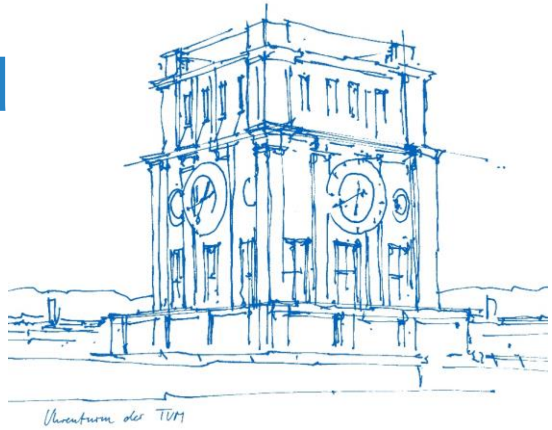
Heavy Precipitation and Flash Flood



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Outline

ML : Machine Learning / HL : Hydrological Modeling / HD : Hydrodynamic Modeling

1. Flash Floods

What causes a flash flood ?

Micro burst at the lake of Milstädt, Austria

Definitions

Pluvial and Fluvial Floods

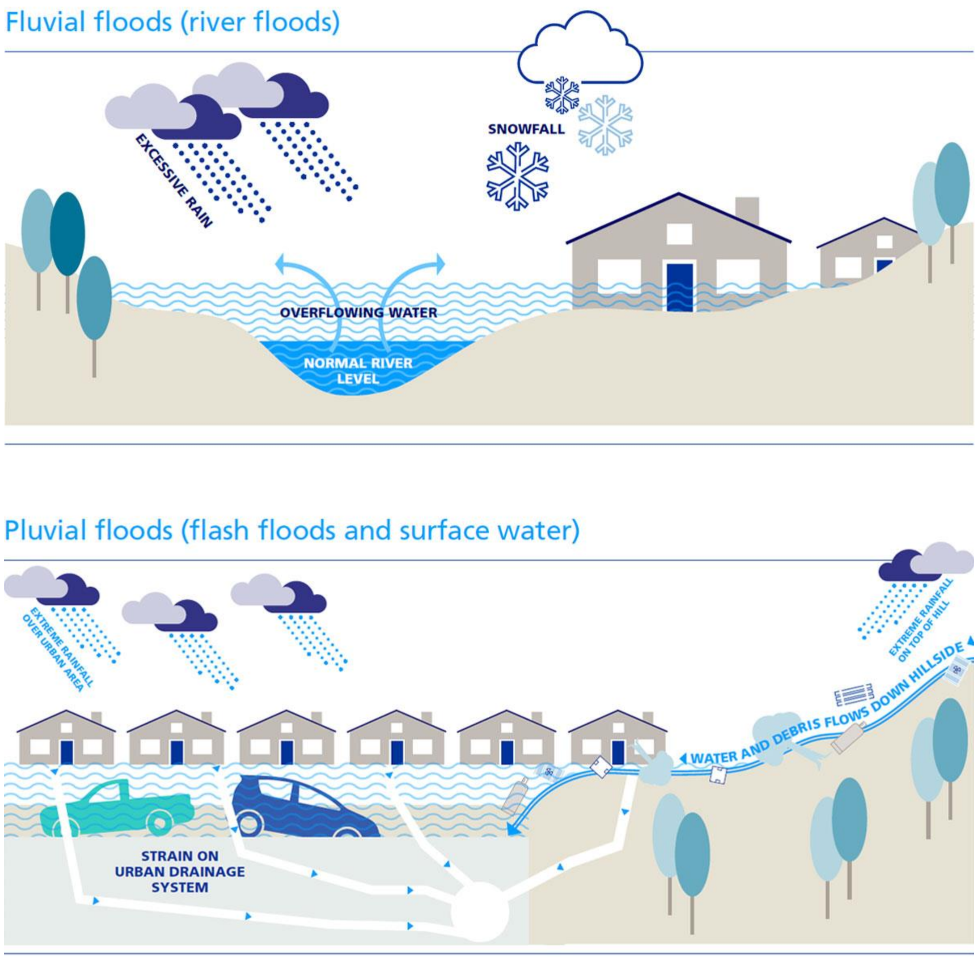
Fluvial flood

A fluvial, or river flood, occurs when the water level in a river, lake or stream rises and overflows onto the surrounding banks, shores and neighboring land. The water level rise could be due to excessive rain or snowmelt.

Pluvial flood

A pluvial flood occurs when an extreme rainfall event creates a flood independent of an overflowing water body. A common misconception about flood is that you must be located near a body of water to be at risk. Yet pluvial flooding can happen in any location, urban or rural; even in areas with no water bodies in the vicinity. There are two common types of pluvial flooding:

- Surface water floods
- Flash floods



(Source: Zurich insurance)

Definitions

Surface Water and Flash Floods

Surface water floods

Surface water floods occur when an urban **drainage system is overwhelmed** and water flows out into streets and nearby structures. It **occurs gradually**, which provides people time to move to safe locations, and the level of **water is usually shallow** (rarely more than 1 meter deep). It creates no immediate threat to lives but may cause significant economic damage (Source: Zurich insurance).

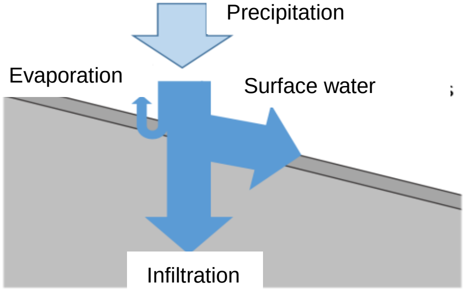
Flash floods

Flash floods in the context of heavy precipitation events are exceptionally fast rising flood waves, which are facilitated by a very large amount of surface water. The surface water is generated by a **combination of precipitation** (intensity and volume) **and the limited retention capacity of the soil**. In combination with an **available relief potential**, the fast concentrating surface runoff accumulates to fastly rising water levels and discharge waves with extreme peak discharges in concentration paths and channels (Source: HiOS-project).

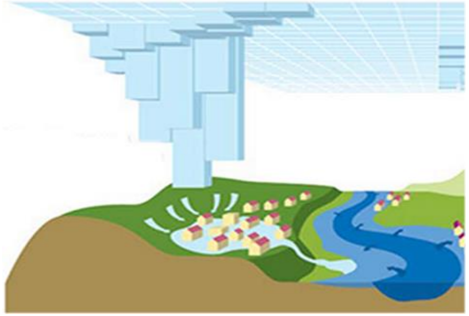
Heavy precipitation - problems

Heavy, short and local precipitation events. → Difficult forecast. Stationary approach not possible.

The volume of accumulated rainfall is small. → Extremly sensitive with respect to infiltration and retention.



All incoming water fluxes are generated by precipitation. → The input into the hydrodynamic model has to be calculated via hydrological modeling.

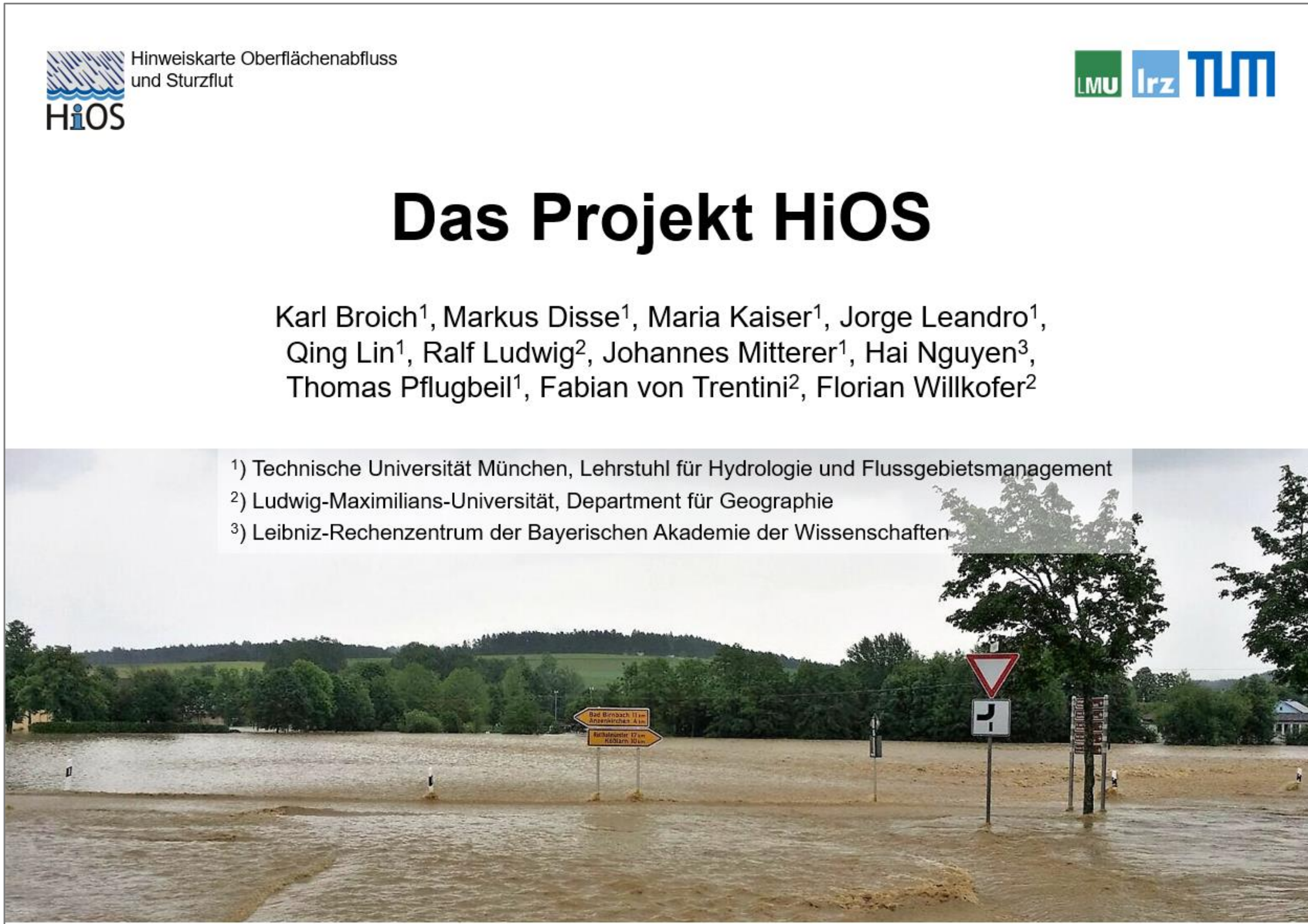


The flash flood event 2016 in Simbach a. Inn

Flash flood in Simbach a. Inn, 1.6.2016. © pa/dpa/Walter Geiring.

Project HiOS

Flash Floods and Excessive Surface Runoff in Bavaria



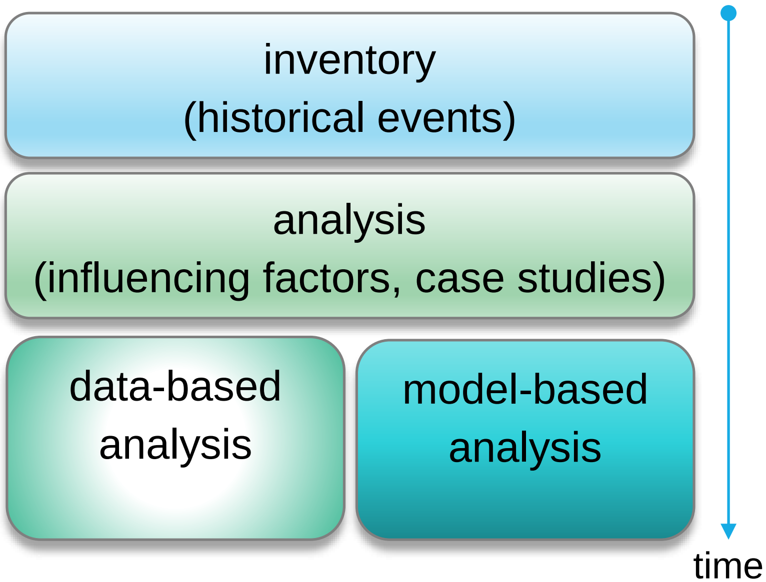
Project goals

- Development of a method to estimate the surface runoff and flash flood hazard of Bavarian communities using GIS and geostatistics (**indication map**)
- Development of a scientific guidance document for hydrological and hydrodynamic modelling of surface runoff and flash floods
- Comparative simulation of surface runoff and flash flood events using hydrological and hydrodynamic models
- Gathering experience of using hydrological and hydrodynamic models at high-performance computing environments
- Generation of **model-based hazard maps** for 40 municipalities
- Development of **guidelines** for the analysis of surface runoff and flash flood hazard

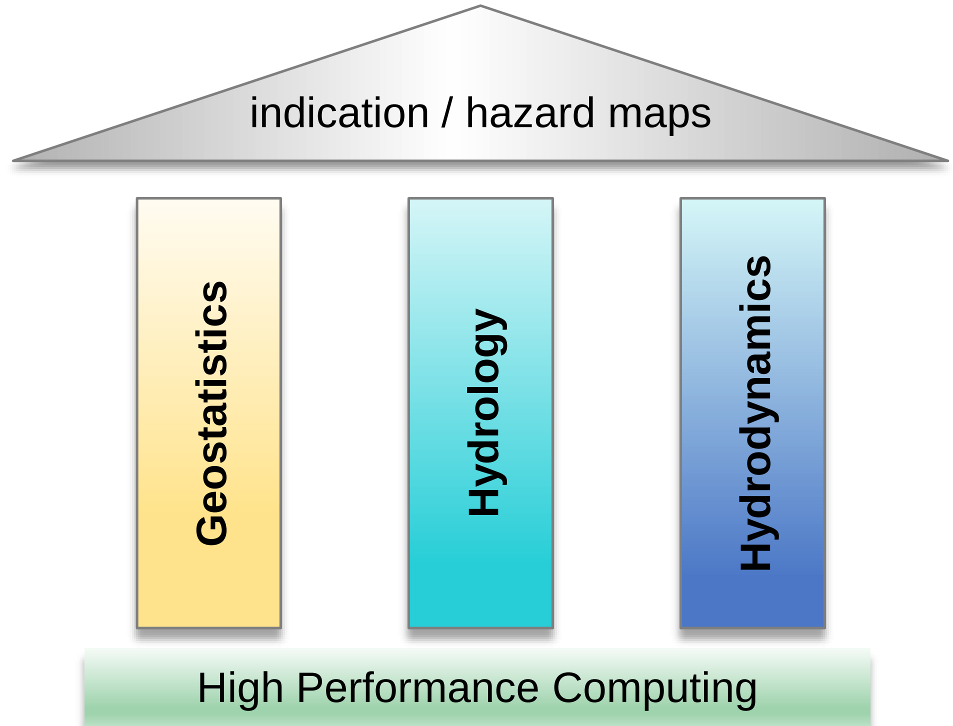
2. Methodology and influencing factors

Concepts and disciplines

Concepts



Disciplines



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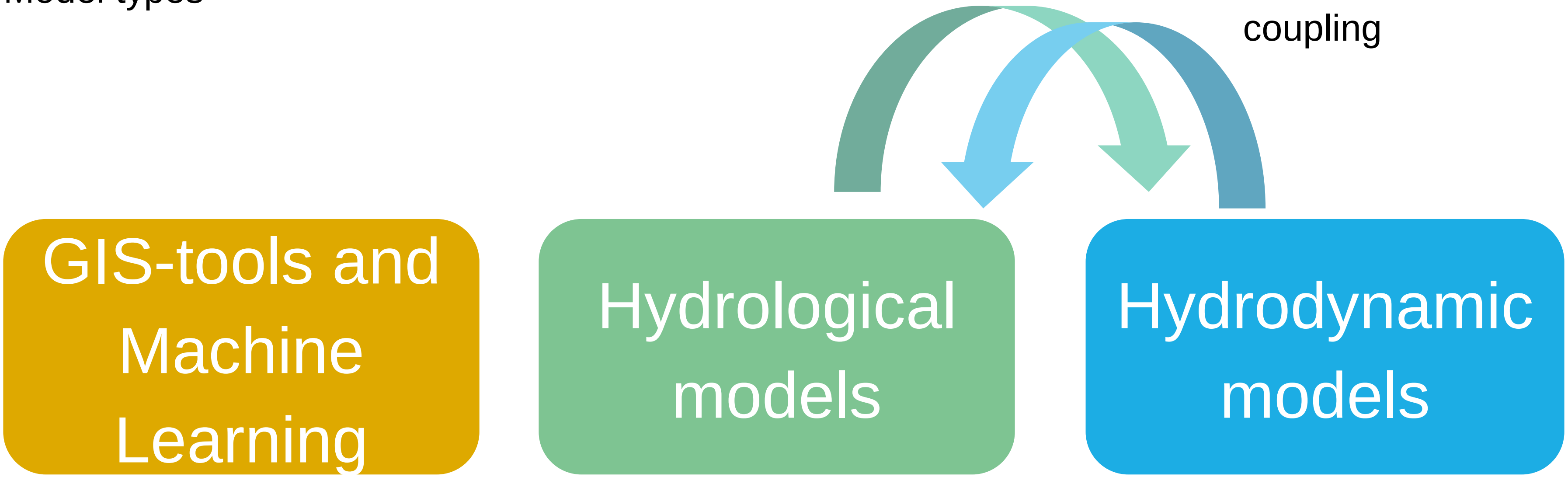
Flash flood analysis

