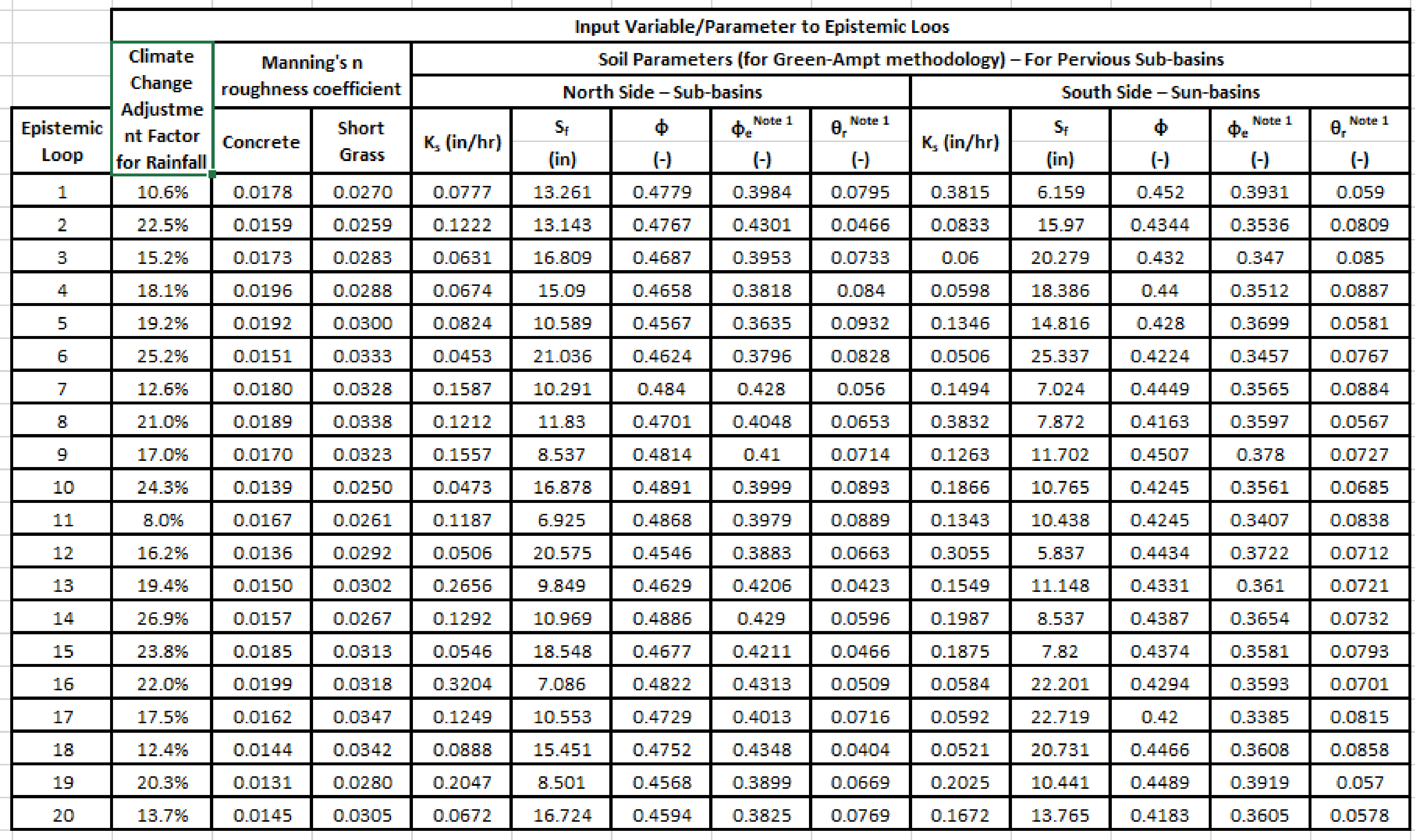
where, S_i = relative saturation, θ_i = initial moisture content, θ_r = residual moisture content, ϕ = total porosity of soil



