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Vinh N. Dang & Calvin Whealton :: Risk & Human Reliability Group :: Paul Scherrer Institute

Extreme Flood Hazard Assessment

Overview of a probabilistic methodology and its implementation for a Swiss river system

5th Probabilistic Flood Hazard Assessment Research Workshop
19-21 February 2020. USNRC, Rockville, MD

Outline

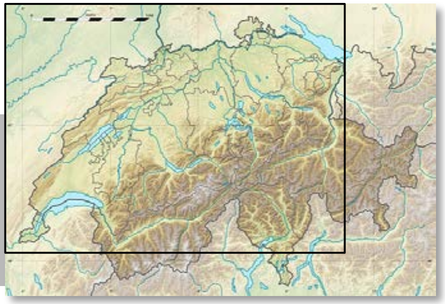
- Background & objectives
- Methodology
  - Hydrology
  - Structures & natural processes
  - Hydraulics
  - Probabilistic synthesis
- Hazard curves and uncertainties
- Findings
- Summary and outlook

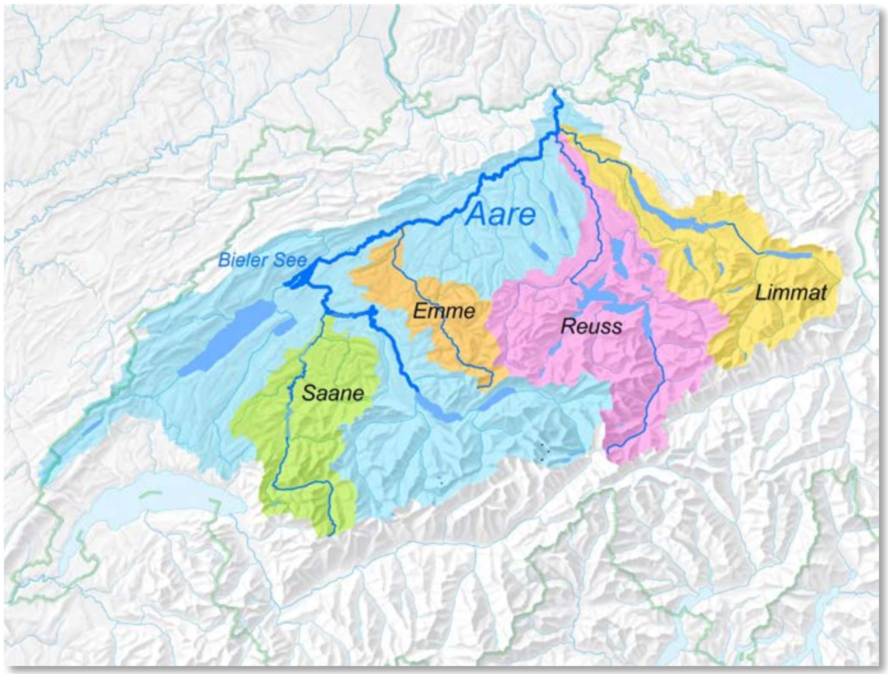
Acknowledgement: Project EXAR is funded by the Swiss Federal Office of the Environment (BAFU), Federal Office of Energy (BFE), Swiss Federal Nuclear Safety Inspectorate (ENSI), Federal Office for Civil Protection (BABS), and the Federal Office of Meteorology and Climatology (MeteoSwiss).

The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the listed organizations.

Aare River Watershed

source: Eric Gaba and user NordNordWest

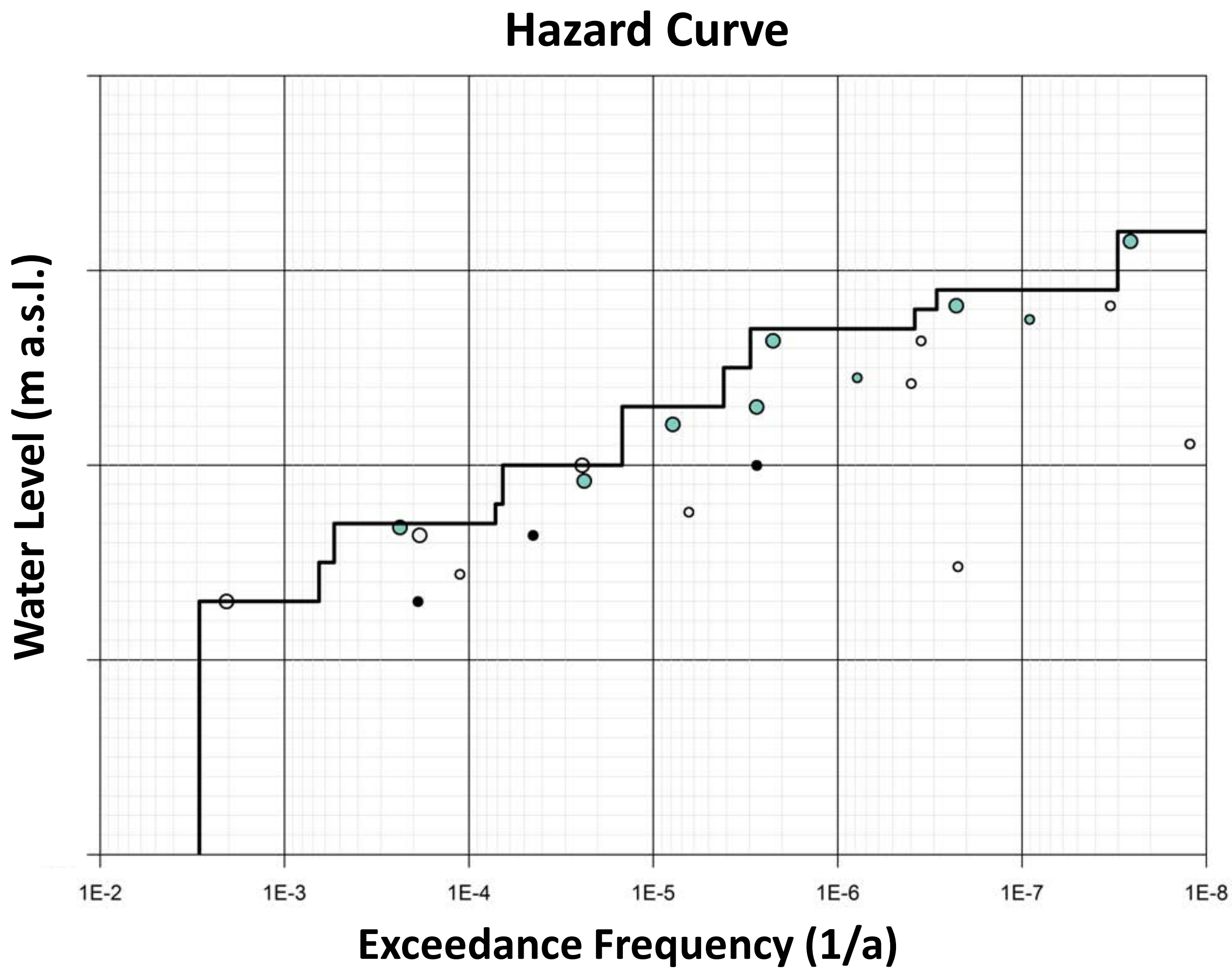




- Develop consistent methodology for probabilistic flood hazard assessment (PFHA)
  - Develop hydrological dataset for PFHA
  - Hazard assessment for selected sites on Aare
    - Frequency range of 1E-3 to 1E-7/a
    - Including conditional events

- The Aare catchment
  - 295 km (183 mi) to Rhine (at Koblenz, CH)
  - Catchment area 17’675 km² (6’870 sq. mi.)
    - 43% of surface area of Switzerland
    - High alpine to farmland and urban
    - 4 major subcatchments
    - Highly engineered system

Hazard Curve



Hazard measure

- ➢ Elevation head (in m.a.s.l.)

- o Total head
- o Velocity
- o Shear stress

Input: triplets (scenario, frequency, hazard level)

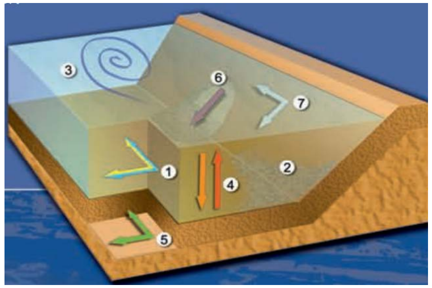
Methodology Overview

Weather & Hydrology

- Weather
- Runoff
- Routing

289k years,
Q-hourly, at all points

Hydraulics



stage-discharge
time of failure

stage(scenarios)