Model types



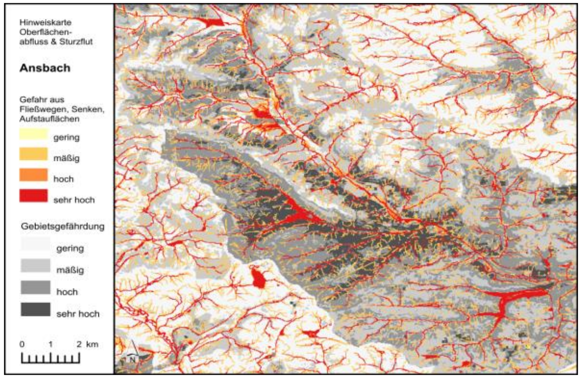
- WaSiM
- LARSIM
- eglx

- TELEMAC-2D
- HYDRO_AS-2D
- Pdwave
- FloodArea

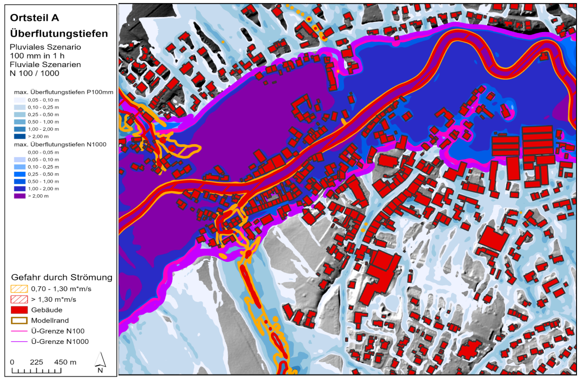
Hazard maps – an important tool for risk communication

There are two types of hazard maps for surface water and flash floods

- **Indicator map**: a hazard map derived using
    a. machine learning,
    b. GIS-based analysis and
    c. additional local hazard information.

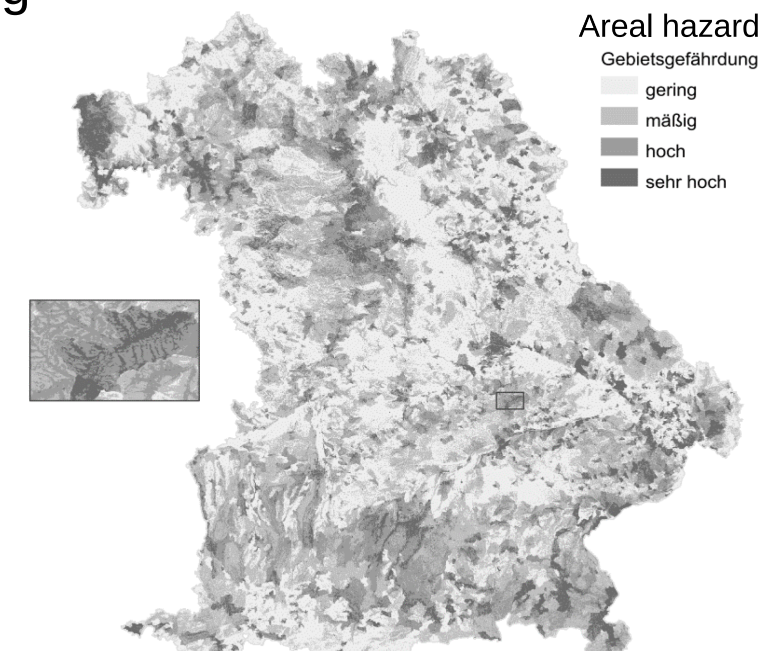


- **Model-based hazard maps**: derived using hydrological and hydrodynamic modeling



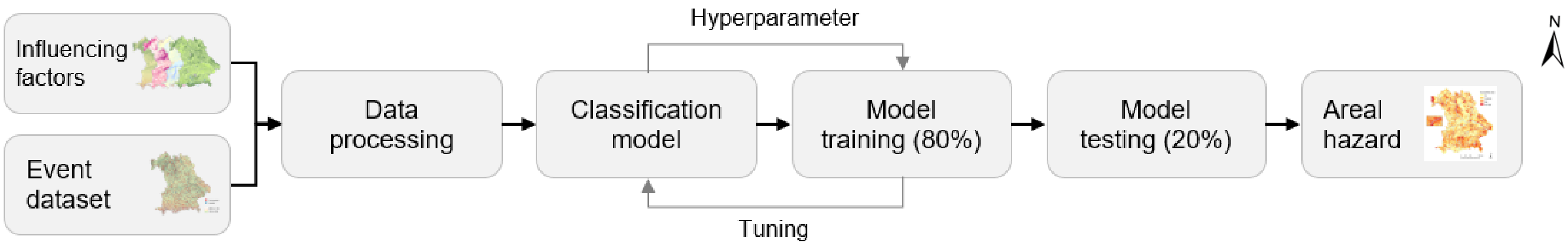
Data-based approach

Indicator map generation – machine learning



GIS – Influencing factors

- Topography
- Land usage
- Soil and geology
- Stream network
- Catchment properties
- Precipitation



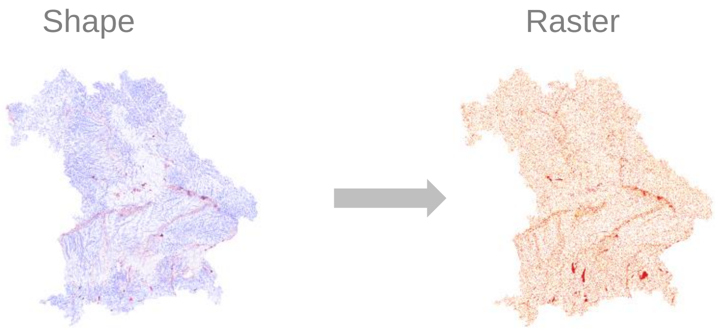
Data-based approach

Indicator map generation – GIS-based hazard layer

Data preparation for GIS-based hazard layer

- The hazard layer classes (flow paths, depressions and backwater areas) were assigned values from 1 to 4, with 1 representing the lowest and 4 the highest hazard level.
- Flow paths, depressions and backwater areas were converted into grids (25 m) and combined, whereby the highest hazard value present was selected for overlaying.
- In addition, the grid of lakes was added to the hazard layer as class 4 (highest hazard level).

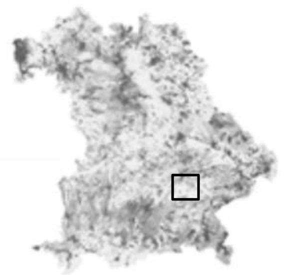
Flow paths		Depressions		Backwater areas	
Klasse	Wert	Klasse	Wert	Klasse	Wert
> 1 – 5 ha	2	> 0,1 – 0,2 m	1	> 0,1 – 0,2 m	1
> 5 – 10 ha	3	> 0,2 – 0,5 m	2	> 0,2 – 0,5 m	2
> 10 ha	4	> 0,5 – 1,0 m	3	> 0,5 – 1,0 m	3
		> 1,0 – 2,0 m	4	> 1,0 – 2,0 m	4
		> 2,0 – 4,0 m	4	> 2,0 – 4,0 m	4
		> 4,0 m	4	> 4,0 m	4



Hazard layer

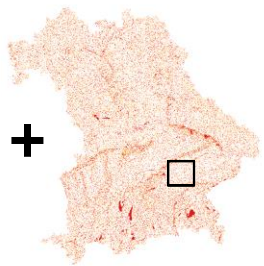
Data-based approach

Indicator map generation – additional local hazard information



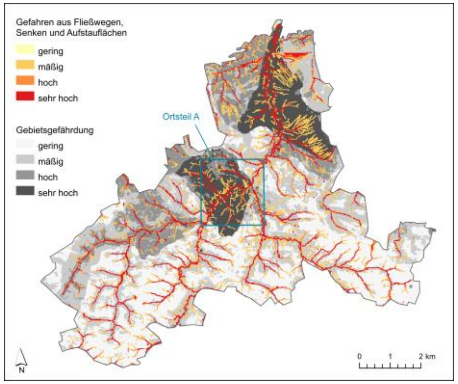
Areal hazard

\+

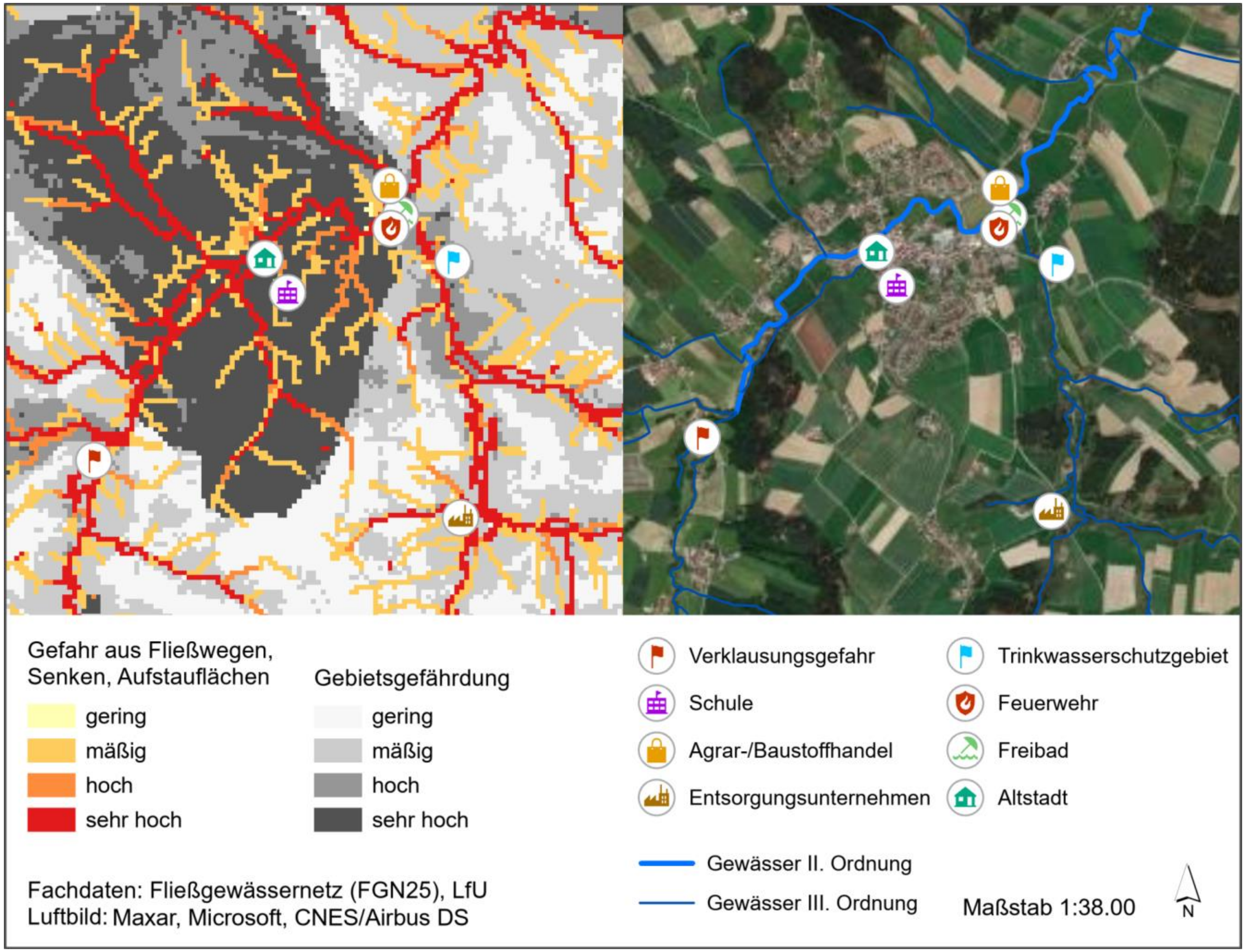


Hazard layer

=



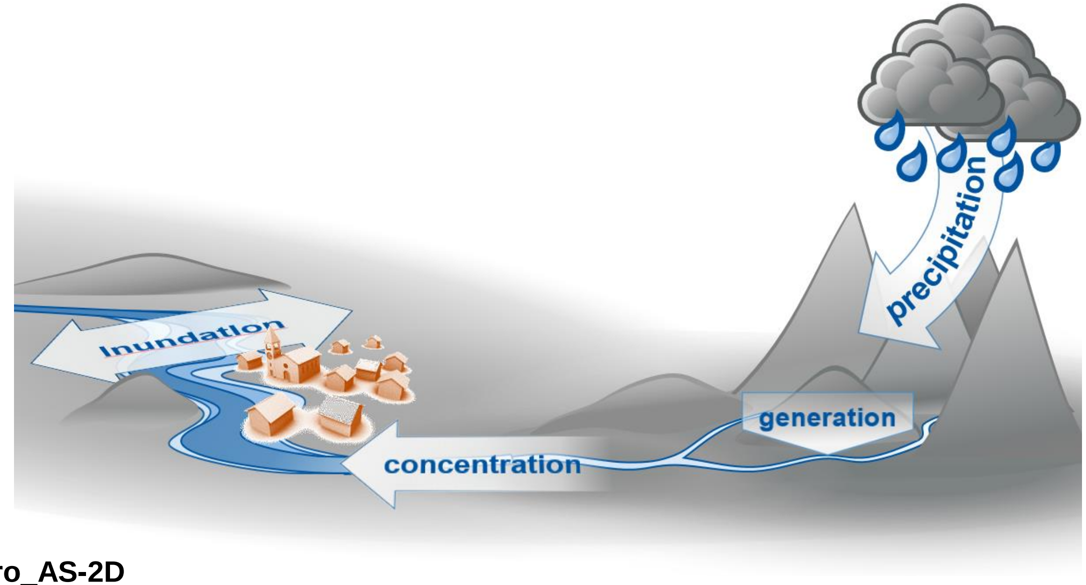
Indicator map



Model-based approach

Overview of models

Lumped hydrological models	**EGL-X**
Distributed hydrological models	**LARSIM** **WaSiM**
Hydrodynamic models	**TELEMAC-2D** **P-Dwave, Hydro_AS-2D**
Hydrodynamic RR-models	**HDNAM** **(TELEMAC-2D + SCS-CN)**
HL-model → HD-model	**LARSIM/WaSiM + TELEMAC-2D**
Sewer netw.model ↔ HD-model	**SWMM + P-DWave**



Legend:

runoff creation	Rounoff concentr. + routing	**processes**

Effective precipitation
Inflow hydrograph
Bidirectional sewer coupling
coupling

Hydrological model
Hydrodynamic model
Sewer network model
model type

Smallest computational unit = HRU
Standard dimension = 10000 m²
Standard timestep: Minutes to hours

Smallest computational unit = Element
Standarddimension = 10 m²
Standard timestep: Seconds

Methodology HDRRM

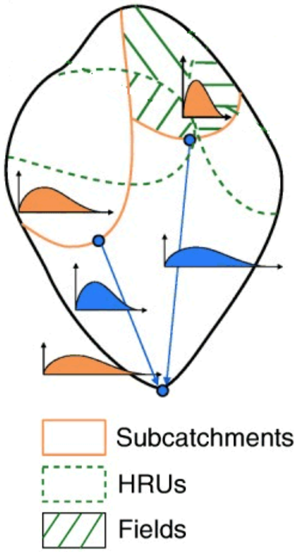
Hydrodynamic Rainfall-Runoff Model HDRRM = 2D-hydrodynamic model with nodal run-off generation

Hydrological model

Conceptual model frame work

Generation → Concentration → Routing

$$Q = f(t, x_c, y_c)$$



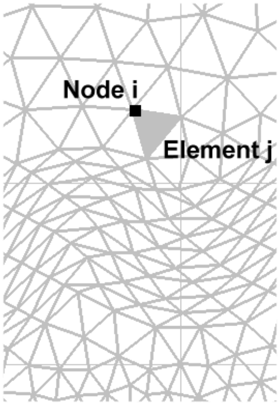
(Fenizia et al., 2016)

Hydrodynamic model

Physical model frame work

Generation → SWE-solver: Concentration + Routing

$$h = f(t, x_i, y_i)$$
$$v_x = f(t, x_i, y_i)$$
$$v_y = f(t, x_i, y_i)$$



Triangular mesh

Model choice: TELEMAC-2D using Finite Elements and SCS-CN-method (Ligier, 2016)

Methodology HDRRM

Modeling of rainfall-runoff	N constant	N variable
in time	**x**	**x**
in space	**x**	

State of the art of HD-modeling rainfall-runoff

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TRITON TUM

Methodology HDRRM

Data

DEM	Laserscan 1x1m raster
Percipitation	DWD RADOLAN YW 5min
Soil	Hydrological soil classes
Landusage	TN, INVEKOS

Demands

- The HD-model has to be able to simulate varying precipitation in time and space.
- Usage of data in high resolution for DEM, precipitation, landusage and soil.
- Calculation of infiltration as sink term at each node
- The quality of the simulation procedure shall be validated using case studies.