- 5,000 simulated saturation values, S_i, distributed based on the seasonality of occurrence of heavy rainfall and uniform probability distribution of saturation.
- Initial soil moisture content for each storm (note that θ_r = residual moisture content and ϕ = total porosity of soil have an epistemic uncertainty):

$$\theta_i = \theta_r + S_i(\phi - \theta_r)$$

Summary of Inputs with Epistemic Uncertainty

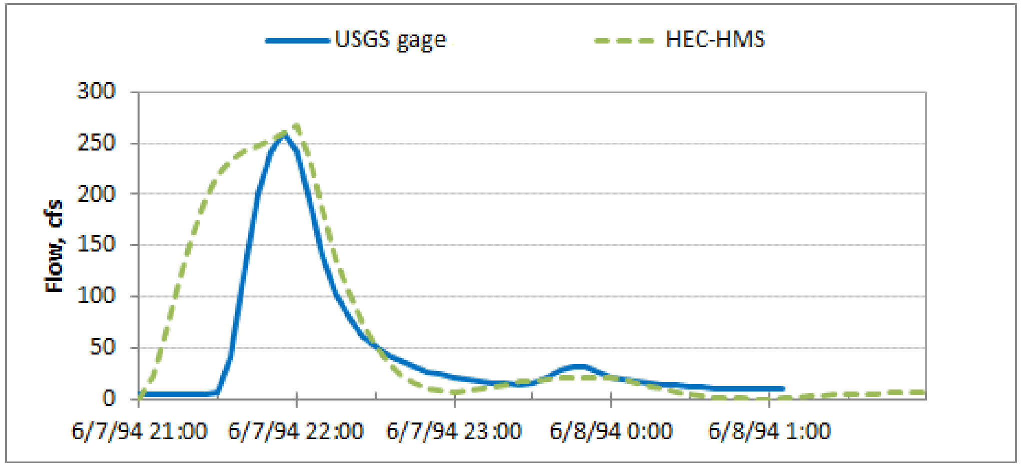


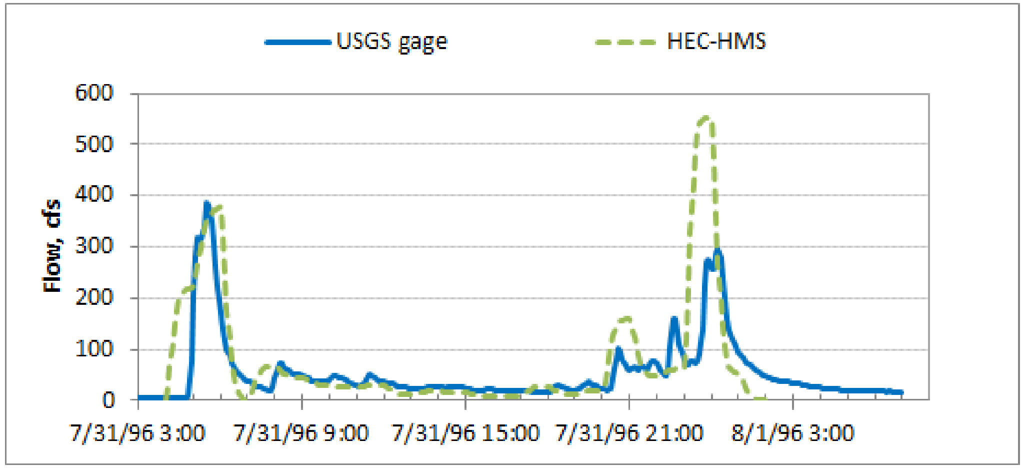
	Input Variable/Parameter to Epistemic Loos													
	Climate Change Adjustment Factor for Rainfall	Manning's n roughness coefficient		Soil Parameters (for Green-Ampt methodology) – For Pervious Sub-basins										
				North Side – Sub-basins					South Side – Sun-basins					
Epistemic Loop		Concrete	Short Grass	K_s (in/hr)	S_f (in)	ϕ (-)	$\phi_e^{\text{Note 1}}$ (-)	$\theta_r^{\text{Note 1}}$ (-)	K_s (in/hr)	S_f (in)	ϕ (-)	$\phi_e^{\text{Note 1}}$ (-)	$\theta_r^{\text{Note 1}}$ (-)
1	10.6%	0.0178	0.0270	0.0777	13.261	0.4779	0.3984	0.0795	0.3815	6.159	0.452	0.3931	0.059
2	22.5%	0.0159	0.0259	0.1222	13.143	0.4767	0.4301	0.0466	0.0833	15.97	0.4344	0.3536	0.0809
3	15.2%	0.0173	0.0283	0.0631	16.809	0.4687	0.3953	0.0733	0.06	20.279	0.432	0.347	0.085
4	18.1%	0.0196	0.0288	0.0674	15.09	0.4658	0.3818	0.084	0.0598	18.386	0.44	0.3512	0.0887
5	19.2%	0.0192	0.0300	0.0824	10.589	0.4567	0.3635	0.0932	0.1346	14.816	0.428	0.3699	0.0581
6	25.2%	0.0151	0.0333	0.0453	21.036	0.4624	0.3796	0.0828	0.0506	25.337	0.4224	0.3457	0.0767
7	12.6%	0.0180	0.0328	0.1587	10.291	0.484	0.428	0.056	0.1494	7.024	0.4449	0.3565	0.0884
8	21.0%	0.0189	0.0338	0.1212	11.83	0.4701	0.4048	0.0653	0.3832	7.872	0.4163	0.3597	0.0567
9	17.0%	0.0170	0.0323	0.1557	8.537	0.4814	0.41	0.0714	0.1263	11.702	0.4507	0.378	0.0727
10	24.3%	0.0139	0.0250	0.0473	16.878	0.4891	0.3999	0.0893	0.1866	10.765	0.4245	0.3561	0.0685