Structures & Processes

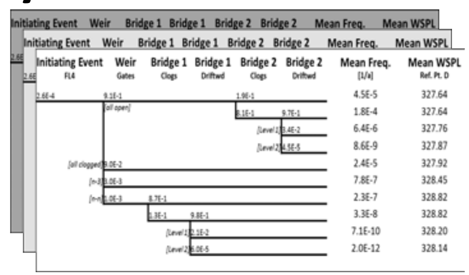
Structure	Relevancy
Weir	None
Bridge	Clogging, collapse
Levee	Overtopping

hazard(scenarios)

scenarios

events,
event probabilities

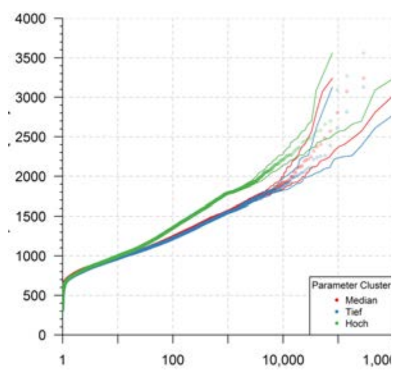
Synthesis & Scenarios



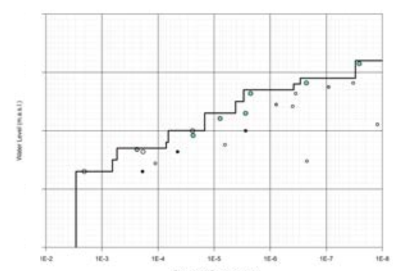
(scenario, frequency, hazard)
triplets

& hydrographs

Discharge-Exceedance

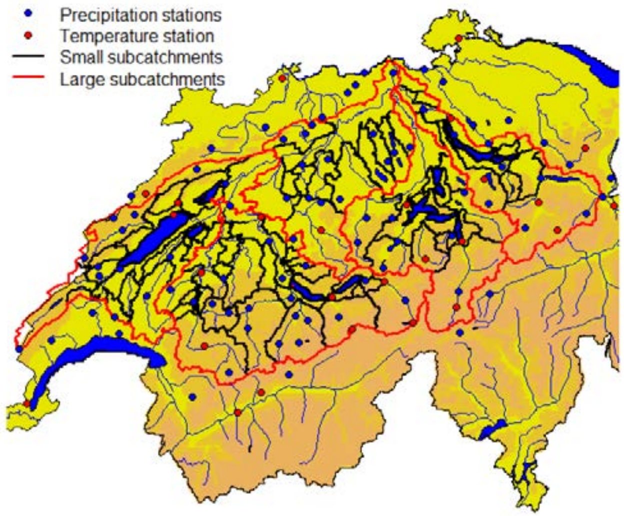


Hazard Curve

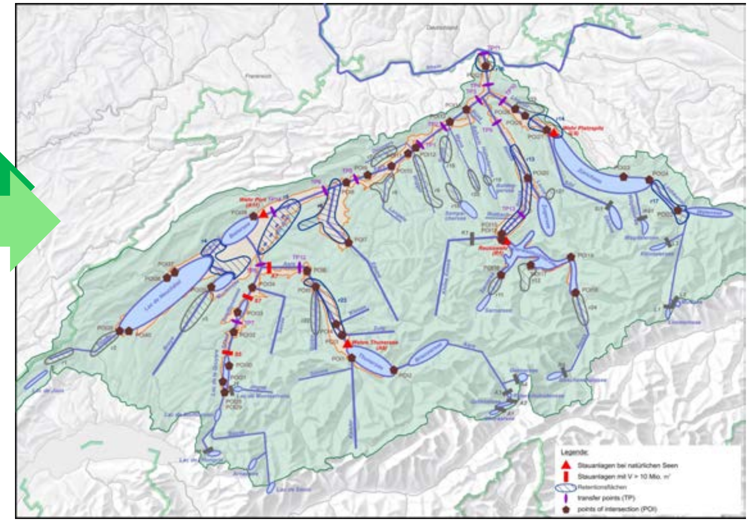


Hydrologic Modeling Chain

Weather & Hydrology
- **Weather**
- **Runoff**
- **Routing**

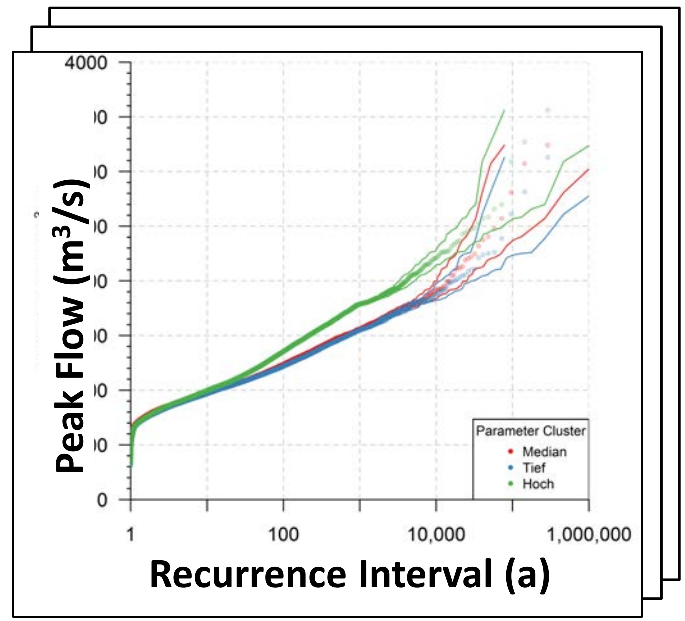


Source: EXAR Detailbericht A, Figure 1



Source: EXAR Phase A Bericht, Fig. 3

Main outputs for next PFHA steps:
- discharge-exceedance curves in the system
- 289,000 years with 3 HBV parameter sets (hourly resolution)



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Hydrologic Modeling Chain

Weather & Hydrology
Weather
Runoff
Routing

Weather **GWEX**: mean average precipitation and temperature (MAP & MAT)

- Precipitation (105 stations) modeled using Extended GPD distribution
- Temperature (26 stations) modeled as MAR(1) process
- Spatially disaggregated to catchments using Thiessen polygons
- Temporally disaggregated from 3-days to 1-hr using meteorological analog

Runoff **HBV**: hourly runoff values for each elementary catchment

- Semi-distributed catchment model
- 89 elementary catchments in the system (40 ungauged)
- Cluster analysis used to define lower, median, and higher simulated floods

Routing **RS Minerve**: hourly flow values at transfer points

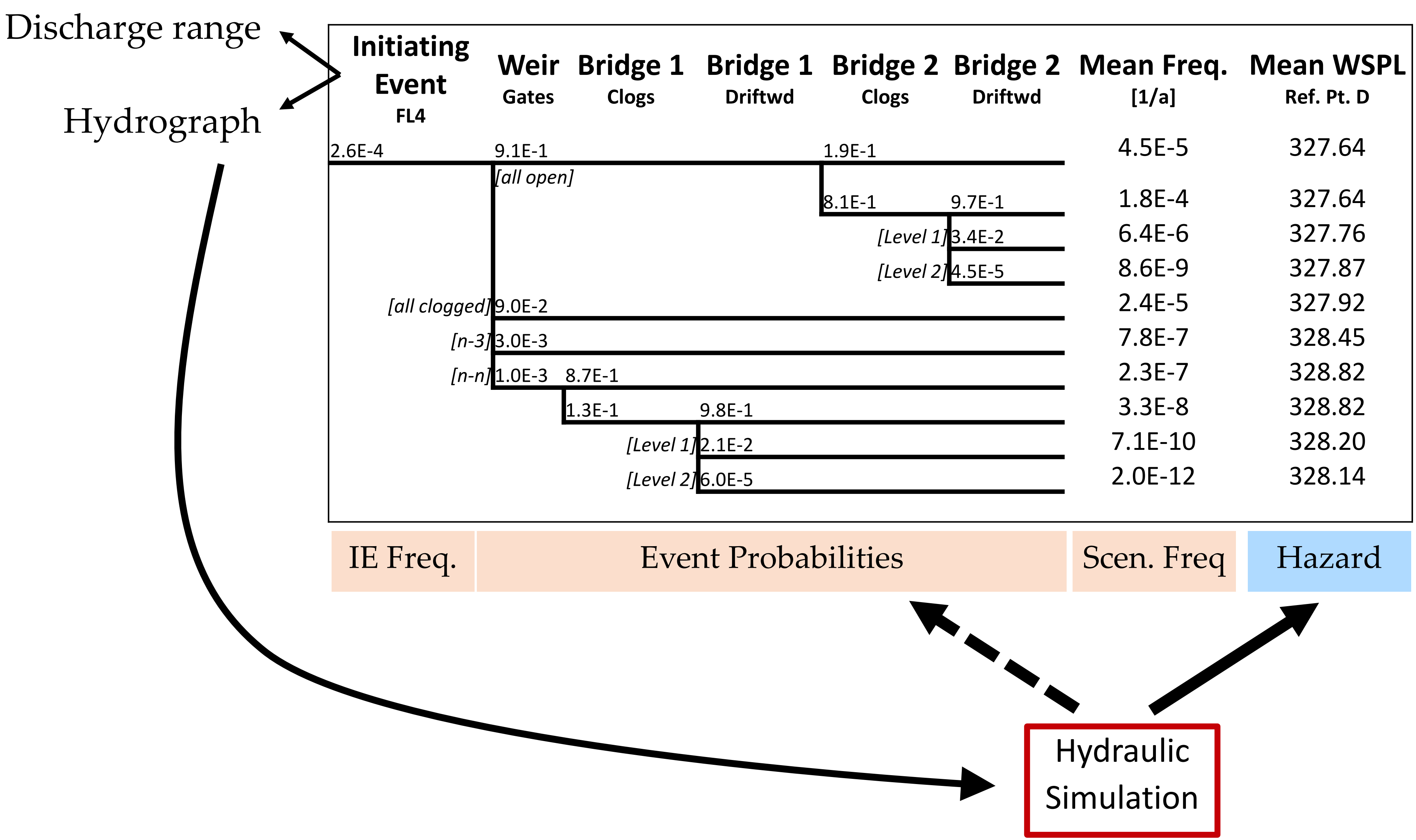
- Aggregated elementary catchment runoff to flow in main tributaries and Aare
- Includes lake regulation
- Calibrated to 2005 flood and validated to 2007 flood (both ~100-yr return period)

Probabilistic Scenario Modeling

scenario,
frequency,
hazard level

	Scenario	
	Initiating event	*Top events*
Hydraulic simulation	**Representative hydrograph**	• **Natural process** • **Structure-related** induced, correlated, independent
Quantification (estimation of probabilities)	**Discharge range frequency**	**Event probabilities**
Basis	Discharge exceedance frequency curve	Fragilities, estimated occurrence, …