Model choice

Suitable HD models :

- **TELEMAC-2D**
- **HYDRO_AS-2D**
- ...

Validation

Case study for the two neighboring catchements Simbach and Triftern. Kalibration Simbach, Validation Triftern.

Goal

Validated **H**ydro**D**ynamic **R**ainfall-**R**unoff **M**odel **HDRRM**

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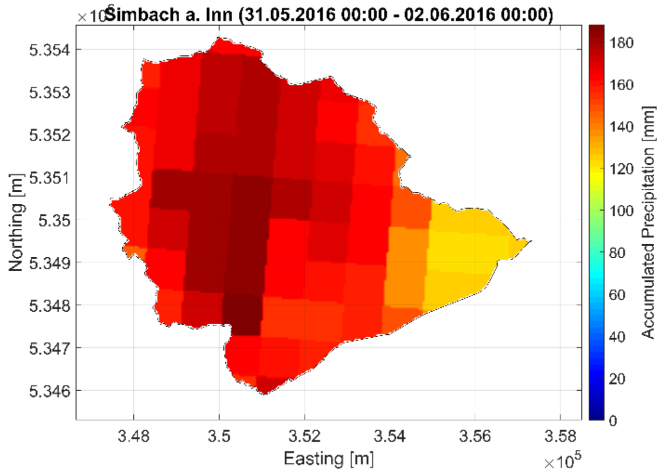
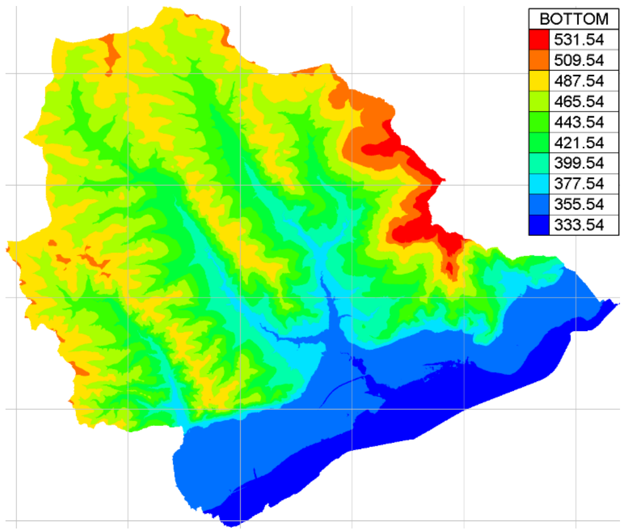
Methodology HDRRM

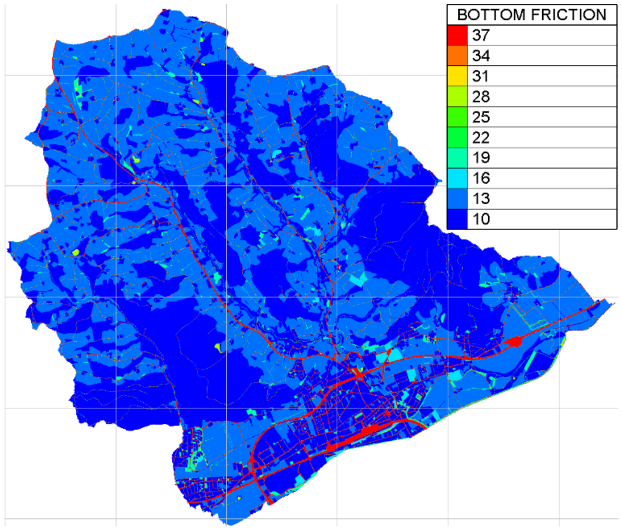
Precepitation [mm]



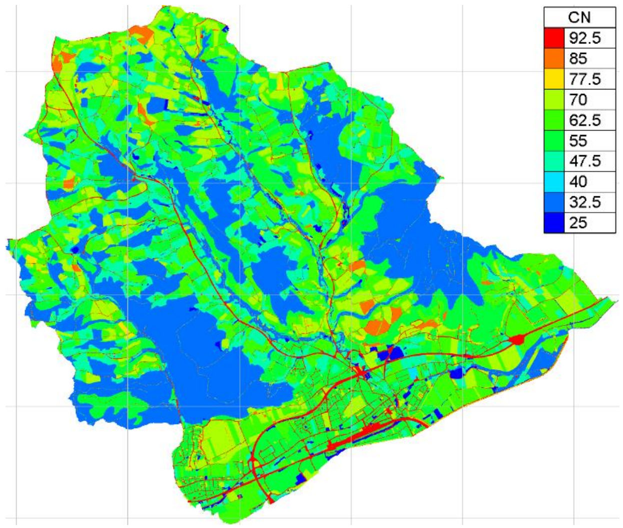
DEM [m]



Roughnes [$m^{1/3}/s$]



CN-values [-]



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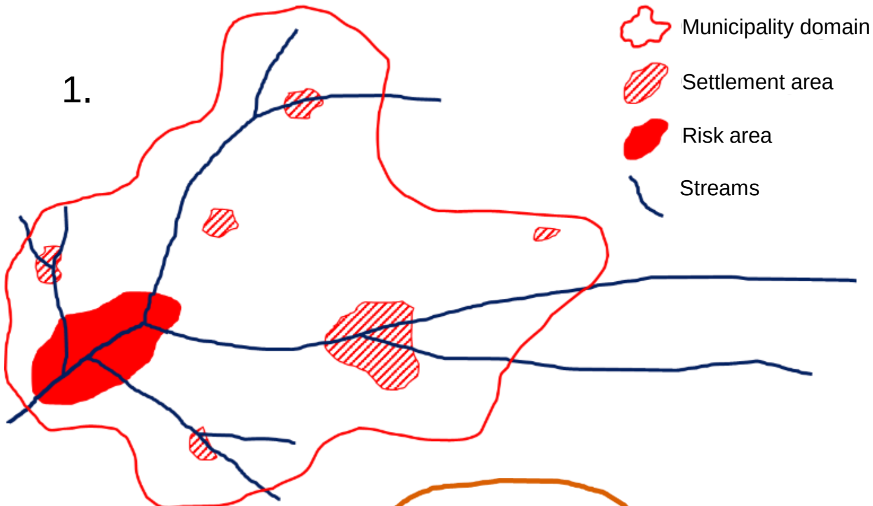
Model-based hazard map generation –pluvial and fluvial scenario

Definition of risk area

1.



2
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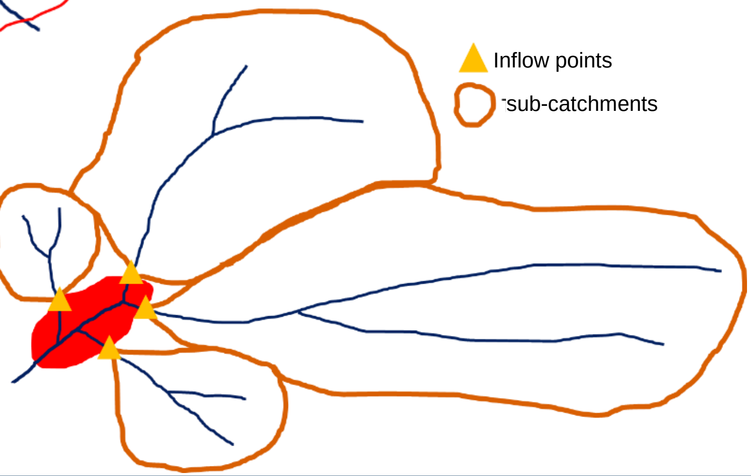
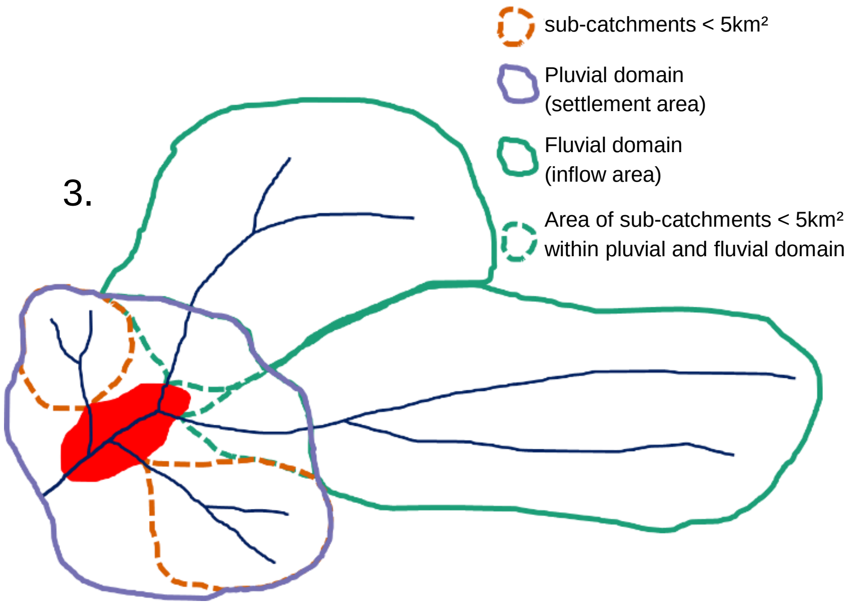


Definition of pluvial and fluvial domain

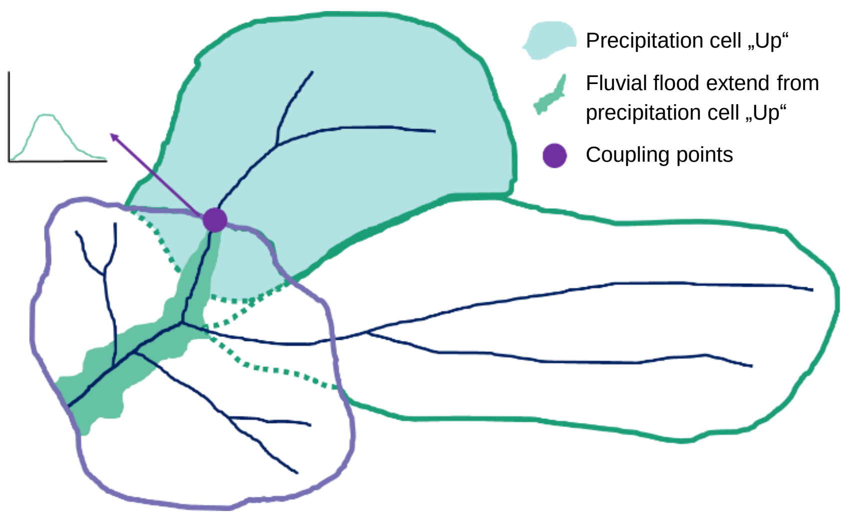
3.

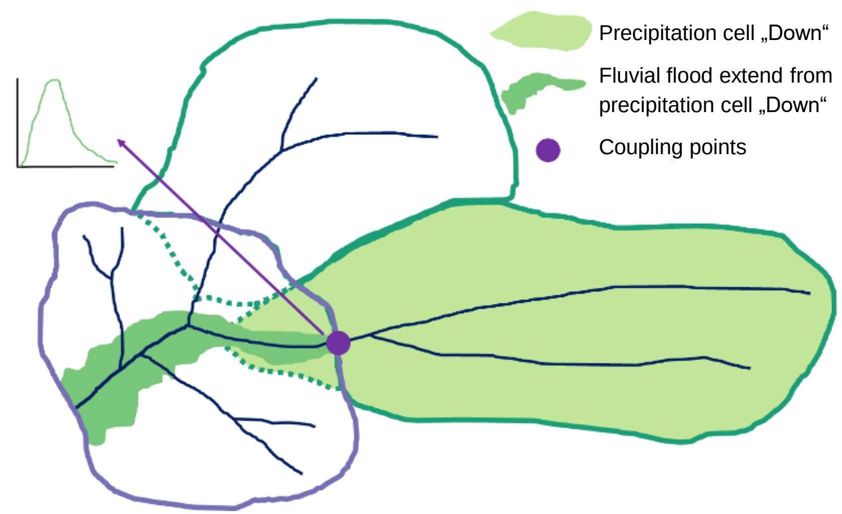


Definition of sub-catchments

Model-based hazard map generation – fluvial scenario

- Two scenarios: 100 a und 1000 a
- Separate precipitation in sub-catchments
- Simulation of fluvial domain using hydrological models – Interface to hydrodynamic model at inlet points (BC)

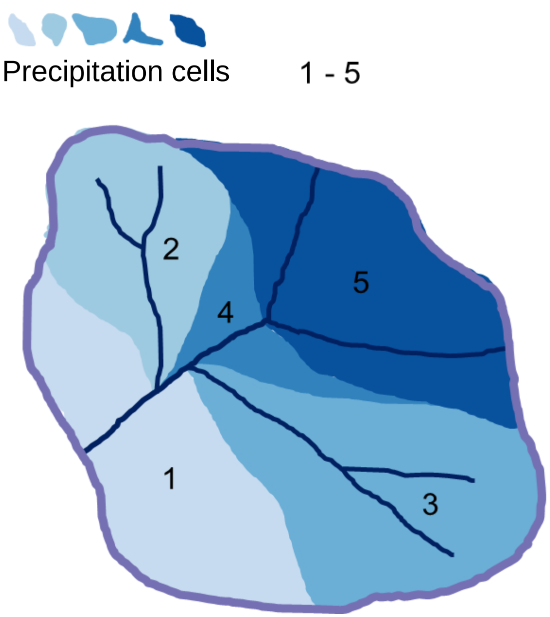




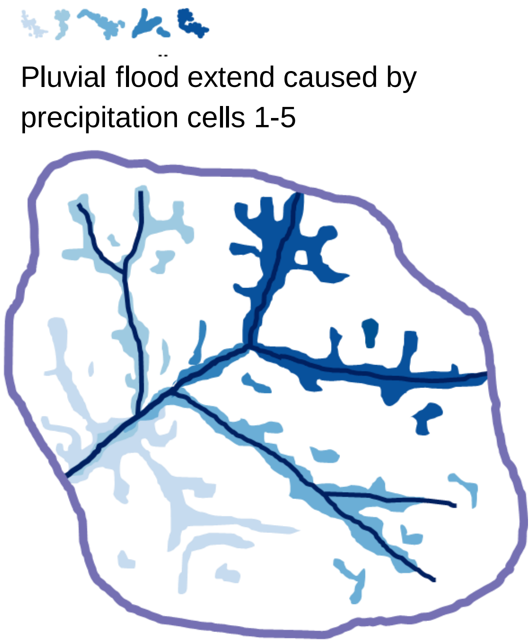
Model-based hazard map generation – pluvial scenario

- Rain just in settlement area taken into consideration
- Several precipitation cells are superposed
- end-emphasised, uniform rain, **100 mm / 1 h**