11	8.0%	0.0167	0.0261	0.1187	6.925	0.4868	0.3979	0.0889	0.1343	10.438	0.4245	0.3407	0.0838
12	16.2%	0.0136	0.0292	0.0506	20.575	0.4546	0.3883	0.0663	0.3055	5.837	0.4434	0.3722	0.0712
13	19.4%	0.0150	0.0302	0.2656	9.849	0.4629	0.4206	0.0423	0.1549	11.148	0.4331	0.361	0.0721
14	26.9%	0.0157	0.0267	0.1292	10.969	0.4886	0.429	0.0596	0.1987	8.537	0.4387	0.3654	0.0732
15	23.8%	0.0185	0.0313	0.0546	18.548	0.4677	0.4211	0.0466	0.1875	7.82	0.4374	0.3581	0.0793
16	22.0%	0.0199	0.0318	0.3204	7.086	0.4822	0.4313	0.0509	0.0584	22.201	0.4294	0.3593	0.0701
17	17.5%	0.0162	0.0347	0.1249	10.553	0.4729	0.4013	0.0716	0.0592	22.719	0.42	0.3385	0.0815
18	12.4%	0.0144	0.0342	0.0888	15.451	0.4752	0.4348	0.0404	0.0521	20.731	0.4466	0.3608	0.0858
19	20.3%	0.0131	0.0280	0.2047	8.501	0.4568	0.3899	0.0669	0.2025	10.441	0.4489	0.3919	0.057
20	13.7%	0.0145	0.0305	0.0672	16.724	0.4594	0.3825	0.0769	0.1672	13.765	0.4183	0.3605	0.0578

- Time of concentration not shown (different for each of the sub-basins)

HEC-HMS Model – Observed Events Performance

- Observed rainfall events are used for the verification of the HEC-HMS model
- Historical USGS gaging station within the study area is used for the observed events.
- For input parameters, the expected values (averages) are used.
- Buried stormwater drains, culverts, and passages beneath bridges, are not included in the HEC-HMS model (only overland flow).
- Not a calibration. To demonstrate the performance of model with observed events.





- Model results are reasonable compared to the observed events

HEC-HMS Model

- HEC-HMS 4.1 is used to perform the 100,000 simulations.
- HEC-HMS uses text files for reading input variables, for where to save results etc.
- Fortran codes where use to create the text files.
- Results are saved in *.dss files.
- Python script is used to extract the peak discharge of each hydrologic element for each simulation.