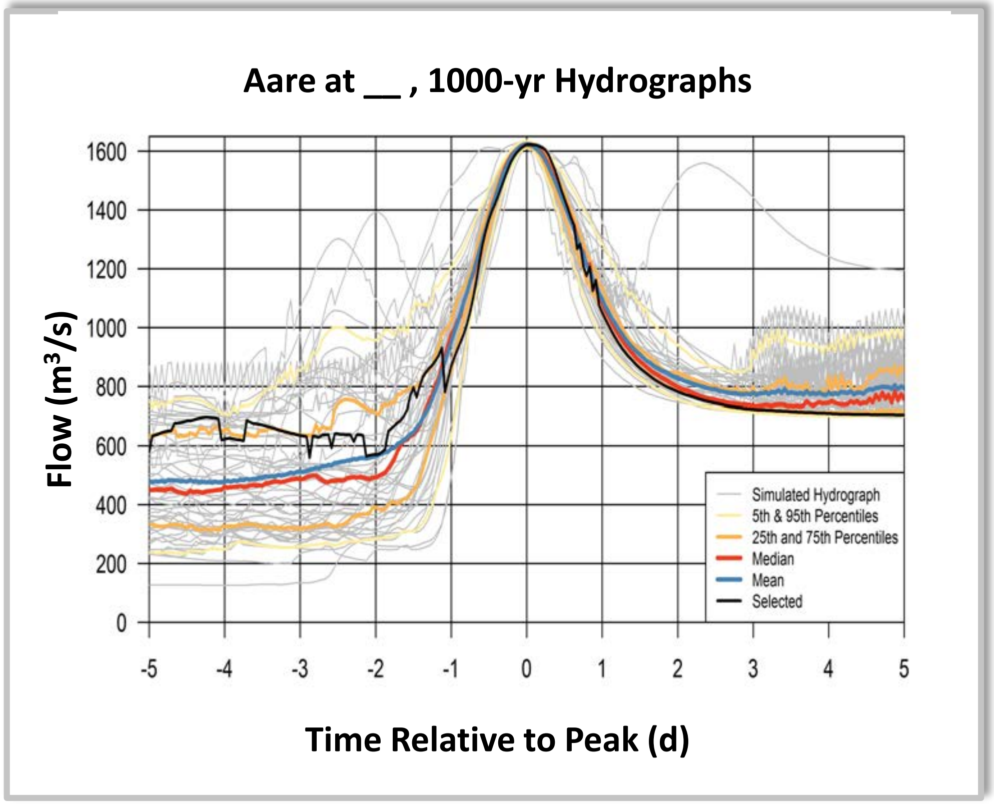
Event Tree



Discharge range
Hydrograph
Initiating Event FL4
Weir Gates
Bridge 1 Clogs
Bridge 1 Driftwd
Bridge 2 Clogs
Bridge 2 Driftwd
Mean Freq. [1/a]
Mean WSPL Ref. Pt. D
2.6E-4
9.1E-1
[all open]
1.9E-1
8.1E-1
9.7E-1
[Level 1] 3.4E-2
[Level 2] 4.5E-5
[all clogged] 9.0E-2
[n-3] 3.0E-3
[n-n] 1.0E-3
8.7E-1
1.3E-1
9.8E-1
[Level 1] 2.1E-2
[Level 2] 6.0E-5
4.5E-5 327.64
1.8E-4 327.64
6.4E-6 327.76
8.6E-9 327.87
2.4E-5 327.92
7.8E-7 328.45
2.3E-7 328.82
3.3E-8 328.82
7.1E-10 328.20
2.0E-12 328.14
IE Freq.
Event Probabilities
Scen. Freq
Hazard
Hydraulic Simulation

Hydrograph selection

- Each initiating event is a discharge range with a frequency.
- To compute the hazard, a hydrograph is needed



➢ Three discharge ranges

Discharge range IE	Freq. [/yr]	Qpeak Fexc [/yr]
FL3	~ 3E-3	1E-3
FL4	~ 3E-4	1E-4
FL5	~ 3E-5	1E-5

➢ More difficult cases: confluence, peak-duration

Structures & Processes

Relevance criteria

1) ability to change downstream frequencies or hydrograph behavior
2) impact on hazard at local assessment site

- Weirs/Dams
  - Waves from collapse
    (Q -> h[reservoir] -> P)
  - Backwater from closed/clogged gates
    (scoping P)

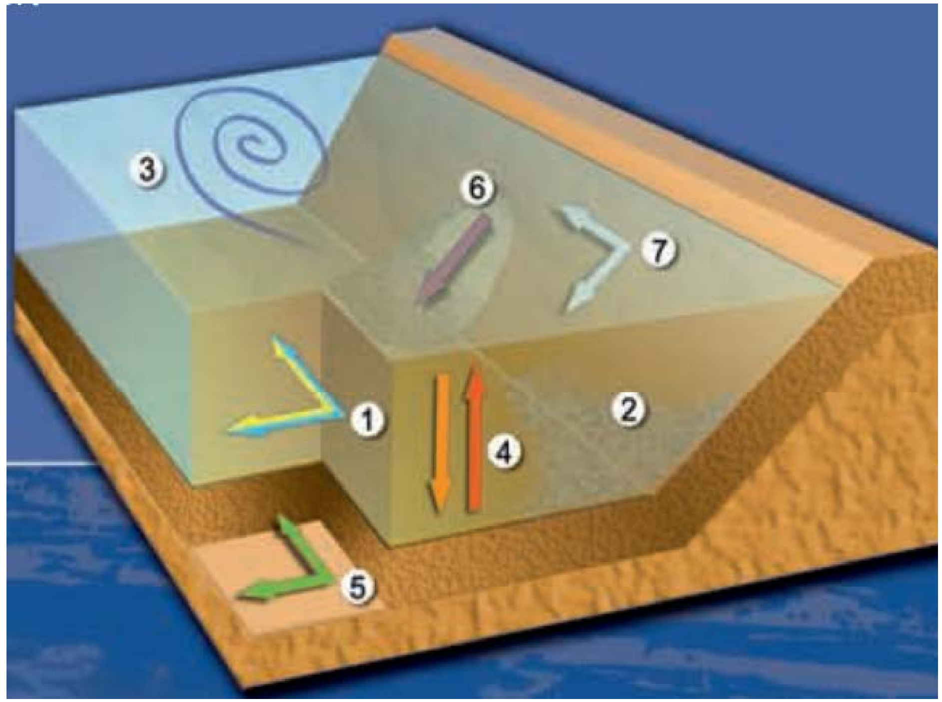
- Levees
  (Q -> h at levee -> P)
  - New flowpaths
  - Retention changing hydrograph timing or peak

- Landslides
  (higher water table -> P)
  - Backwater from channel blockage
  - Local flowpaths

- Driftwood
  (Q -> flow at structure -> P)
  - Backwater
  - Local flowpaths

Hydraulic Simulation

- 2-D model of reach using BASEMENT v3 (https://basement.ethz.ch/)
  - Saint-Venant equations
  - Morphology model
  - Main inputs: DEM and roughness values
- Parameters calibrated using surrogate modeling
- Morphology capabilities used for small set of scenarios
  - bed load transport, aggradation, resuspension