Precipitation cells 1 - 5



Pluvial flood extend caused by precipitation cells 1-5



Influencing factors

Hydrological influencing factors

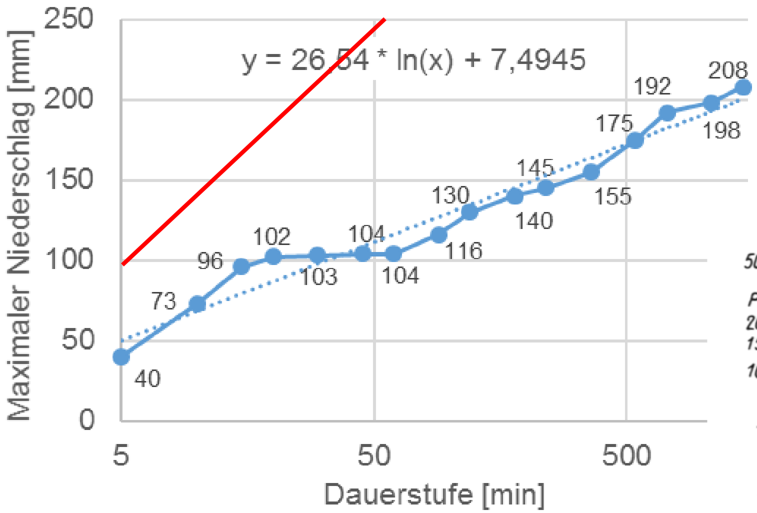
- Infiltration
- Soil moisture
- Sealing
- Rainfall intensity
- Rainfall distribution

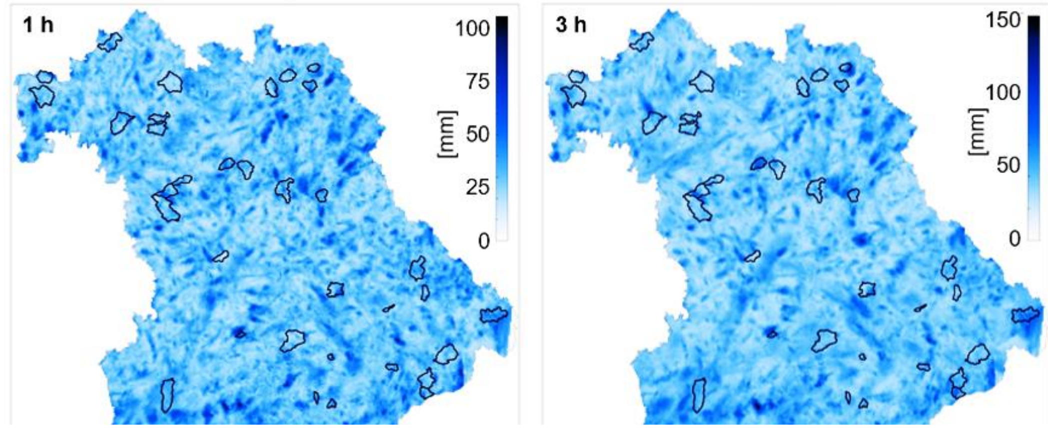
Hydrodynamic influencing factors

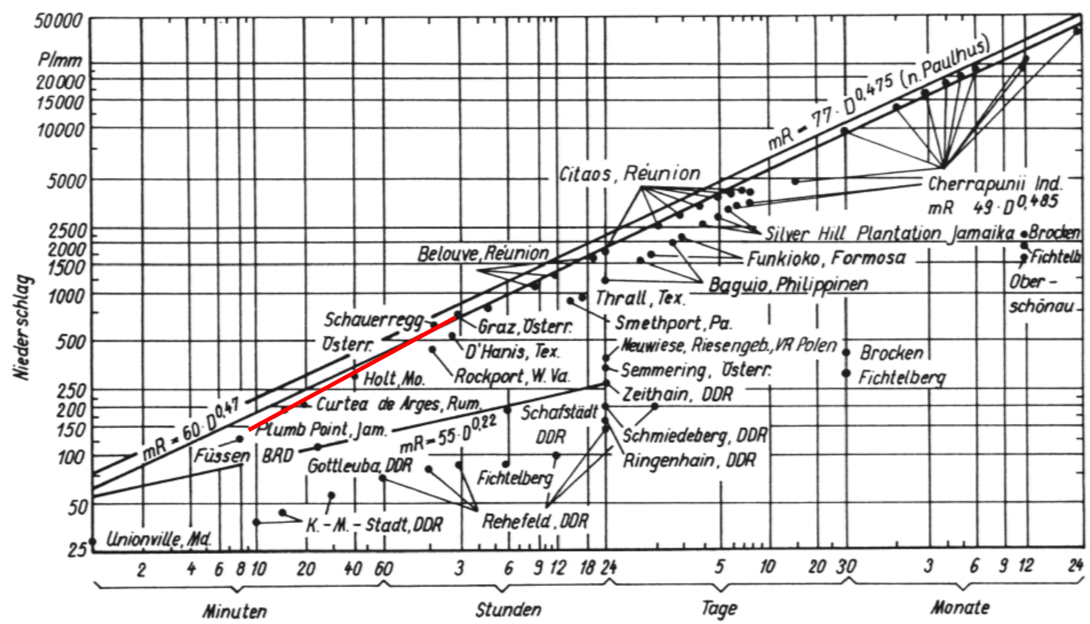
- Bottom slope
- Roughness
- Building density
- Sewer drainage
- Culverts and bridges

Heavy precipitation characteristics

Events in Bavaria (2001-2018)







Red line: Extreme values for alpine region (Dyck/Peschke, 1995)

Extreme Niederschlagsereignisse, weltweit (Dyck/Peschke, 1995)

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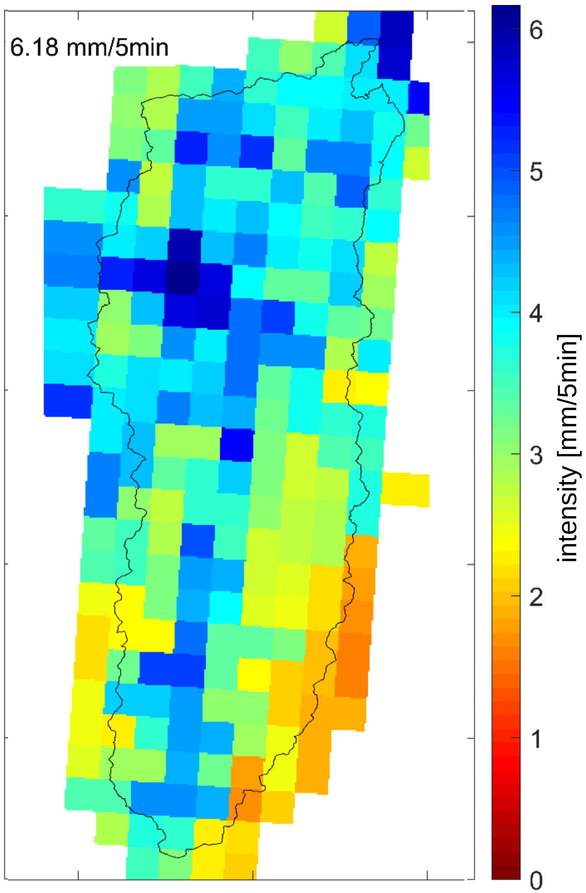
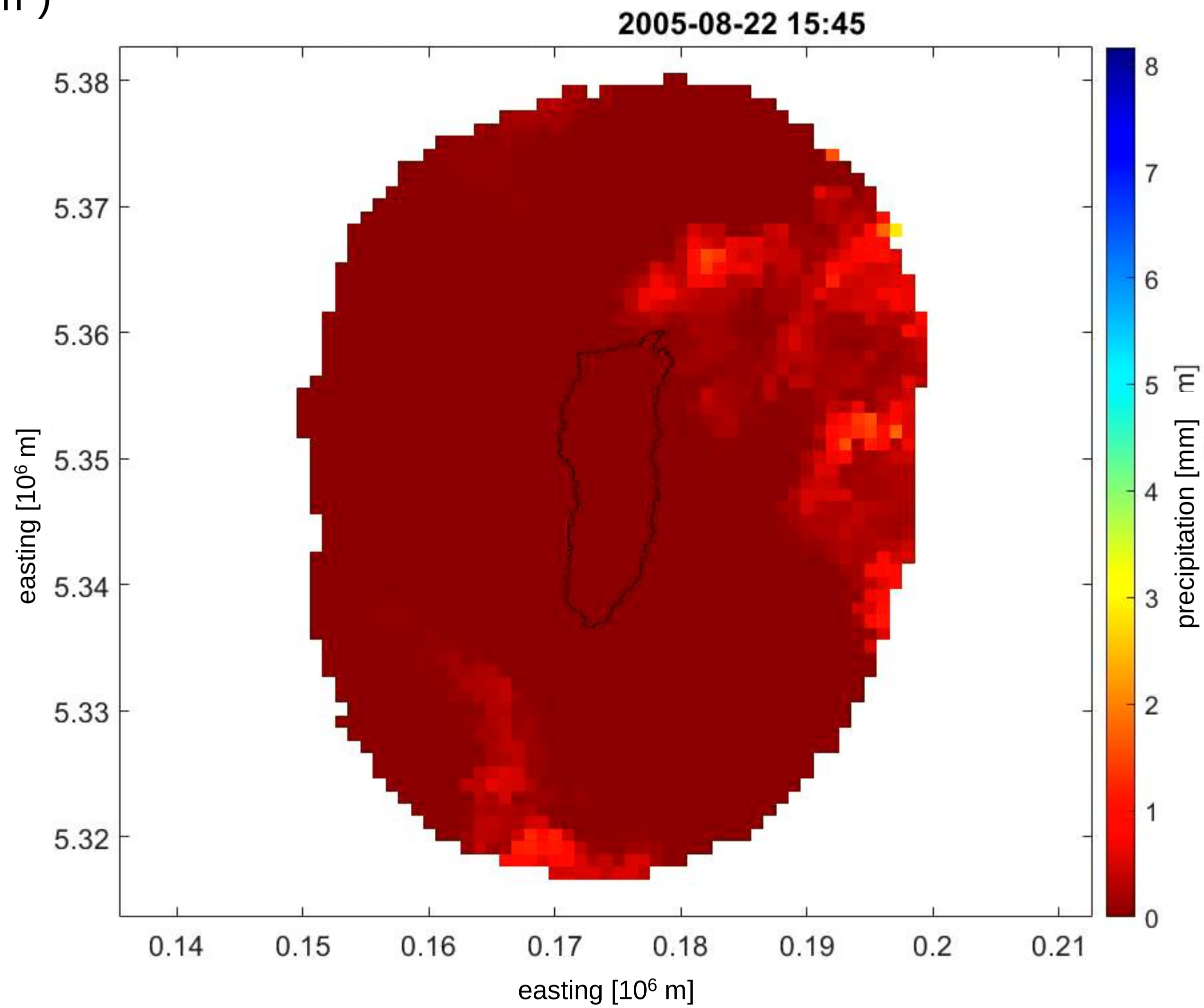
Precipitation characteristics - example

Fischach catchment (area ~120 km²)

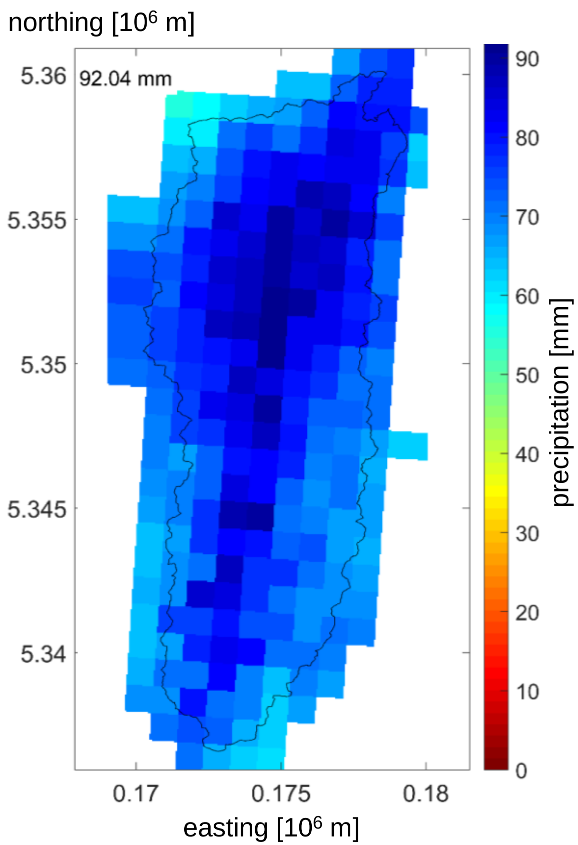


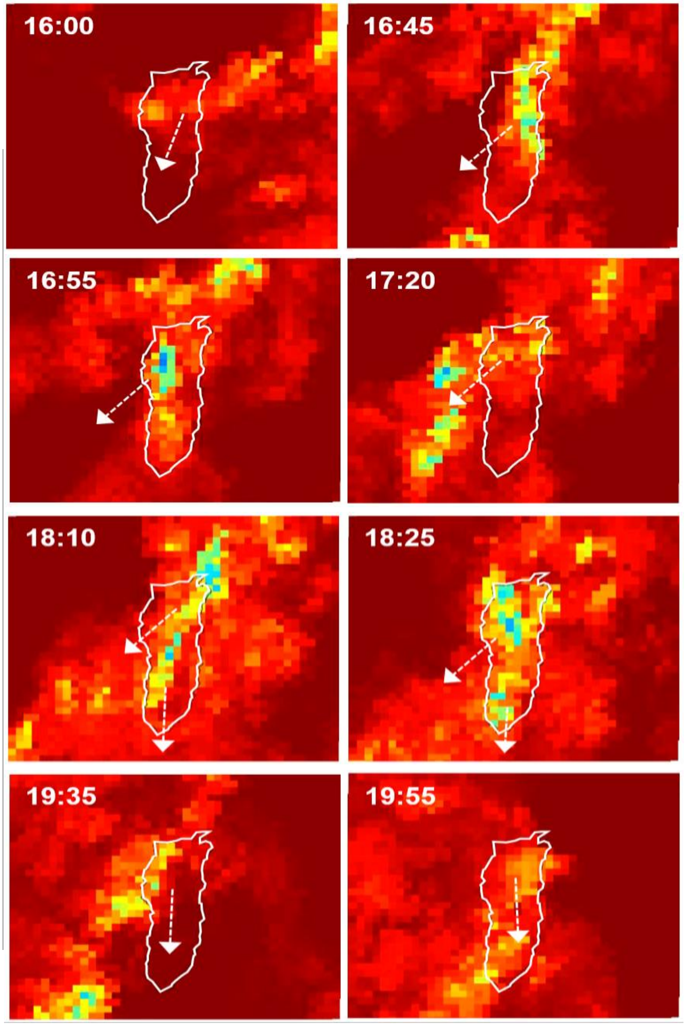


Precipitation characteristics - example

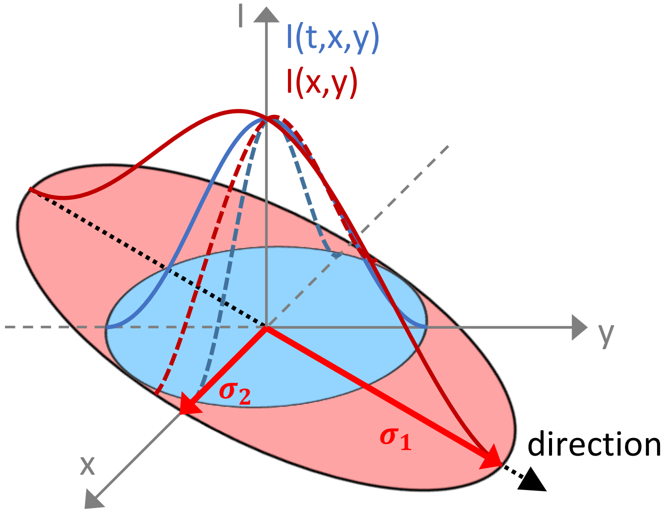
Fischach catchment (area ~120 km²)

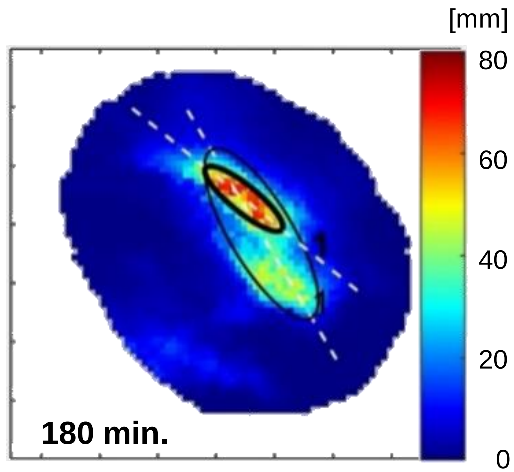
- → Most important variables: **duration, intensity, distribution in space and time**
- → State of the art: Tracking of single heavy precipitation cells, but until now **barely statistics for extreme precipitation events**
- → **Especially successive or quasi-statiionary precipitation cells result in high volumes**, but have not been treated separately, yet.