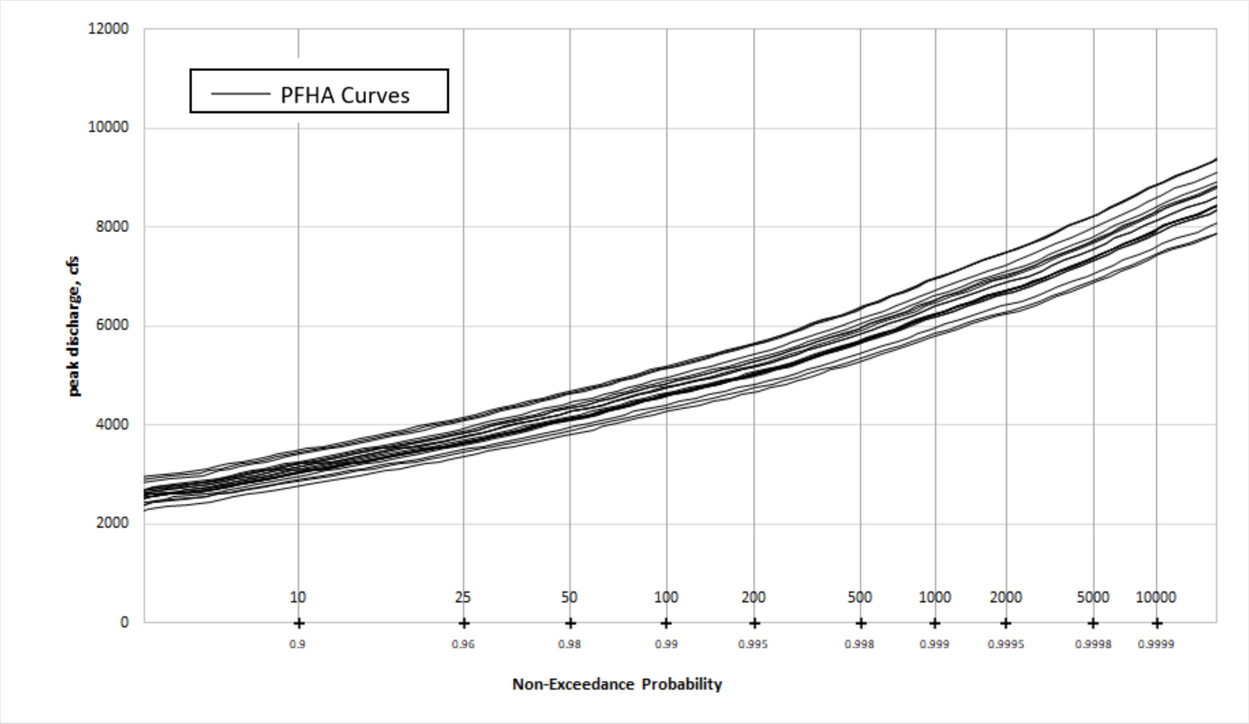
Post Processing

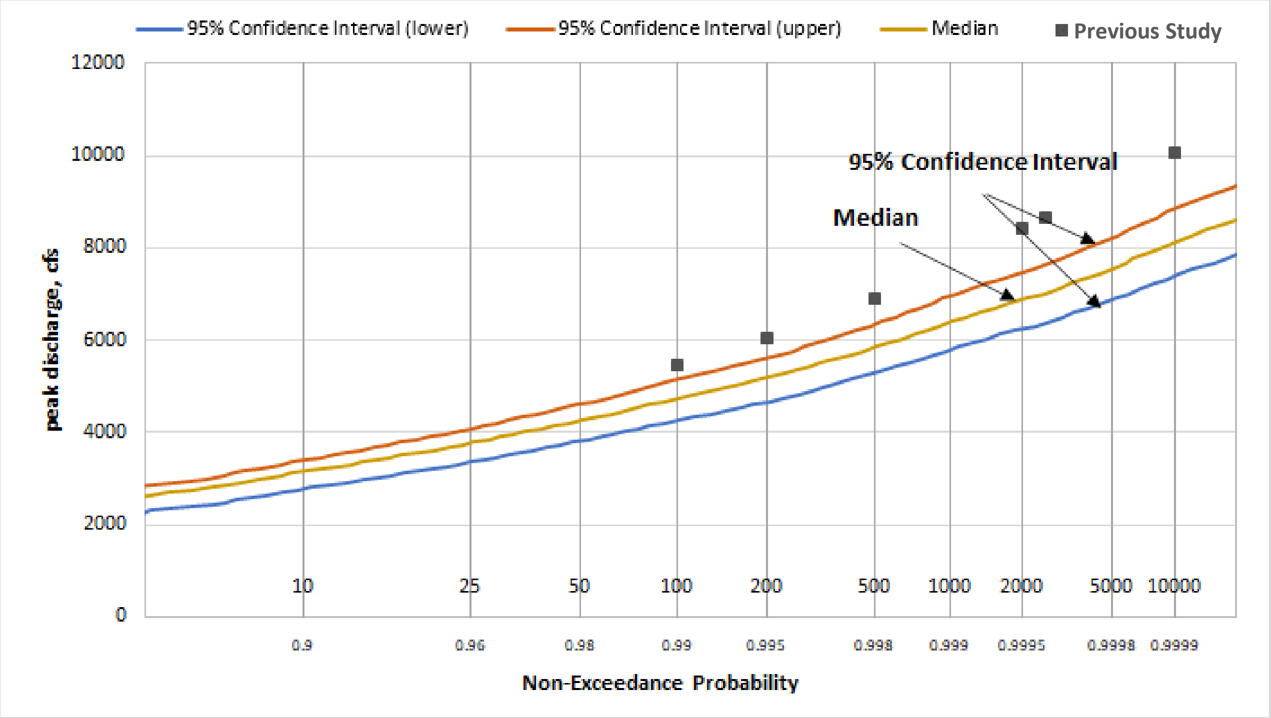
- For one epistemic loop, 5000 peak discharges, *Q*, are estimated for a location of interest.
- Total probability theorem is used to yield expected probability estimates of the flood frequency curve.
- The expected probability that a peak discharge *Q* exceeds a particular flow value *q*, is calculated from the total probability theorem as follows:

$$p(Q > q) = \sum_{i} p\left[Q > q \middle| R_i\right] * p[R_i]$$

- where *i* is the number of the stratified probability interval (50 is the total number of intervals in the current study), $p[R_i]$ represents the probability that the design storm occurs within the interval *i*.

Results – at downstream end of watershed





- Reduction of the peak discharges compared to previous study at the downstream end is in the order of 20% (2,000-yr return period).

Next step – Estimate Flood Levels

- Extract the peak discharges at different return periods (i.e. 10-, 100-, 200-, 1000-, 2000-, 5000-yr).
- 20 epistemic loops with HEC-RAS model and the extracted peak discharges.
- Additional probabilistic input variable: Manning’s n roughness coefficient.
- Use Steady State to complete runs.
- Extract flood levels from results.
- Develop the Flood Level Hazard Curves at buildings of interest with use of a plotting position (i.e Weibull).