Source: https://basement.ethz.ch/about.html

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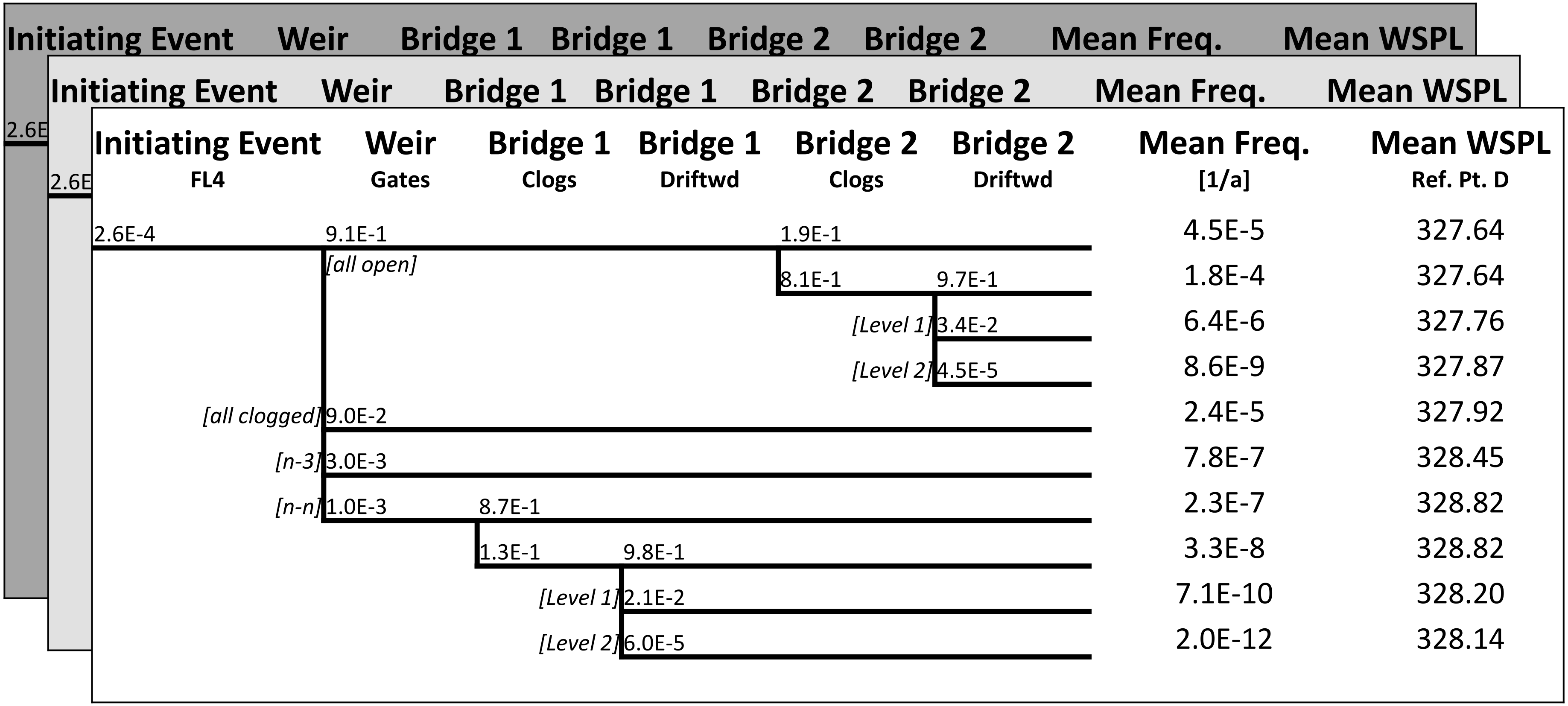
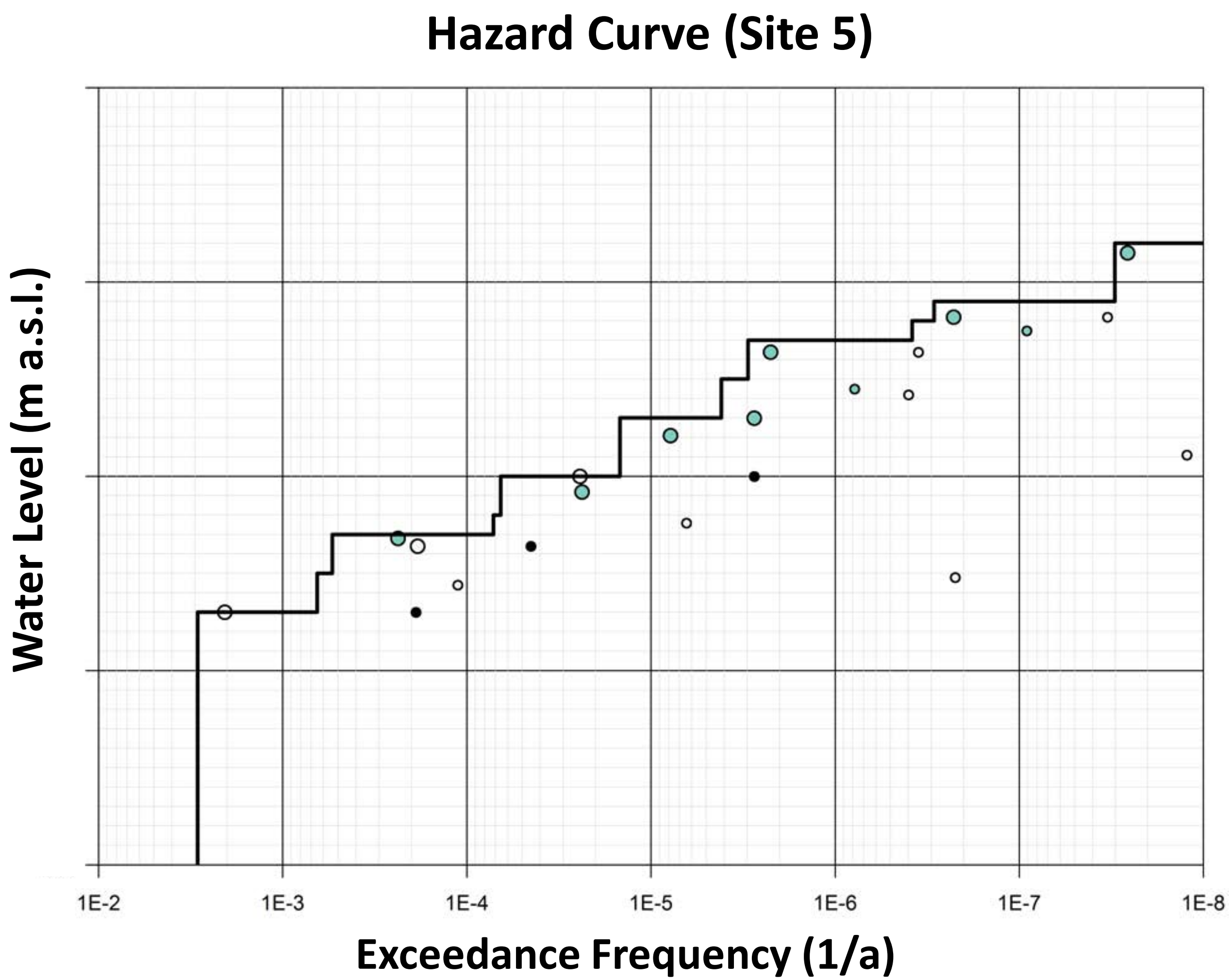
Scenarios to hazard curves…



Hazard Curve

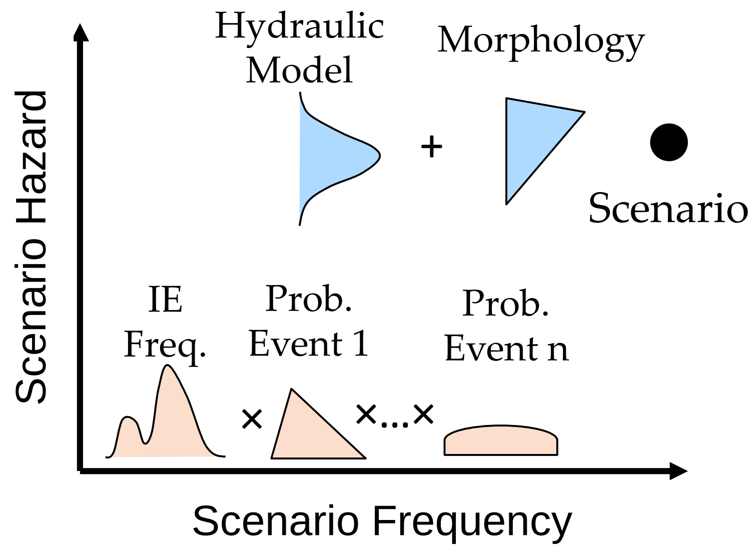
Point estimate hazard curve:

Exceedance plotted from scenario points at (mean frequency, mean hazard value)



Hazard Curve Uncertainty

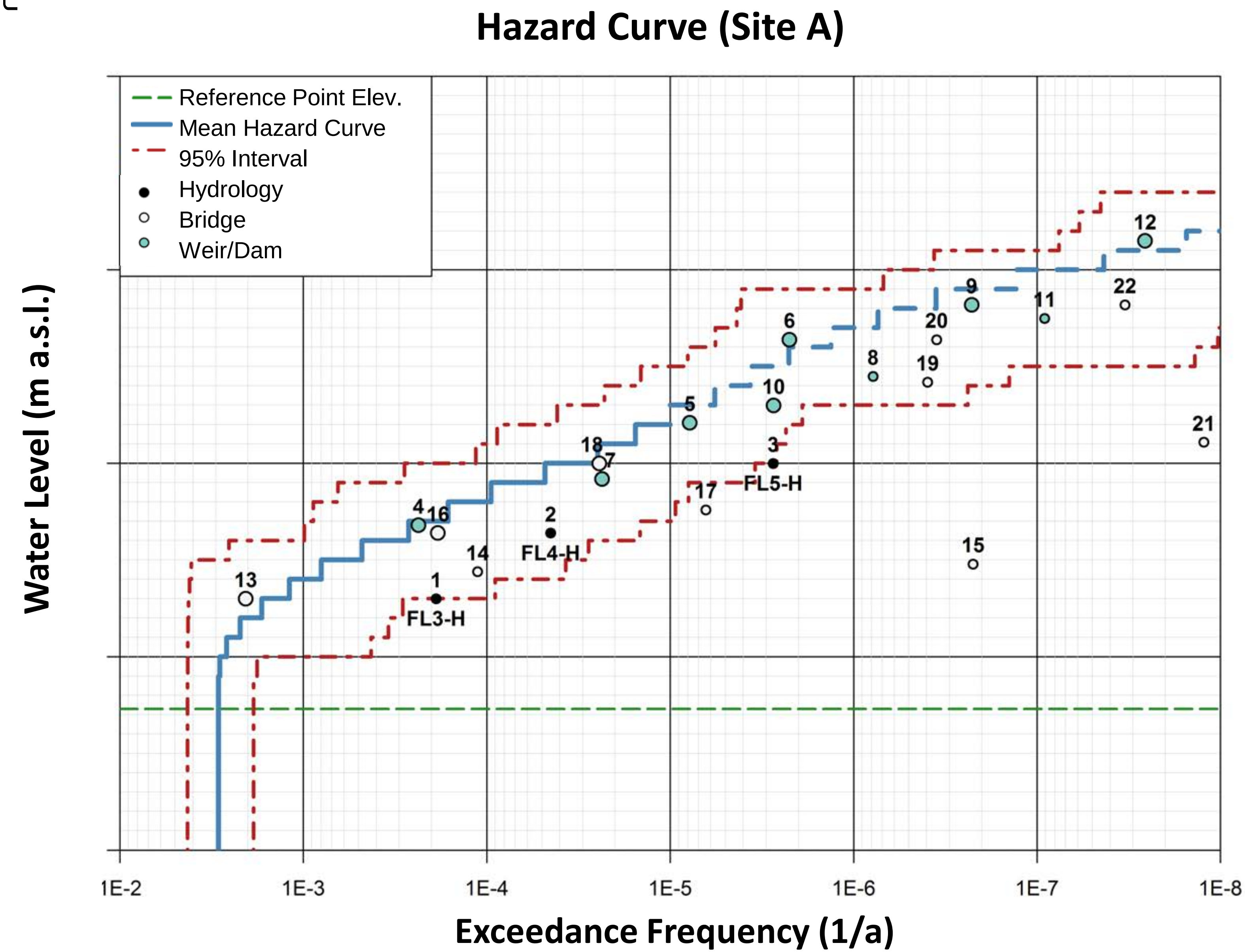
- Uncertainties in frequency space
  - Initiating Event Frequency (HBV parameter set curves)
  - Probabilities (uncertainty of failure models, clogging models, etc.)
- Uncertainties in hazard space
  - Water Levels (water levels from 2-D model and morphology)