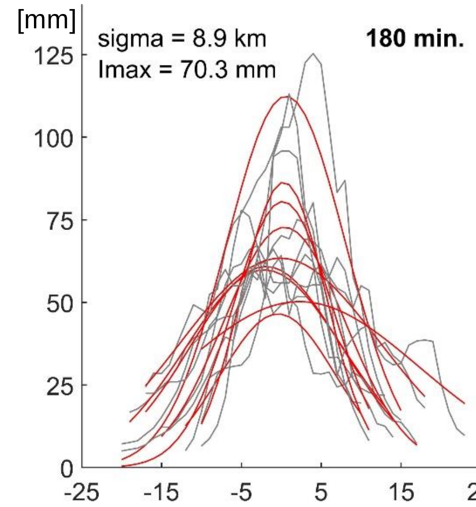


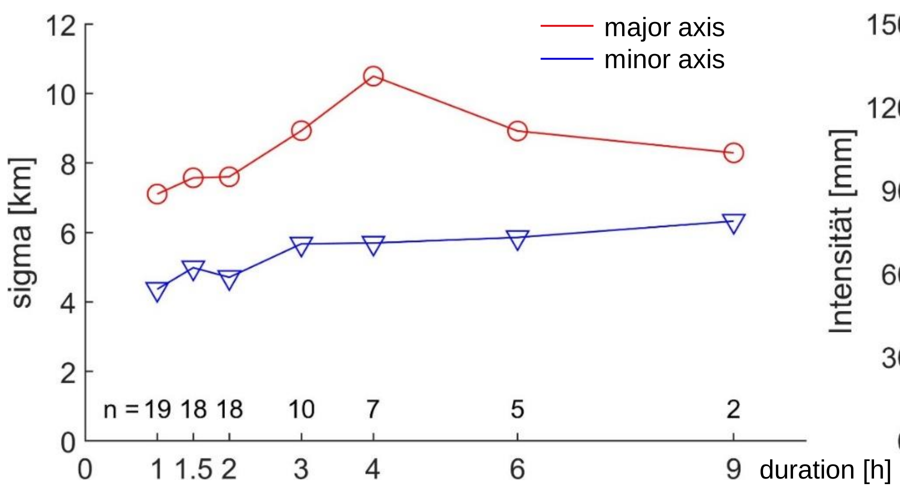


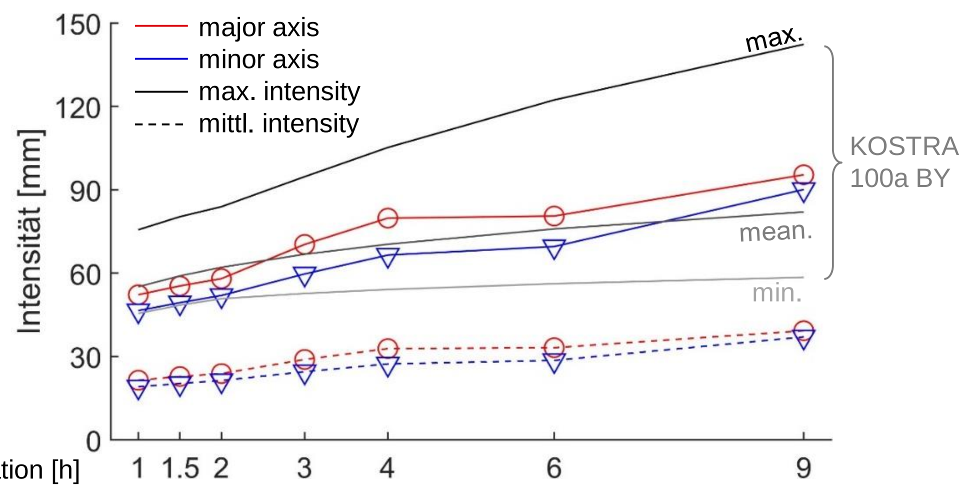
Statistical analysis of precipitation characteristics



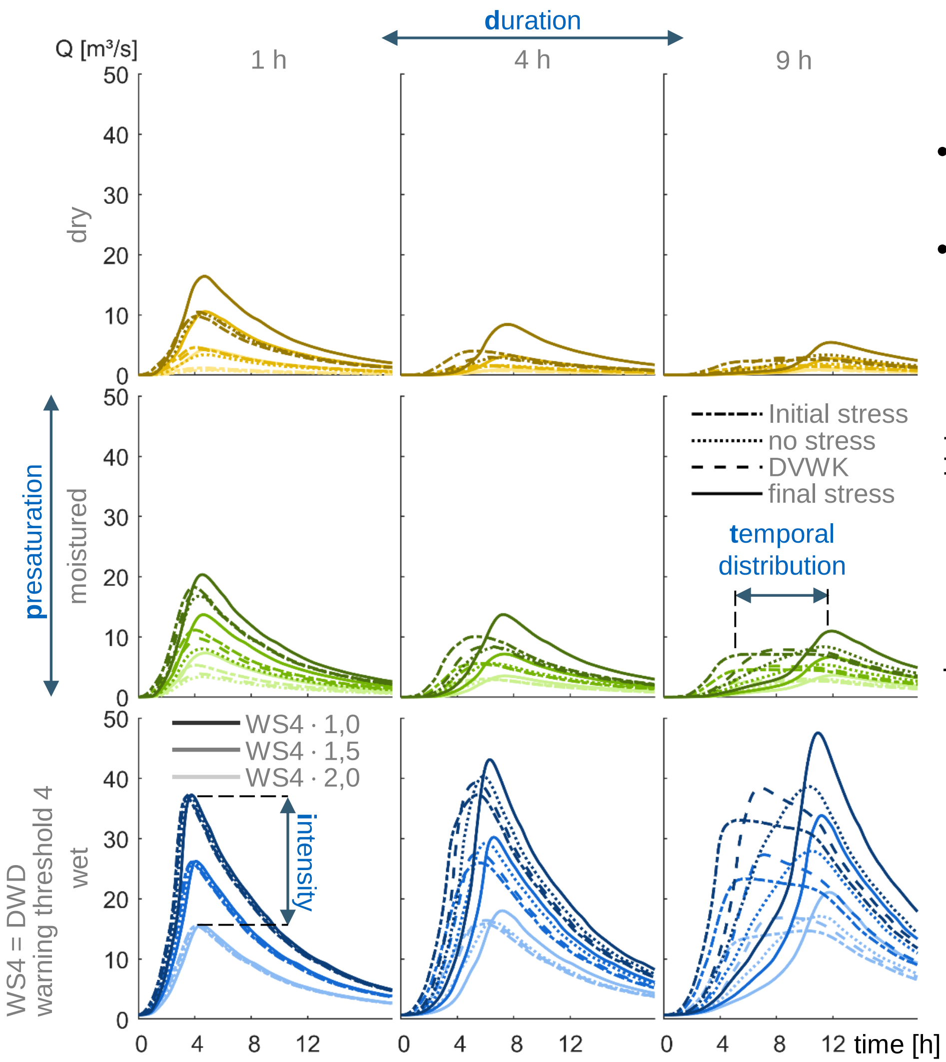




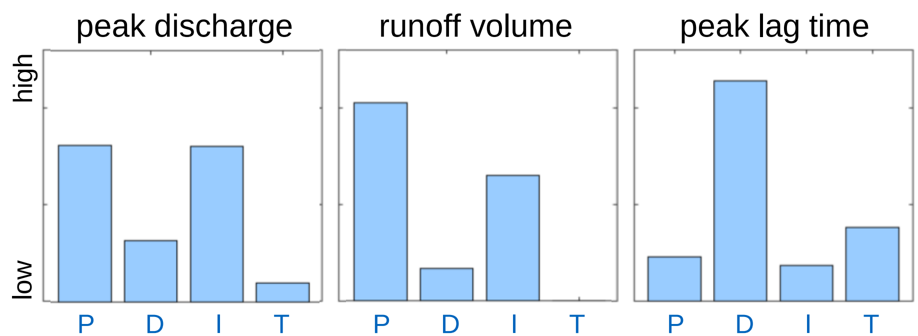




Influence of precipitation and presaturation



- Variation for models LARSIM and WaSiM, the results of both models are similar
- Assessment using Random Forest und Bootstrapping methods (MATLAB TreeBagger)

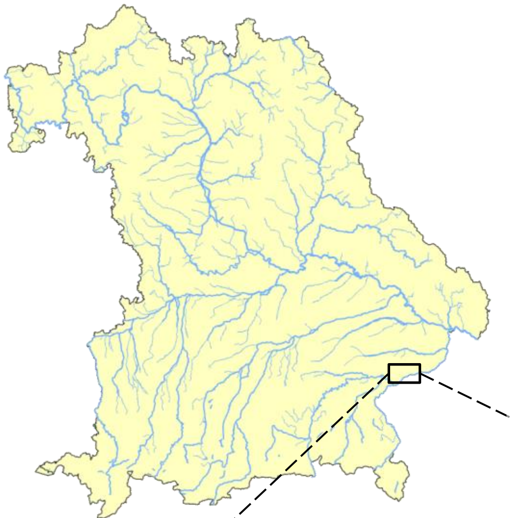


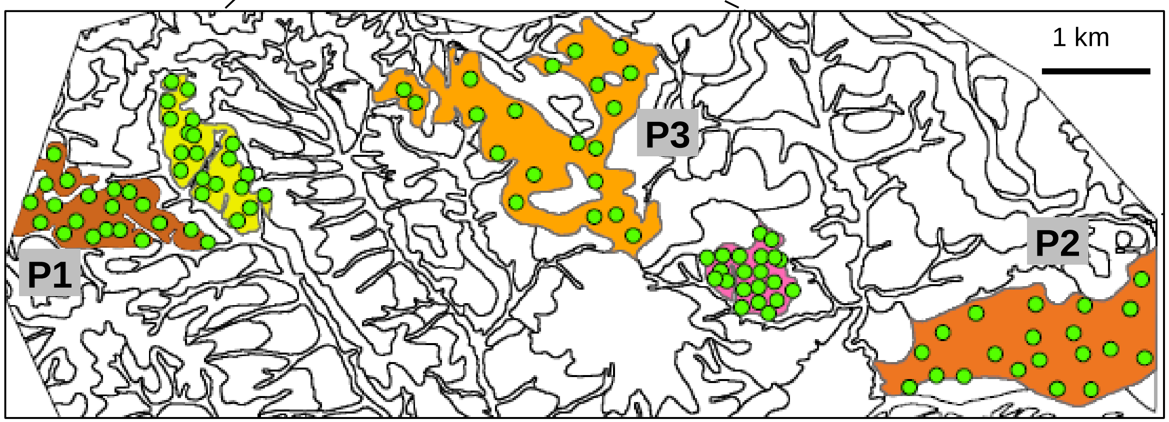
→ **Intensity** and **presaturation** dominate **peak discharge** and **runoff volume**.

→ **Duration** and less temporal distribution influence the **peak lag time**.

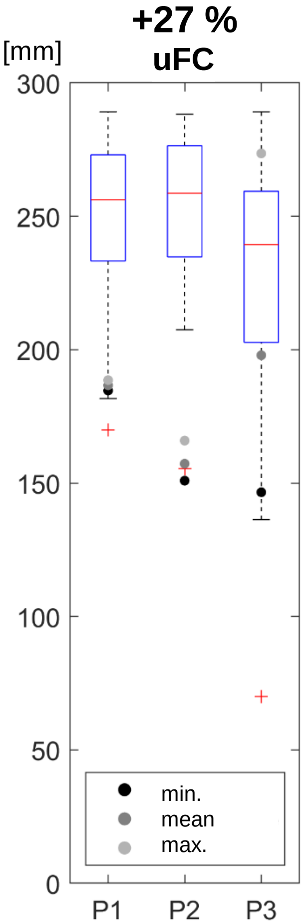
Example of the validity of static soil information

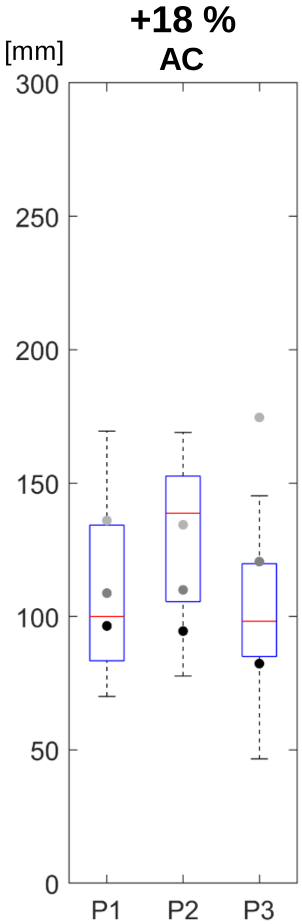
Assessment example of available static soil data (Thesis of Simon Schweiger)





each polygon 20 positions with 3 probes





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HiOS

Estimation of potential infiltration capacity

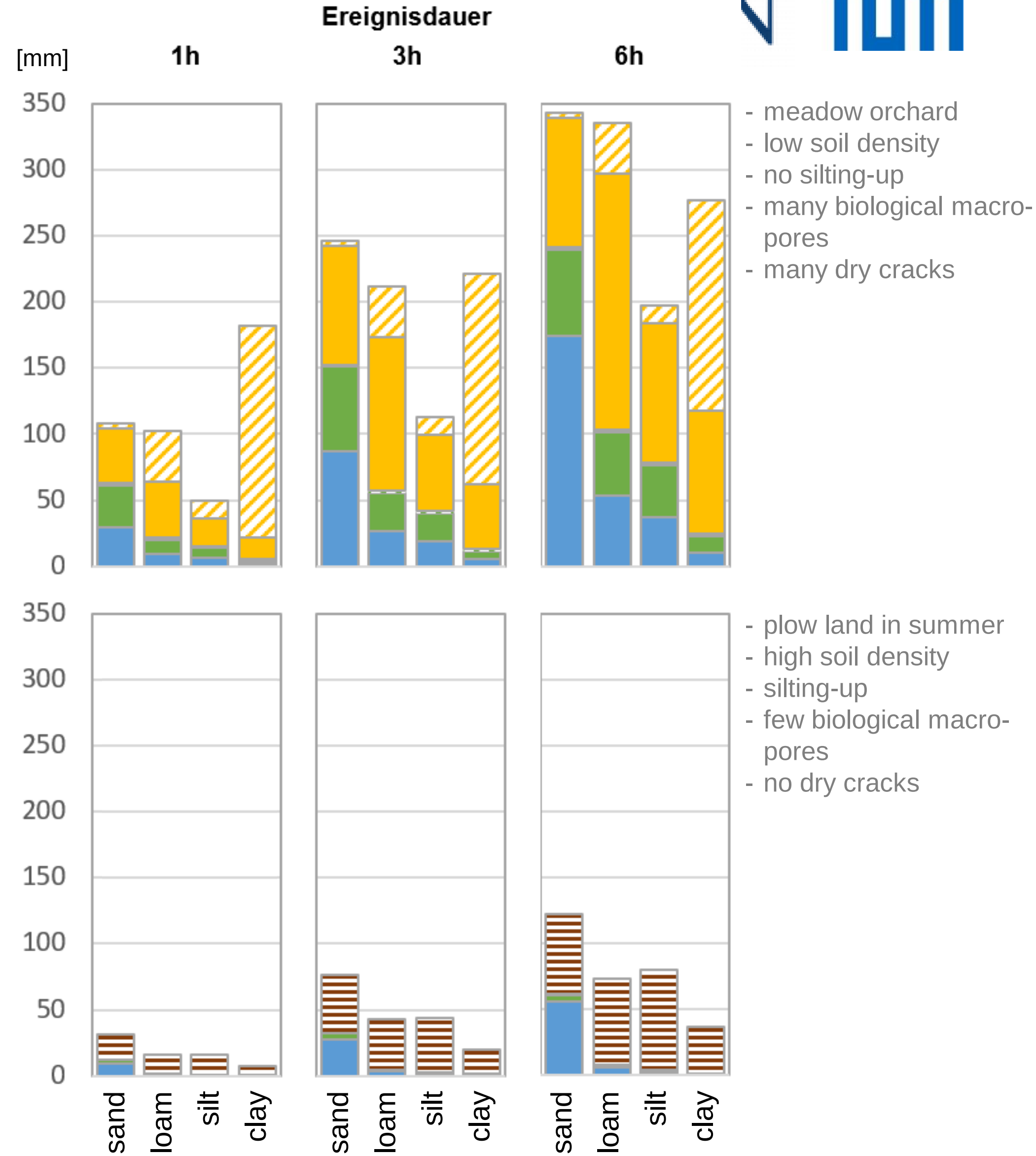
Mean potential infiltration volume from event duration and soil types