- Example of Flood Level Hazard Curve from previous study

Flood Level Hazard Curve

Summary & Conclusions

- Development of a Probabilistic Flood Hazzard Assessment for a watershed.
- Epistemic, aleatoric uncertainty of input variables:
  - LHS sampling for variables with epistemic uncertainty.
  - Stratified sampling for variables with aleatoric uncertainty.
- Different components of the hydrologic model:
  - Loss method: Green-Ampt
  - Reach Routing method: Muskingum-Cunge
  - Rainfall-Runoff model: SCS Unit Hydrograph
  - Climate Change Adjustment Factor for Rainfall
  - Antecedent Moisture Conditions
- Performing the simulations:
  - Outer loop for epistemic uncertainty
  - Inner loop for aleatoric uncertainty

Summary & Conclusions (cont.)

- Tested performance of model with observed events (reasonable results).
- Development/execution of HEC-HMS model for 100,000 simulations.
- Post Processing of peak discharges: Total probability theorem is used to develop flood hazards curves.
- Reduction of the peak discharges compared to previous study at the downstream end, in the order of 20% (2,000-yr return period) due to additional probabilistic elements and more realistic reach routing.
- Next Step: Develop the Flood Level Hazard Curves at locations of interest with use of HEC-RAS.

- Effort/time needed for a PFHA vs Deterministic Assessment: end result more realistic with PFHA.