➢ Need to transform hazard space uncertainty into frequency space

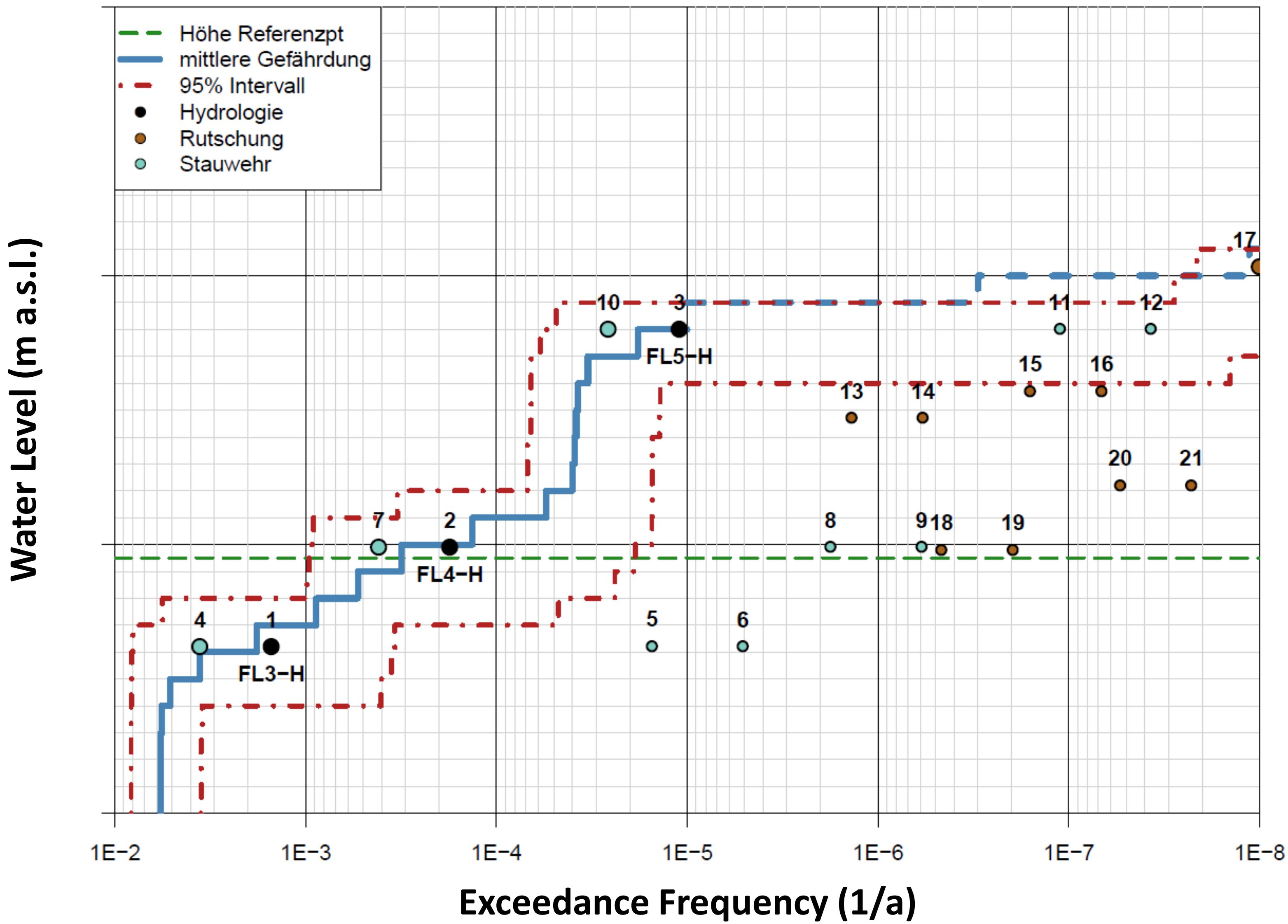
- Monte Carlo approach
  - Each sample of the set of uncertainty distributions => realization of the 3 event trees
  - 5000 samples => 5000 hazard curves
  - Statistics obtained from 5,000 curves : mean curve, frequency quantiles

Hazard Curve: Mean & Envelope from Uncertainty



Hazard Curve: Mean & Envelope from Uncertainty

Hazard Curve (Site B)



Core findings – flood hazard

Key Findings:

- Dominant sources of site hazard "hydrological" or "natural processes + engineered structures"
- Also dependent on frequency range of interest
- Some scenarios and results on hazard below 1E-5/yr but incomplete picture due to lack of credible estimate for 1E-6/yr hydrological flood

Site-specific Findings

- For the assessed sites, levee failures are not dominant
  (and overtopping more important than duration/volume)
- No dominant scenarios with landslides (co-occurrence with flood event is low)
- At multiple sites, driftwood volume and clogging are important contributors
- Flood management failure important to risk (at extreme end of hazard curve) at one site.

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Summary & Outlook

- State-of-the-art models in hydrologic chain, in hydraulics, structural analysis
- Experts in the relevant disciplines periodically reviewed methodology and implementation and provided suggested modifications and verifications
- Interdisciplinarity enhanced verification and plausibility checks throughout project

- Measurement records essential but some difficulties (e.g. representation of extreme floods for calibration, engineering of the catchment)
- Discharge exceedance curves were judged to be plausible
- More hydrological parameter sets recommended to address (HBV) uncertainty better – at lowest frequencies

  Rare/extreme hazard is based on top 0.1% of annual maxima (1E-3/yr, 300 events, 300’000 annual maxima)

- 3 discharge ranges (IEs) sufficient to characterize hazard

Outlook

- o Better characterization driftwood generation and retention, as well as clogging is required
- o Flood management strategy and implementation during extreme floods
  - Modeling
  - Strategy
- o Computational challenge for morphology
- o Scope: Upper catchment floods (mountain regions) ; Rhine

My thanks go to the EXAR Team

WSL

IUB Engineering

GEOTEST GEOLOGEN / INGENIEURE / GEOPHYSIKER / UMWELTFACHLEUTE

Hunziker, Zarn & Partner
Ingenieurbüro für Fluss- und Wasserbau

Universität Zürich[UZH]

u[b] UNIVERSITÄT BERN

Grenoble INP

UNIVERSITÉ Grenoble Alpes

EPFL

ETH zürich

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References and further reading

Andres N., Badoux A., Hegg Ch. (Ed.) 2019: Grundlagen Extremhochwasser Aare. Hauptbericht Projekt EXAR. Methodik und Resultate. (*Bases for the extreme flood hazard on the Aare River. Main report of project EXAR.*) Swiss Federal Institute for Forest, Snow and Landscape Research WSL. (in German, forthcoming.)

EXAR Detailed reports (in English)

- Staudinger, M., Viviroli, D. 2019: Extremhochwasser an der Aare. Detailbericht A Projekt EXAR. Hydrometeorologische Grundlagen [EN: *Hydrometeorological Elements*]. Universität Zürich. Zürich: 382 S.

- Sutter, A., Karrer, T., Whealton, C. 2019: Extremhochwasser an der Aare. Phase B. Detailbericht C: Rutschungen und Schwemmholz [EN: *Landslides and Driftwood*]. ARGE GEOTEST-HZP-IUB. Zollikofen: 85 S. [Landslides and part of Driftwood in English]

- Dang, V.N., Whealton, C. 2019: Extremhochwasser an der Aare. Detailbericht G Projekt EXAR. Ereignisbaumanalyse und Gefährdungskurven [EN: *Event Trees and Hazard Curves*]. Paul Scherrer Institut PSI. 113 S.

[Journal Articles in Preparation]

References and further reading

GWEX

- Evin, G.; Favre, A.C.; Hingray, B. (2018). Stochastic generation of multi-site daily precipitation focusing on extreme events. *Hydrology and Earth System Sciences 22*(1):655-672. doi: 10.5194/hess-22-655-2018

HBV

- Bergström, S. (1992). The HBV Model: Its Structure and Applications,Swedish Meteorological and Hydrological Institute (SMHI), Hydrology,Norrköping, 35 pp.
- Seibert, J.; Vis, M.J.P., 2012: Teaching hydrological modeling with a user-friendly catchment-runoffmodel software package. *Hydrology and Earth System Sciences 16*: 3315-3325. doi:10.5194/hess-16-3315-2012

RS Minerve (www.crealp.ch/fr/accueil/outils-services/logiciels/rs-minerve.html)

- García Hernández, J., Paredes Arquiola, J., Foehn, A., Roquier, B., 2016: RS MINERVE – Technical Manual v2.7. For Software version 2.4.2.0. , Centre de recherche sur l'environnement alpin (CREALP); HydroCosmos SA [manuals in English].

BASEMENT (basement.ethz.ch/about.html)

- Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich (2019). BASEMENT v3 Reference Manual [in English].