- reduction through silting-up
- crack volume } dry cracks
- matrix infiltration } dry cracks
- pore volume } biological macro-pores
- matrix infiltration } biological macro-pores
- matrix infiltration – surface

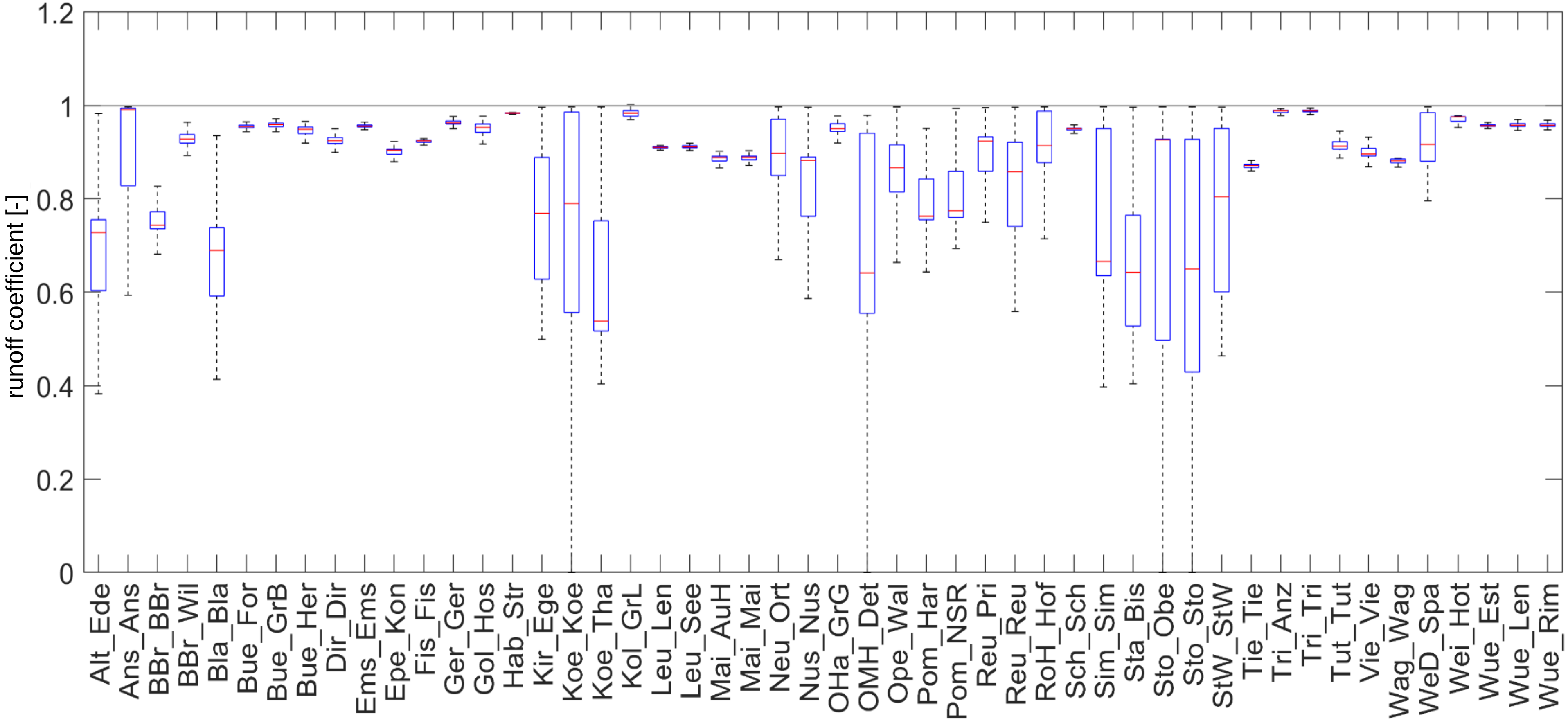
> → Variability of infiltration potential is very high for all soil types – also for high precipitation intensities
>
> → Dependent on the event characteristics the available pore volume or the matrix infiltration is dominant

Literature basis: Ad-hoc AG Boden (2005), LEG (2020) and Steinbriech et al. (2016).

Simplifications: saturated hydraulic conductivity, no tension of the matrix, no hydrophobia, homogenious soil, no sceleton, no backwater

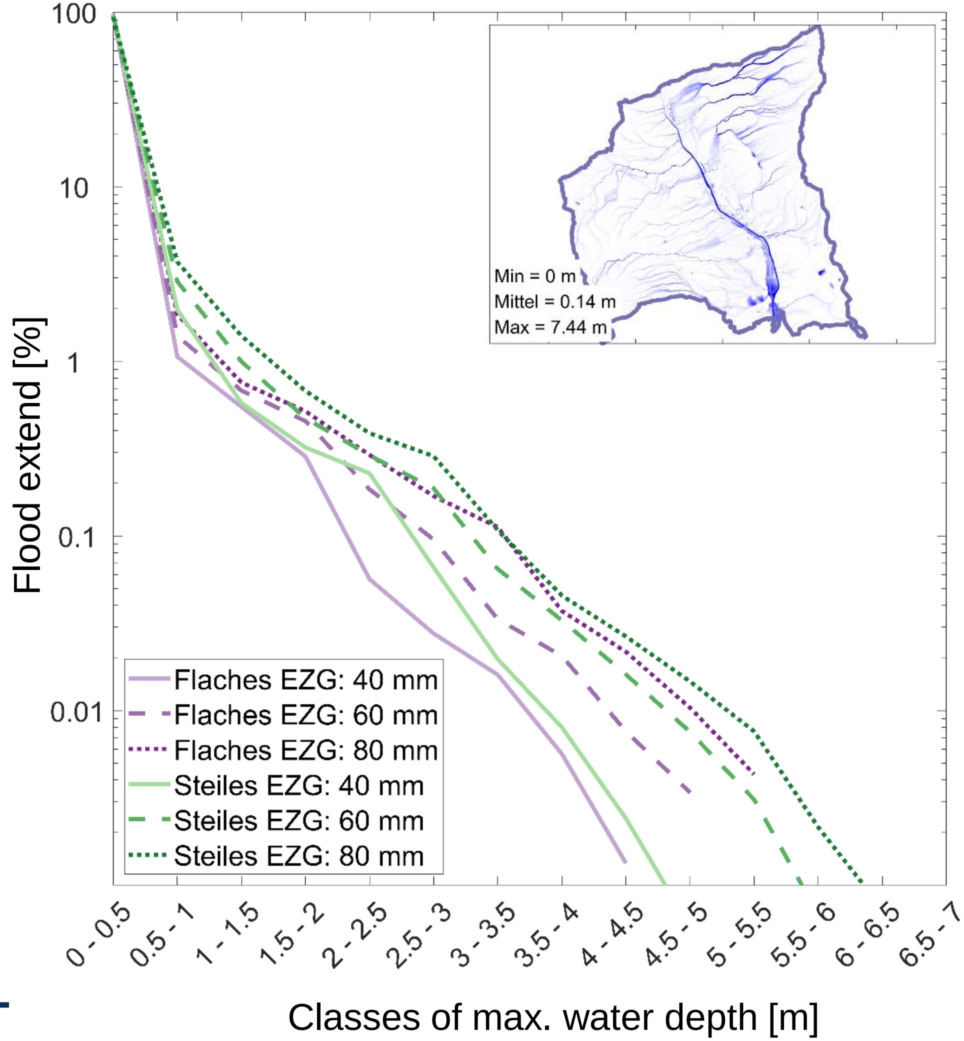


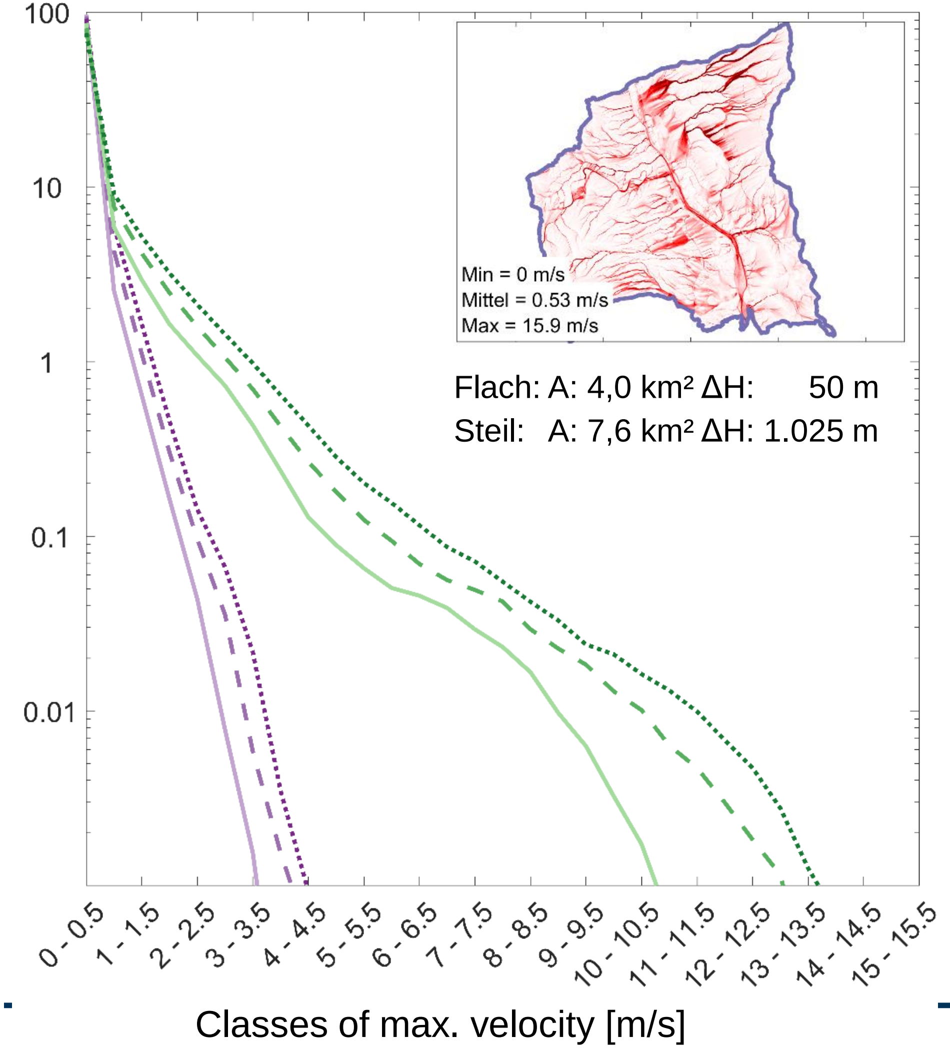
Effect of catchment variabilities on infiltration



karl.broich@tum.de

Influence of precipitation intensity on water depth and flow velocity





Influencing factors of runoff concentration

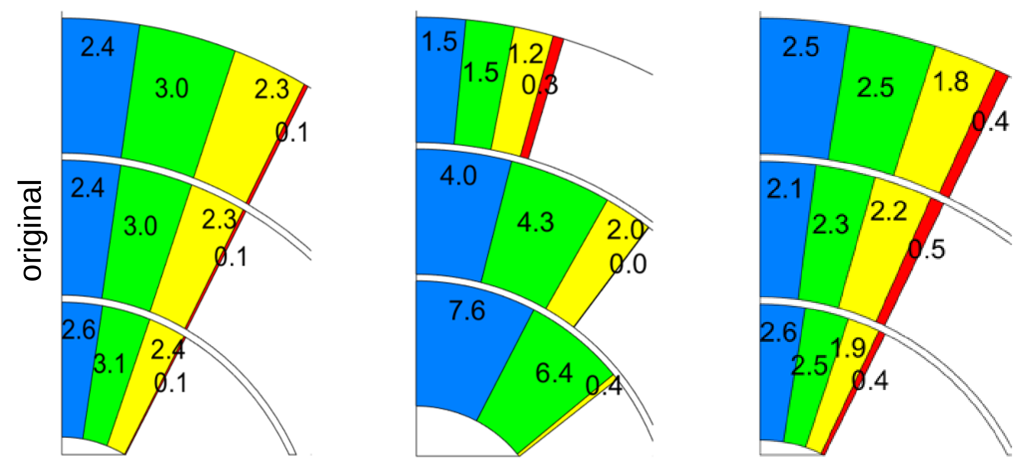
inundation depth classes
0.10 – 0.20 m
0.20 – 0.50 m
0.50 – 2.00 m
> 2.00 m

Variation of roughness, slope, and settlement density

Simulation of combined influence factor combinations

DWD4 = 40mm/h

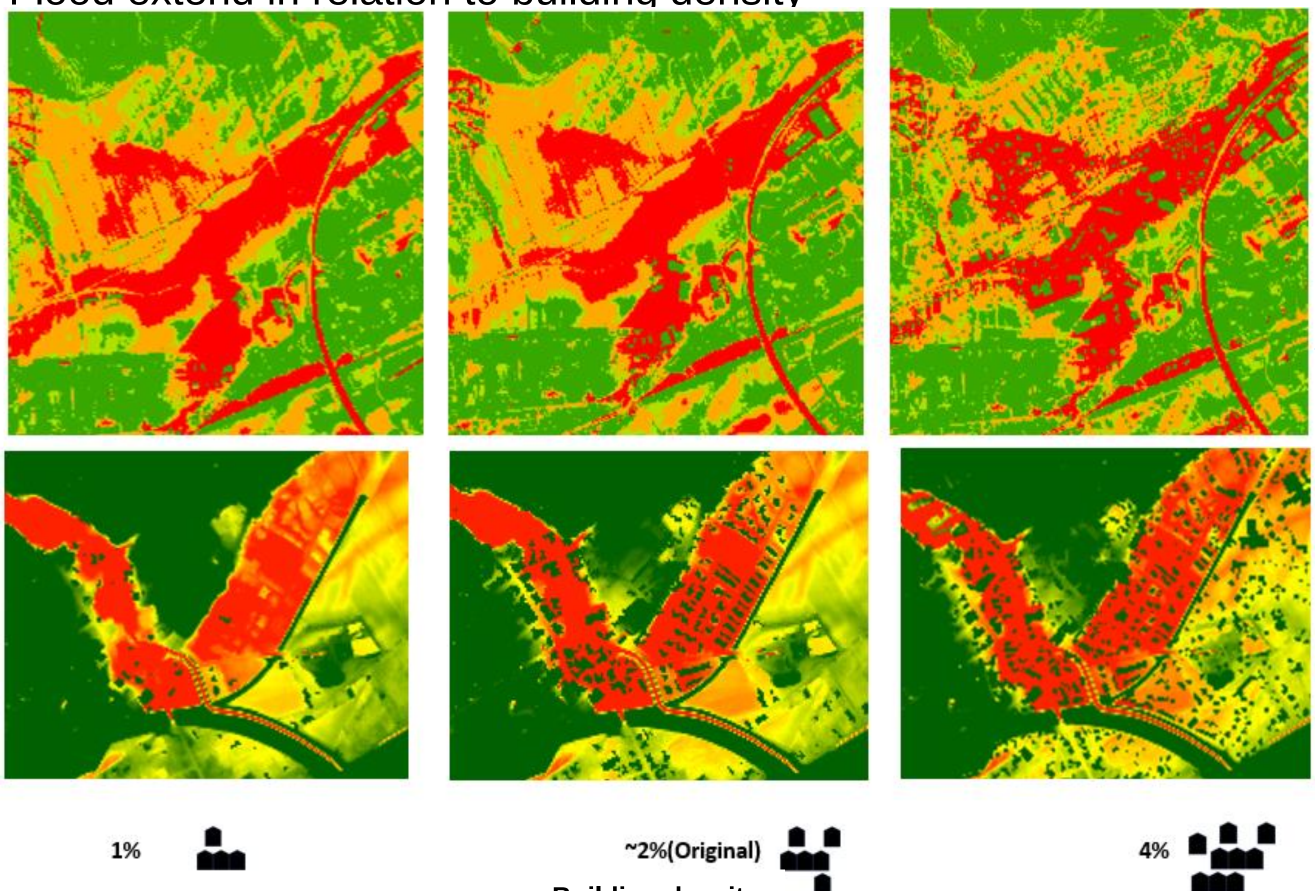
roughness (Kulmbach Süd)	**slope** (Baiersdorf)	**building density** (Simbach)
cropland 15 $m^{1/3}/s$ grassland 20 $m^{1/3}/s$ (forests < 10% of catchm.)	55 %	4 %

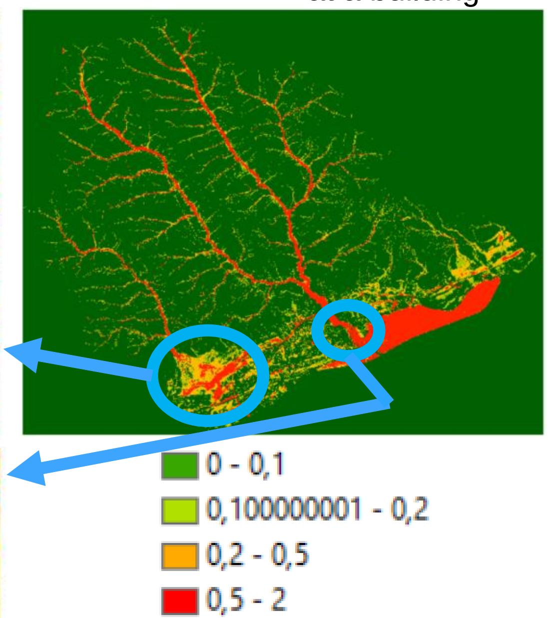


forest 10 $m^{1/3}/s$ (crops and grass < 10% of catchm.)	1 %	1 %

Influencing factor buildings & streets

Flood extend in relation to building density





→ There is no clear relationship between flood extend and building density

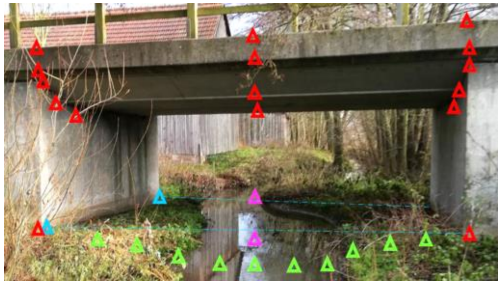
→ Shape and orientation of buildings with respect to flow direction is more important.

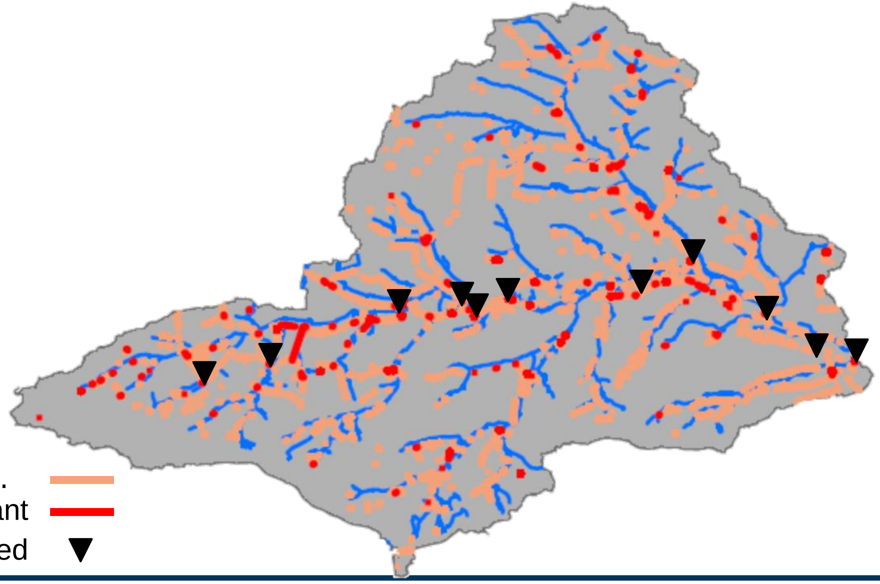
Hinweiskarte Oberflächenabfluss
und Sturzflut

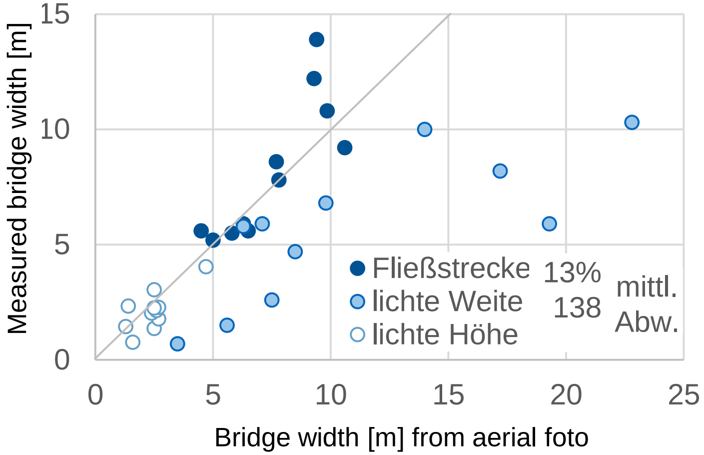
HiOS

Influencing factor structures: Culverts & bridges

Comparison of an estimation of building dimensions from aerial photograph and DTM (1x1 m²) with a GNNS survey for 11 important buildings in Stöckach (Verena Hefter)







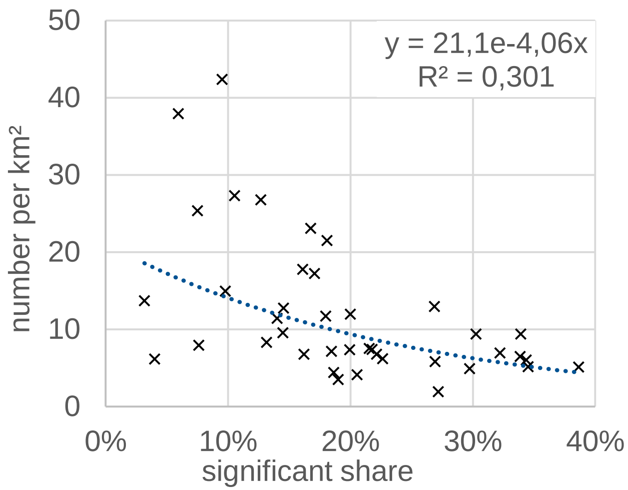
→ Culverts&bridge cross section has to be measured.

→ Estimates are not valid.

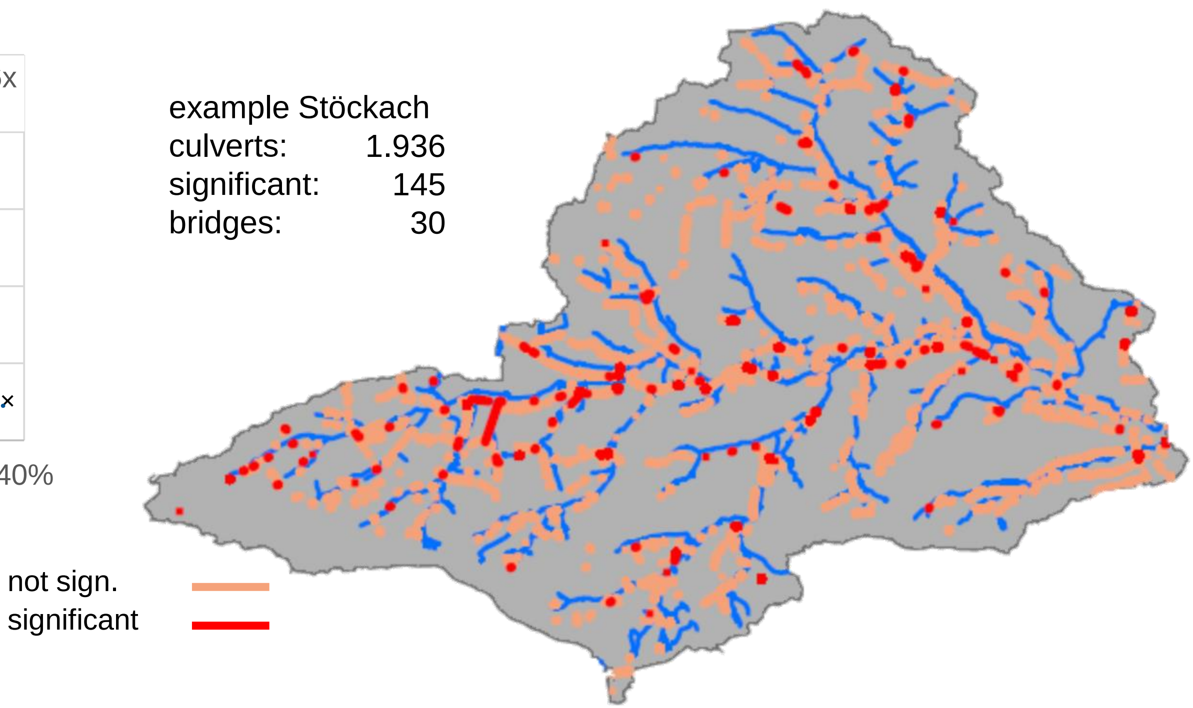
→ Small bridges and culverts are prone to clogging.

Runoff concentration: culverts

Mapping of culverts in 40 catchments using digital elevation model (1x1 m²), areal photographs, land use data (ATKIS), flow accumulation grids and sink polygons (CutFill)



example Stöckach	
culverts:	1.936
significant:	145
bridges:	30



→ around **2 significant structures per km² of catchment**

Influencing factor structures: Culverts

Study on the effect of culvert modeling: example Triftern (Christof Hertle)

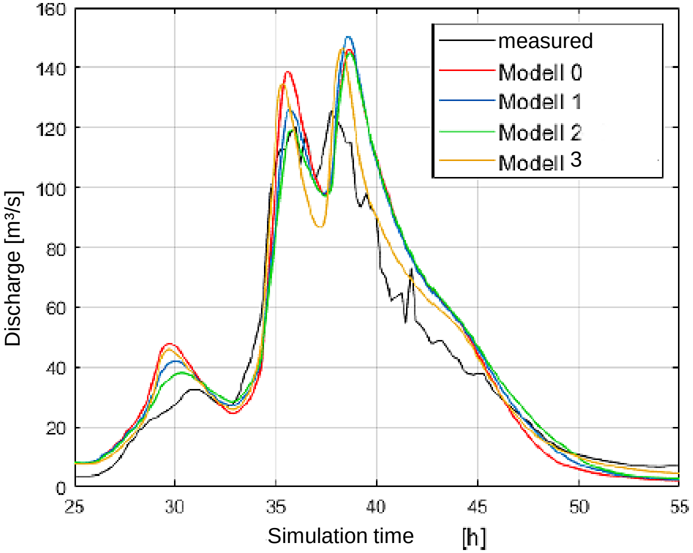
Modell 0 = continous stream model *

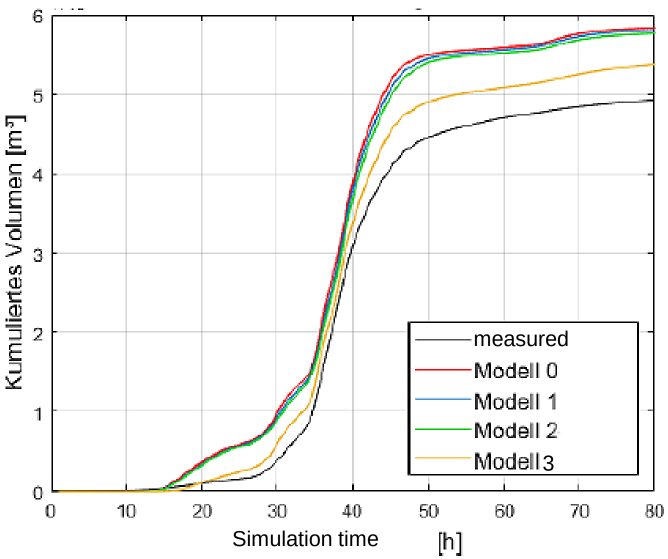
Modell 1 = hydrodynamic modeling of culverts using measured diameter;

Modell 2 = hydrodynamic modeling of culverts using estimates for the diameter;

Modell 3 = non continous stream model

*) the stream bottom elevation is made monton falling in flow direction; blockage by dams is removed (breaching).

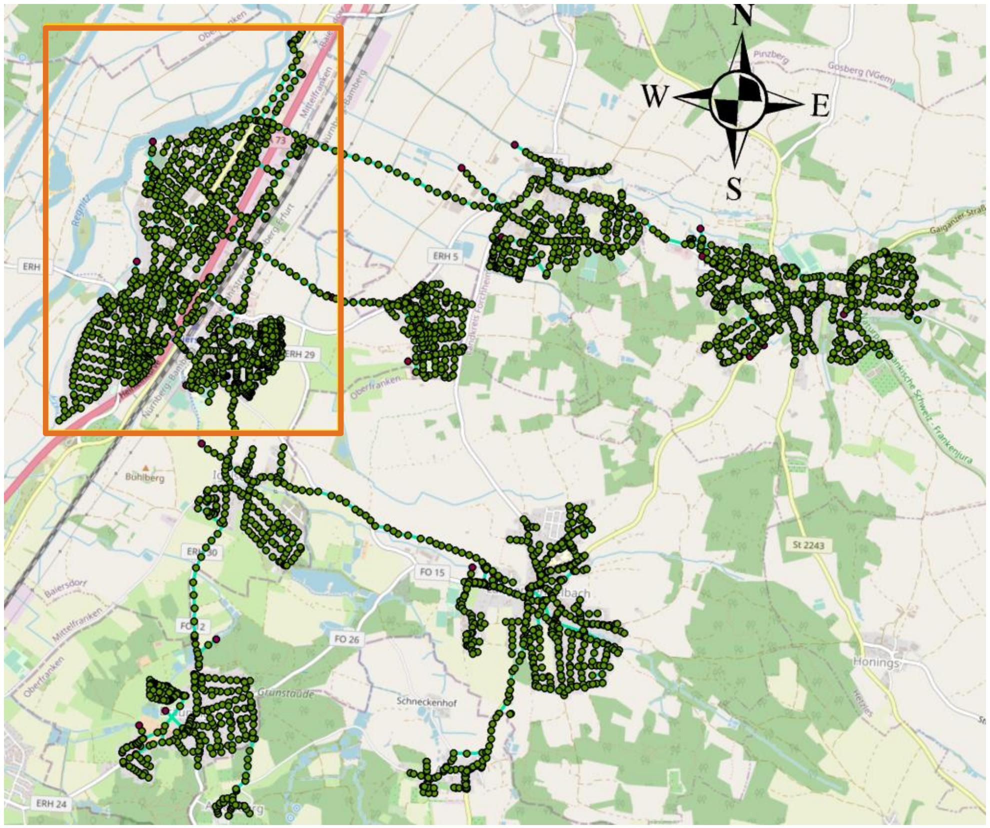




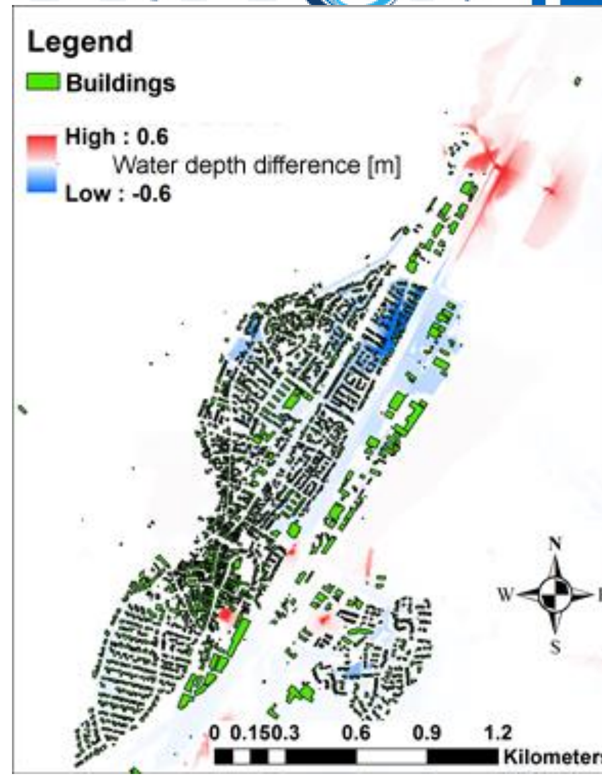
Hinweiskarte Oberflächenabfluss
und Sturzflut