PMP/PMF vs. Simulation

- EXAR hydrologic modeling chain is not based on the PMP/PMF concept
- Several studies have computed PMP/PMF for smaller catchments (table below)
- Maximum simulated floods from EXAR are close to PMP/PMF estimates, with larger differences being for the small catchments that have more variable precipitation distributions
- EXAR simulations are not implausible compared to PMP/PMF

River, location	Study	TP or catchment	PMF [m³/s]	Q_{max} GWEX [m³/s]
Aare, Bern	Felder&Weingartner2016,2017, Zischg et al.2018	SSASSB	1296	1250
Emme, Wiler	Felder et al.2019	SSKSSD	1388	1356
Kander, Hondrich	Felder et al. 2019	KanHon	830	1050
Sihl, Zürich	Kienzler et al.2015	SihZue	975	772

EXAR Detailbericht A, Table 4

Felder G. & Rolf Weingartner R. (2016) An approach for the determination of precipitation input for worst-case flood modelling. *Hydrological Sciences Journal*, 61:14, 2600-2609. doi: 10.1080/02626667.2016.1151980

Felder G., Weingartner R. (2017) Assessment of deterministic PMF modelling approaches. *Hydrological Sciences Journal*, 62:10, 1591-1602. doi: 10.1080/02626667.2017.1319065

Felder G., Paquet E., Penot D., Zischg A., Weingartner R. (2019) Consistency of Extreme Flood Estimation Approaches. *J. Hydrol. Eng.*, 24(7): 04019018. doi: 10.1061/(ASCE)HE.1943-5584.0001797

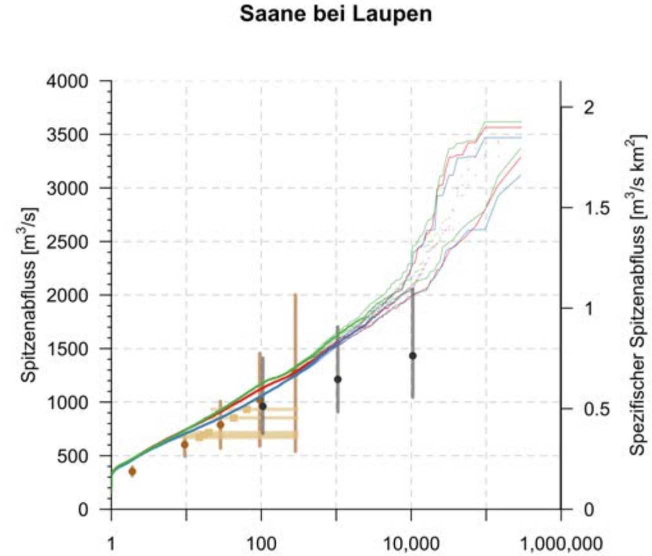
Kienzler P., Andres N., Näf-Huber D., Zappa M. (2015) Herleitung extremer Niederschläge und Hochwasser im Einzugsgebiet des Sihlsees für einen verbesserten Hochwasserschutz der Stadt Zürich. *Hydrologie und Wasserbewirtschaftung HyWa*, 59, 48-58. doi: 10.5675/HyWa_2015,2_1

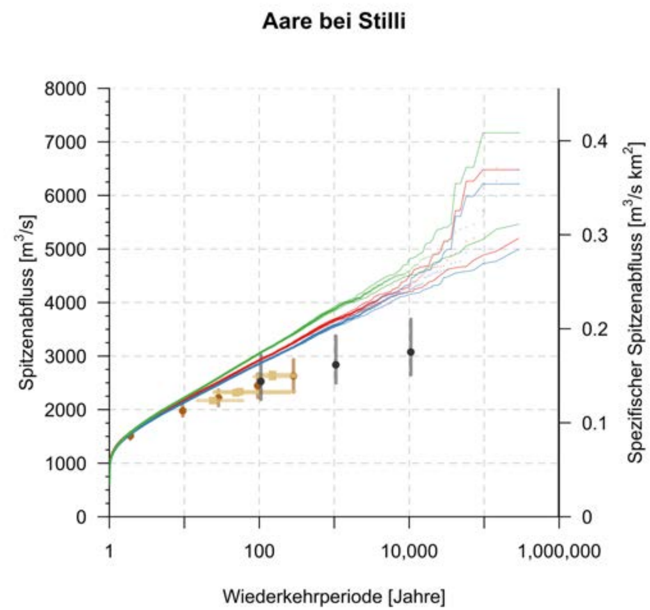
Zischg A. P., Felder G., Weingartner R., Quinn N., Coxon G., Jeffrey N., Freer J., Bates P. (2018) Effects of variability in probable maximum precipitation patterns on flood losses. *Hydrol. Earth Syst. Sci.*, 22, 2759–2773. doi: 10.5194/hess-22-2759-2018

Comparison of Simulation & Gauged Record

- Many transfer points show good agreement between the gauged record, extrapolations from the gauged record, and the simulations within that range
  - Aare above Saane confluence
  - Major Tributaries: Emme, Reuss, Limmat

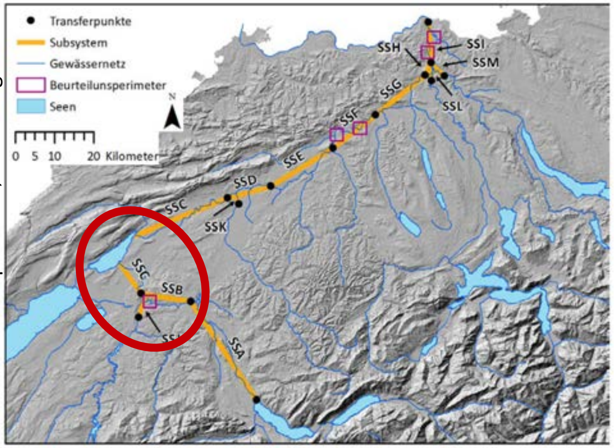
- A few transfer points (Saane Outlet, Aare after Wasserschloss) show markedly higher simulation than extrapolation values (figures right)
  - Superposition is very strong in the extreme events, with over 95% being common
  - Superposition is not typically estimated for single gauge extrapolations





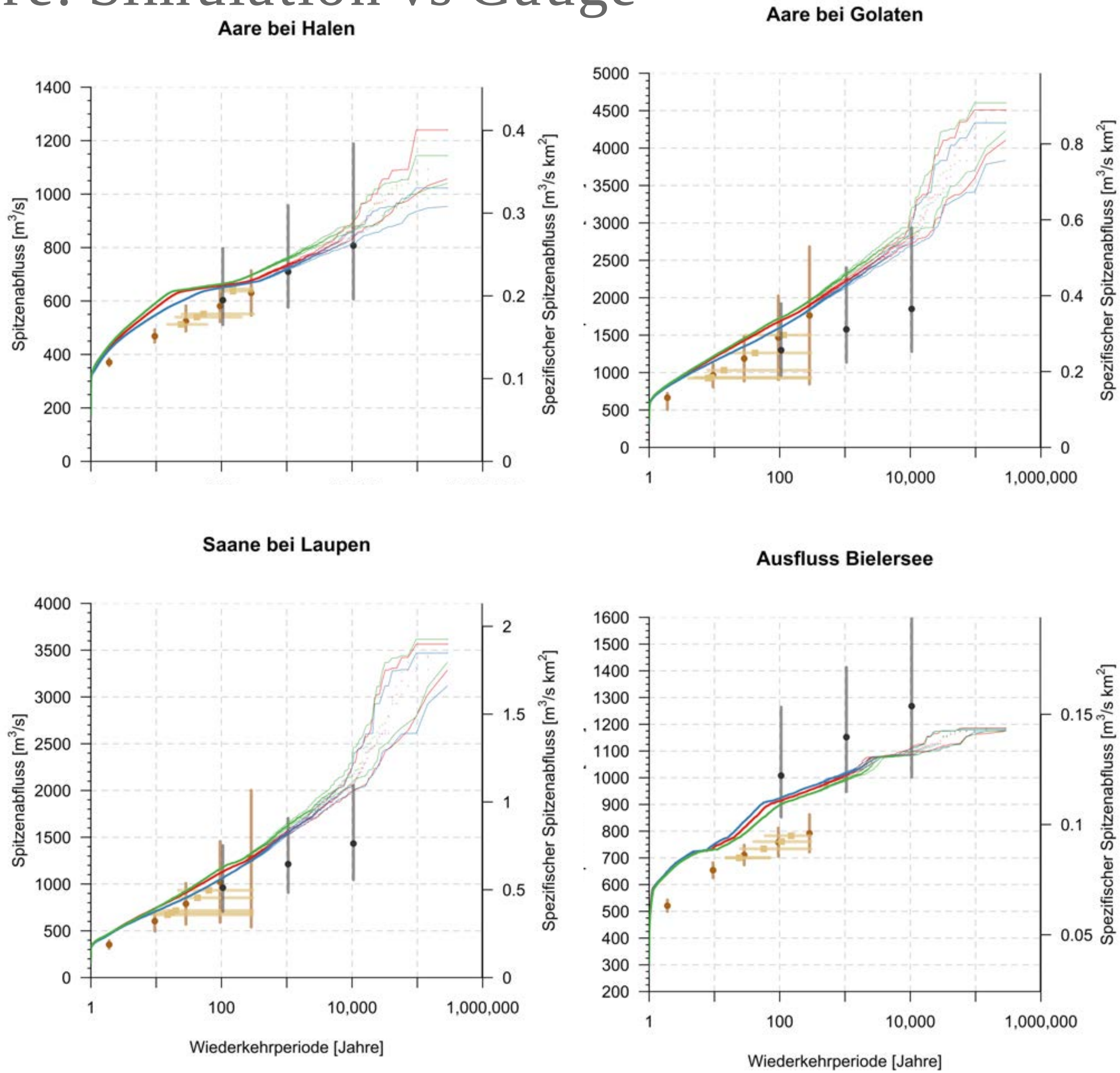
Source: EXAR Detailbericht A, Figure 119

Upper Aare: Simulation vs Gauge



Source: EXAR Hauptbericht, Abbildung 4

- Aare at Halen (SSASSB) is close to EPFL estimate
- Saane (SSJSSB) shows steeper trend than prediction
- Outflow of Bielersee is on low end of EPFL estimate



Source: EXAR Detailbericht A, Figure 119

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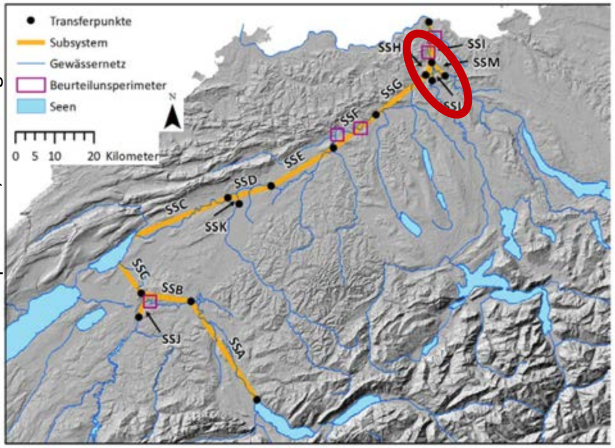
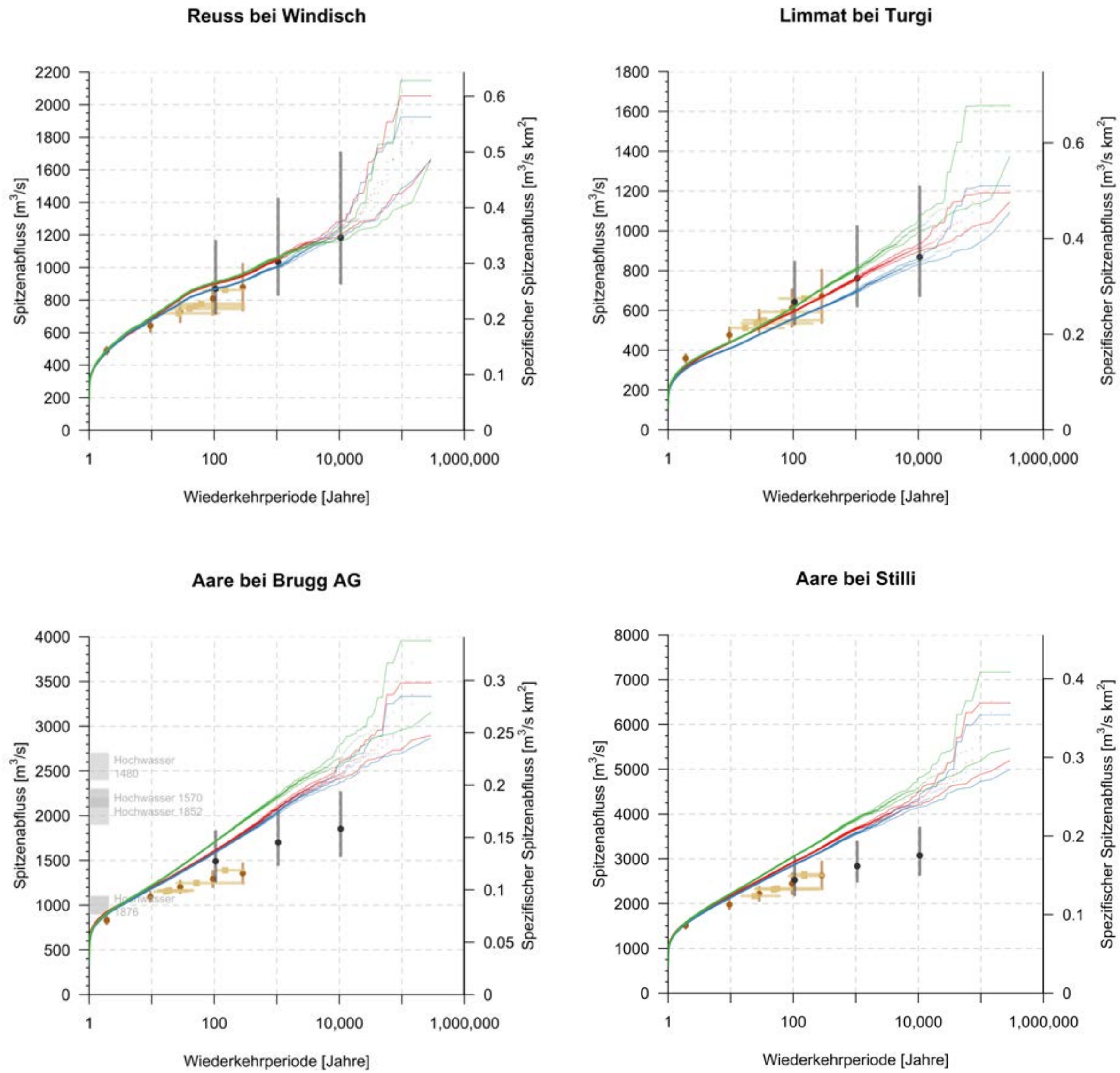
Lower Aare: Simulation vs Discharge

Source: EXAR Hauptbericht, Abbildung 4



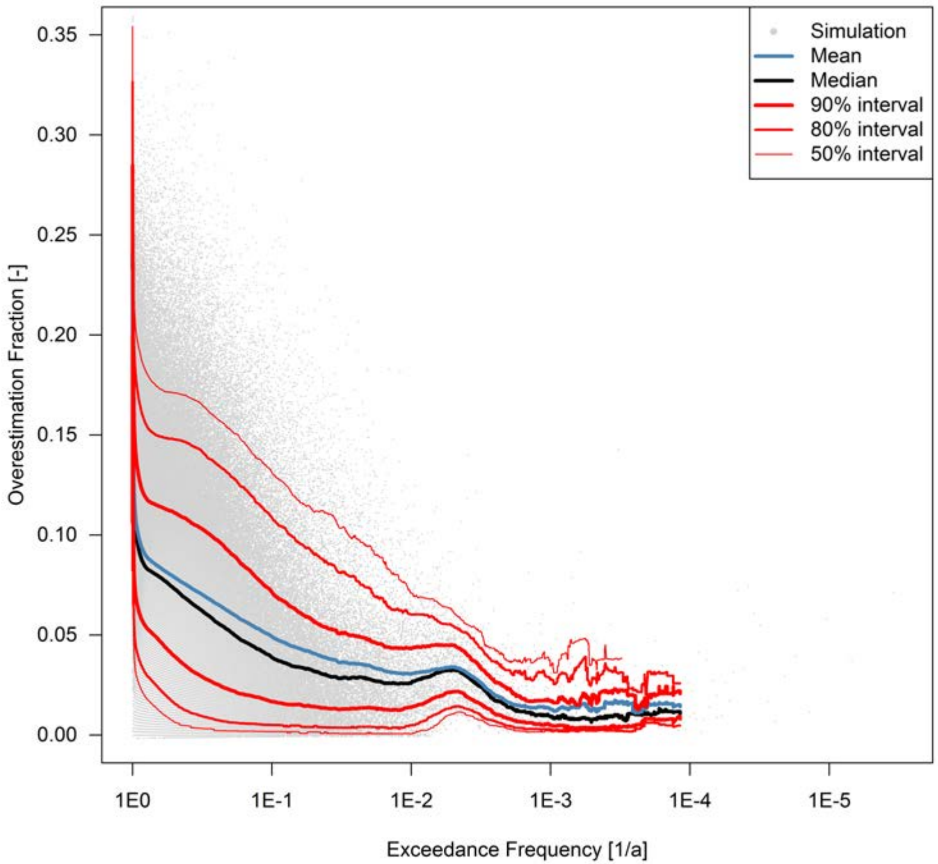


- Reuss and Limmat tributaries very close to estimates
- Aare shows steeper slop, diverges after 100-yr flood
- After confluence, major differences in estimates and simulation
- Analysis shows +95% superposition is common in extreme events

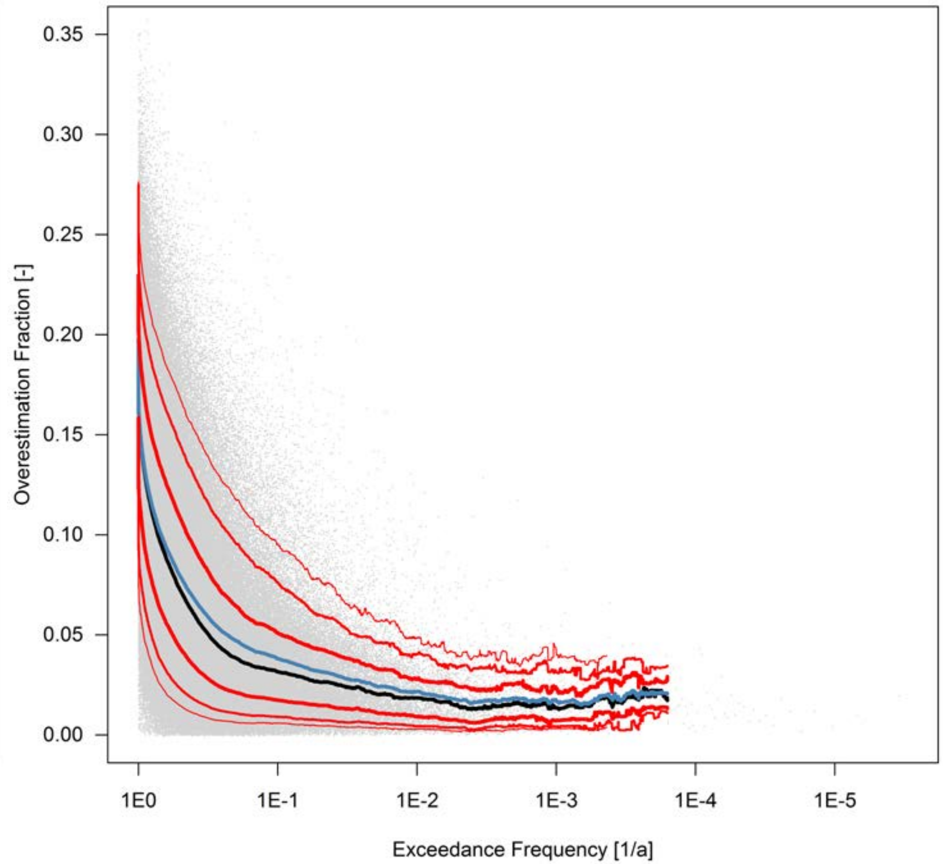
Source: EXAR Detailbericht A, Figure 119

Superposition of Flood Peaks

Aare & Saane Confluence

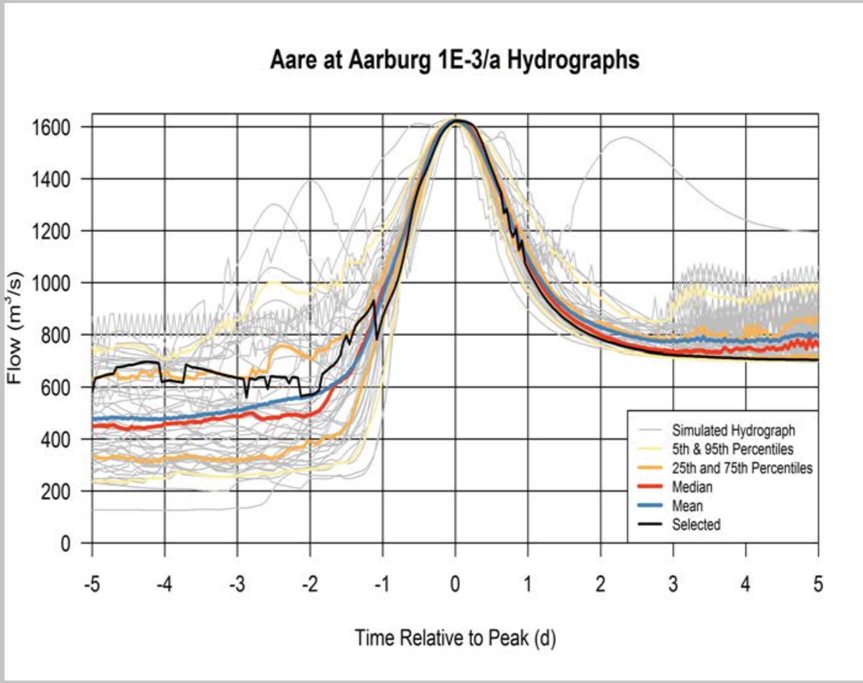


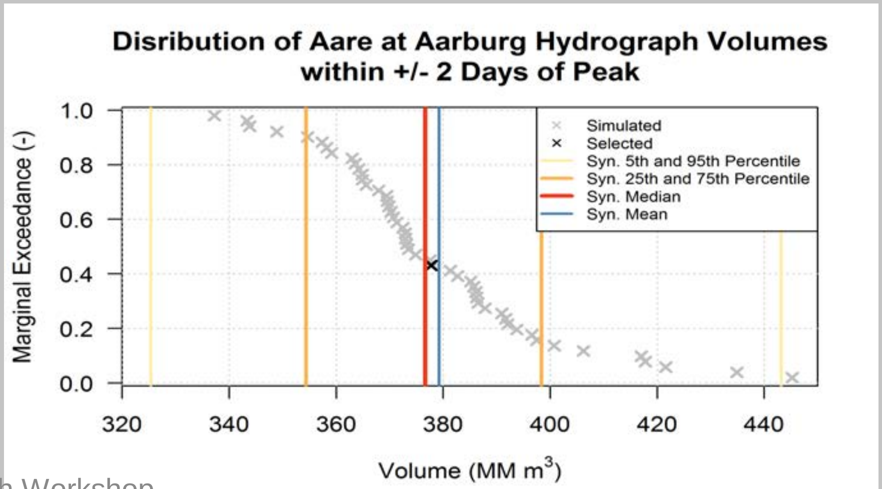
Aare, Reuss & Limmat Confluence



Hydrograph Selection

- Preliminary initiating events chosen to be 1E-3, 1E-4, and 1E-5/a floods (peak flow exceedance criteria)
- Representative or typical hydrographs had to be chosen
  - Project intended to provide best estimate
  - Avoids overly conservative approximations
- Failures and hazard levels dominated by peak flow mechanisms
  - Possible to select hydrograph based on volume, e.g. for levees
  - Analysis showed that most instances of volume/duration failure also peak flow failure





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Driftwood Model

P(clog volume) = P(clog initiates)*P(wood volume)

- P(clog initiates) from Shalko's lab experiments

  depends on flow at site, number of pillars in the channel, distance between water surface and bridge deck, etc

- P(wood volume) determined from the expected range of driftwood volume

  GIS analysis with factors for 30-year and 300-year driftwood volumes used to determine 5th and 95th percentiles of lognormal distribution

Conservative principle applied (Bruttoprinzip)

- Lakes retain all driftwood from upstream
- No retention along the Aare River outside of lakes
- Some retention attributed to tributaries

In event tree model, probability of clogging at downstream structures depends on whether clogging occurred at upstream structures that are in the same event tree

Landslides

General frequency determined using a hazard mapping approach

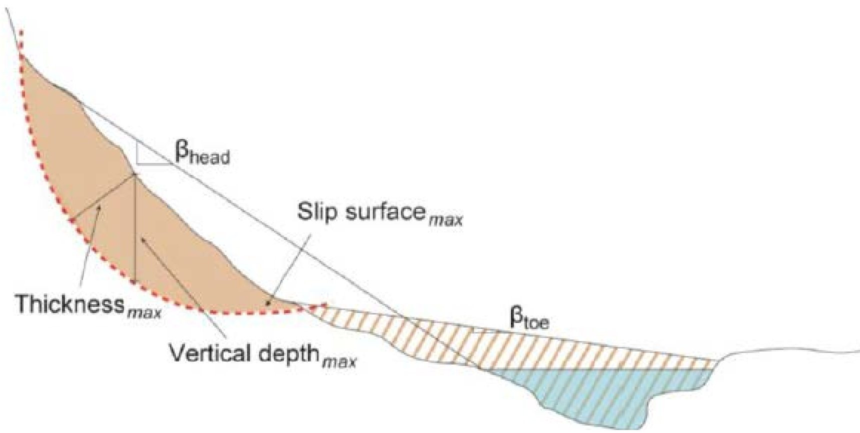
Method of slices with numerical model (Slide2D) for water table (WT) sensitivity

– Hazard mapping frequency assumed WT ~ 13.5 deg

– Elevated WT of 27 deg assumed for EXAR events

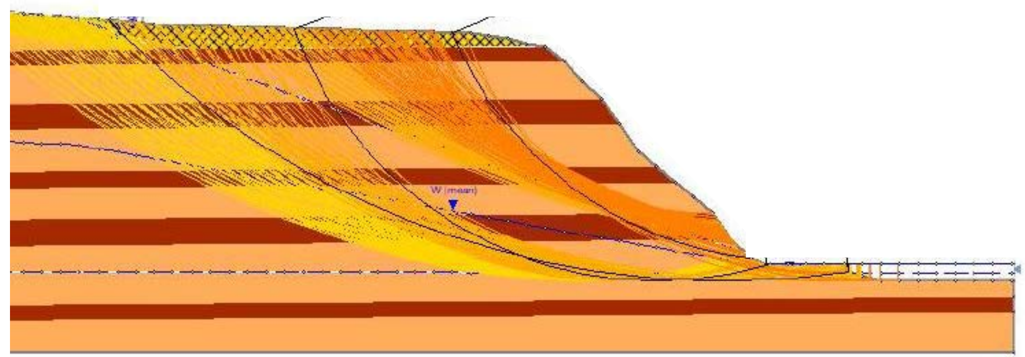
– Most landslides not sensitive to WT (<4x change in frequency)

Estimation of Maximum Volume and Intrusion into Channel



EXAR Detailbericht C, Abbildung 37

Water Table Sensitivity Method of Slices for Different Volumes

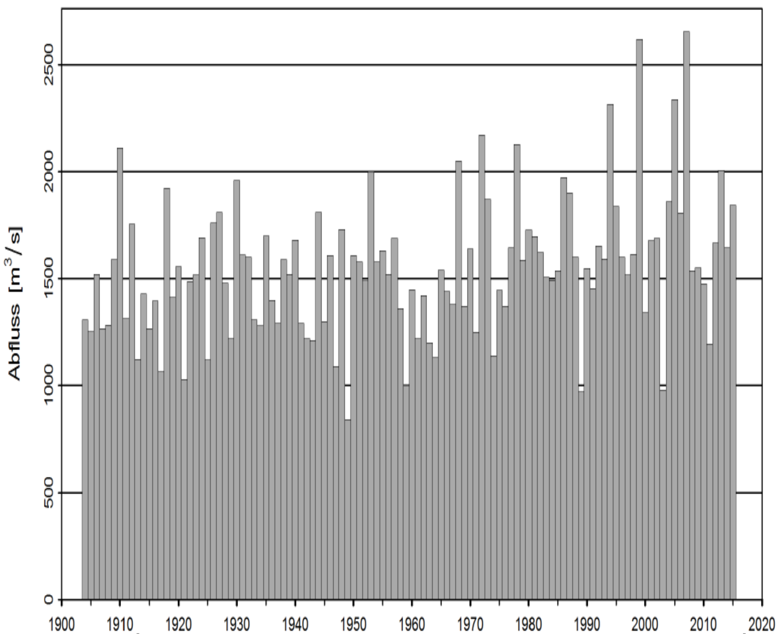


EXAR Detailbericht C, Abbildung 39

Estimating Extreme Floods

- Stream gauge record is limited (<100 years in many places)
- Extrapolate stream record to estimate more extreme events
  - Requires choice of distribution (GEV, log-normal, gamma, log-gamma, LP3,…)
  - Issues of credibility with extrapolations beyond 2x the record length
  - Incorporation of historical data, paelo-flood data, regional precipitation,…
  - Stationarity of series (urbanization of catchment, climate,…)
  - Estimates are expected to be highly uncertain

Annual Maximum Series,
Aare at Stilli (114 years)



Source: https://www.hydrodaten.admin.ch/de/2205.html

GEV Distribution
Only Gauge Record

Aare at Stilli, Discharge-Exceedance