Influencing factor: sewer network

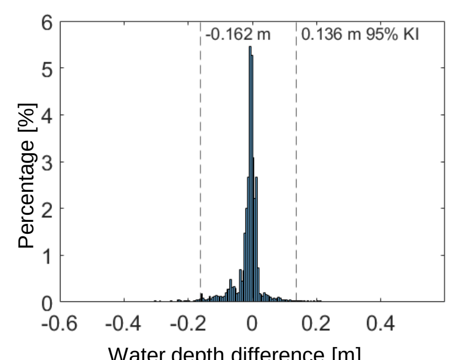
Baiersdorf



[-16 bis 14] cm



Baiersdorf



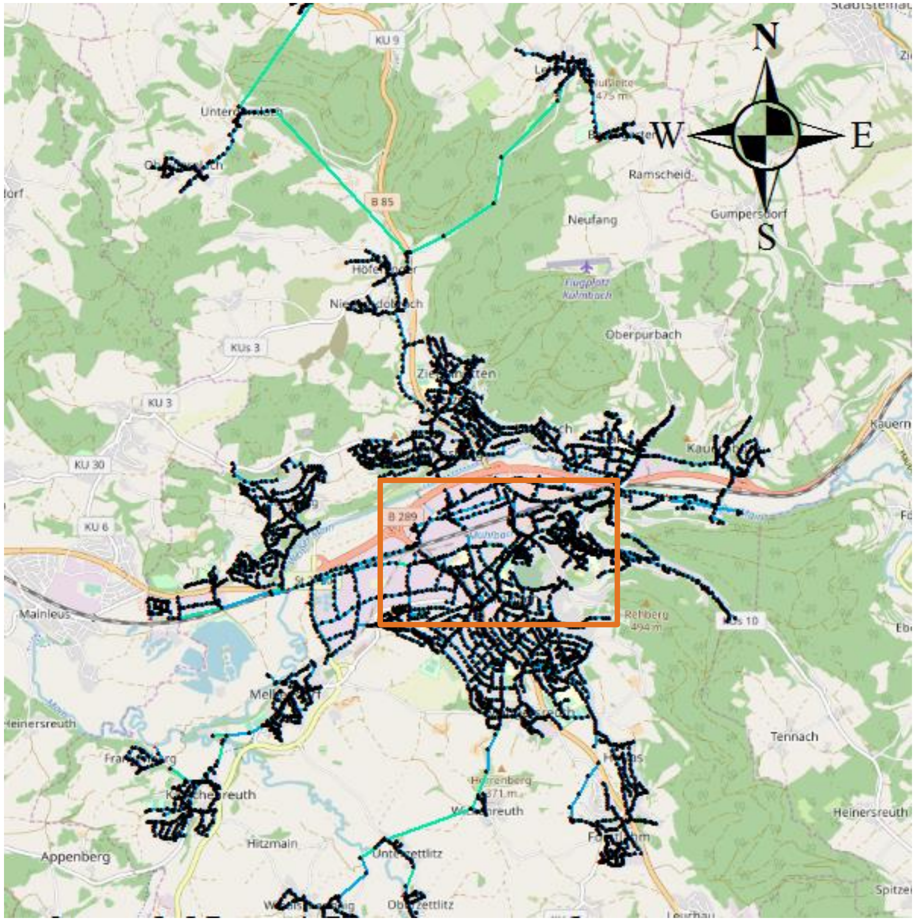
Histogram of the percentage of the difference of water levels in cells

43

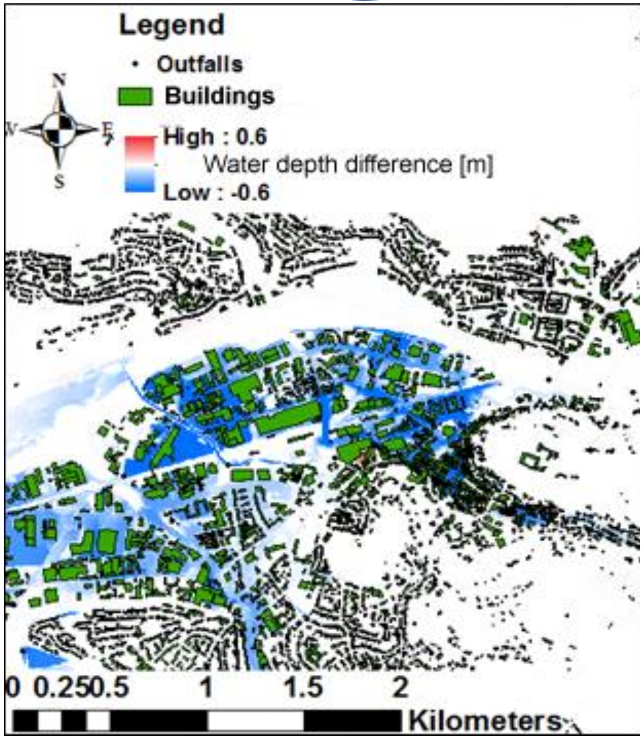
Hinweiskarte Oberflächenabfluss und Sturzflut

Influencing factor: sewer network

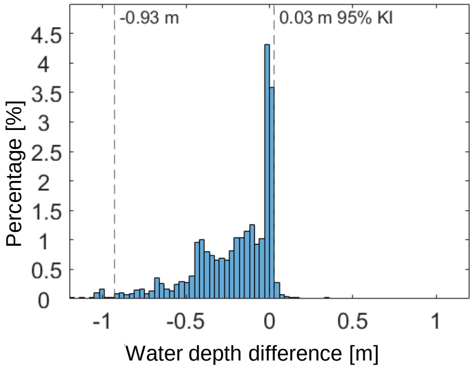
Kulmbach Süd



[-90 bis 3] cm



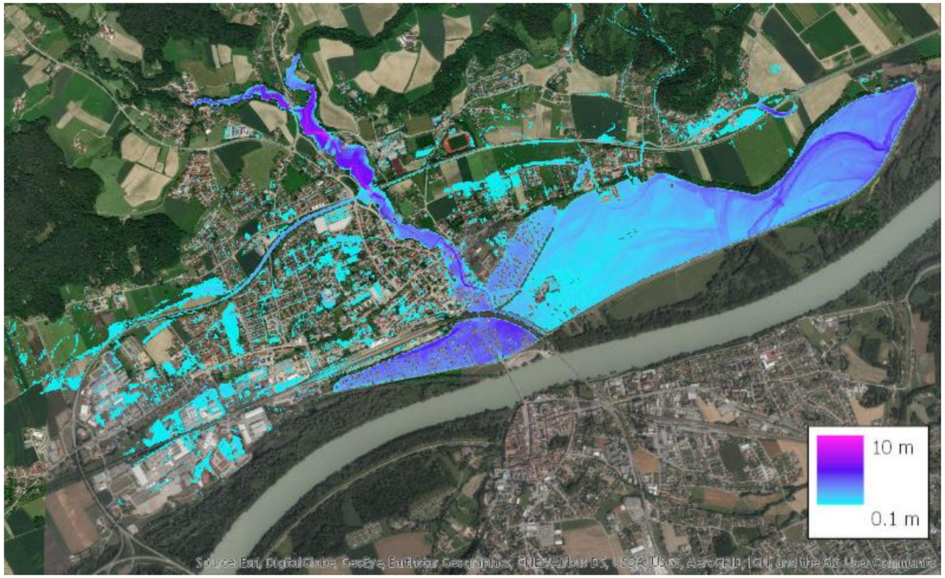
Kulmbach Süd

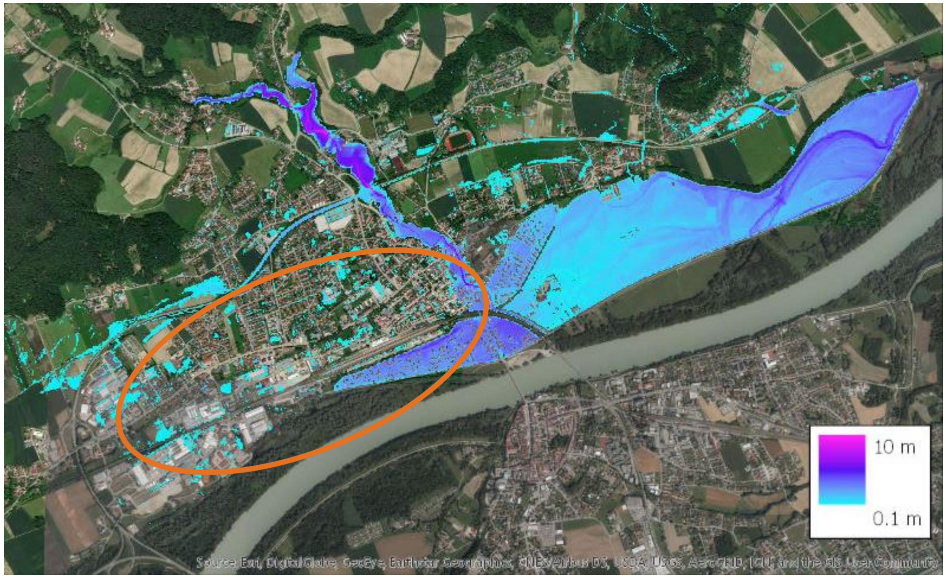


Histogram of the percentage of the difference of water levels in cells

Influencing factor: sewer network

Simulation of flash flood event 1.6.2016, Simbach





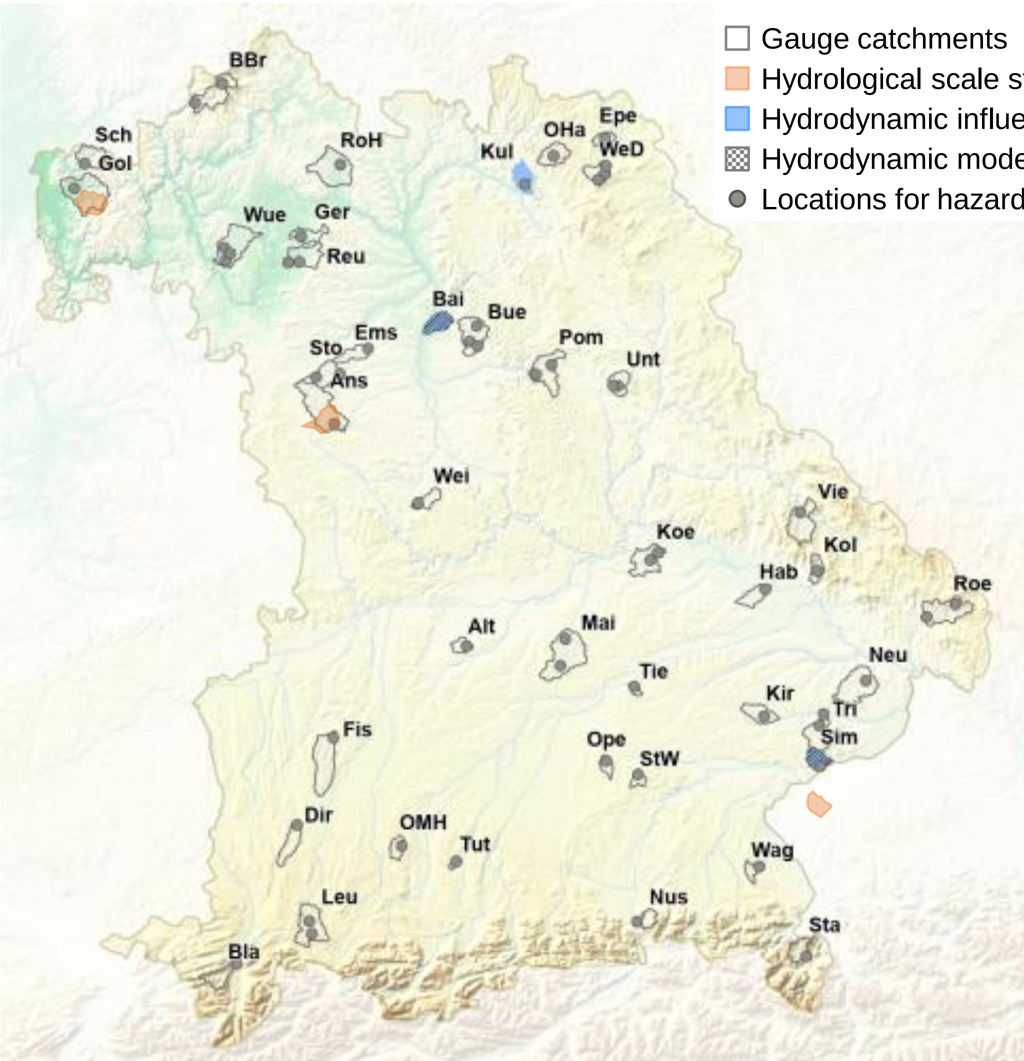
Sewer system

- tubes: 51,8 km
- Manhole: 1525
- Outfalls: 22
- Pumps:3
- Punp failure:1
- Sewage treatment plant:1

Inhabitants: 9954

3. Results

Catchments

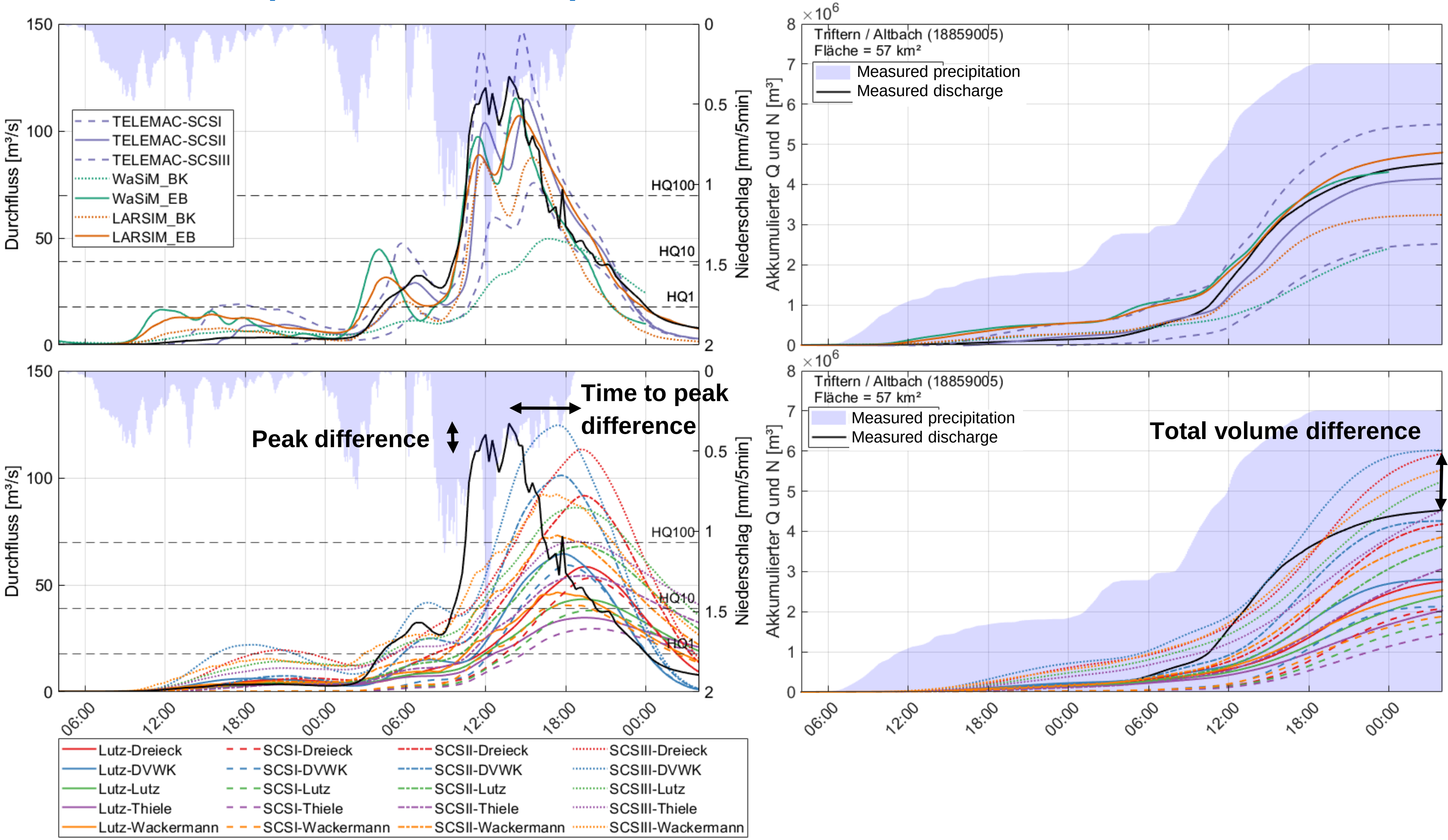


Selected:

→ **40 gauge catchments** with **34** (54) **heavy precipitation events** for event analysis and hydrological influencing factors

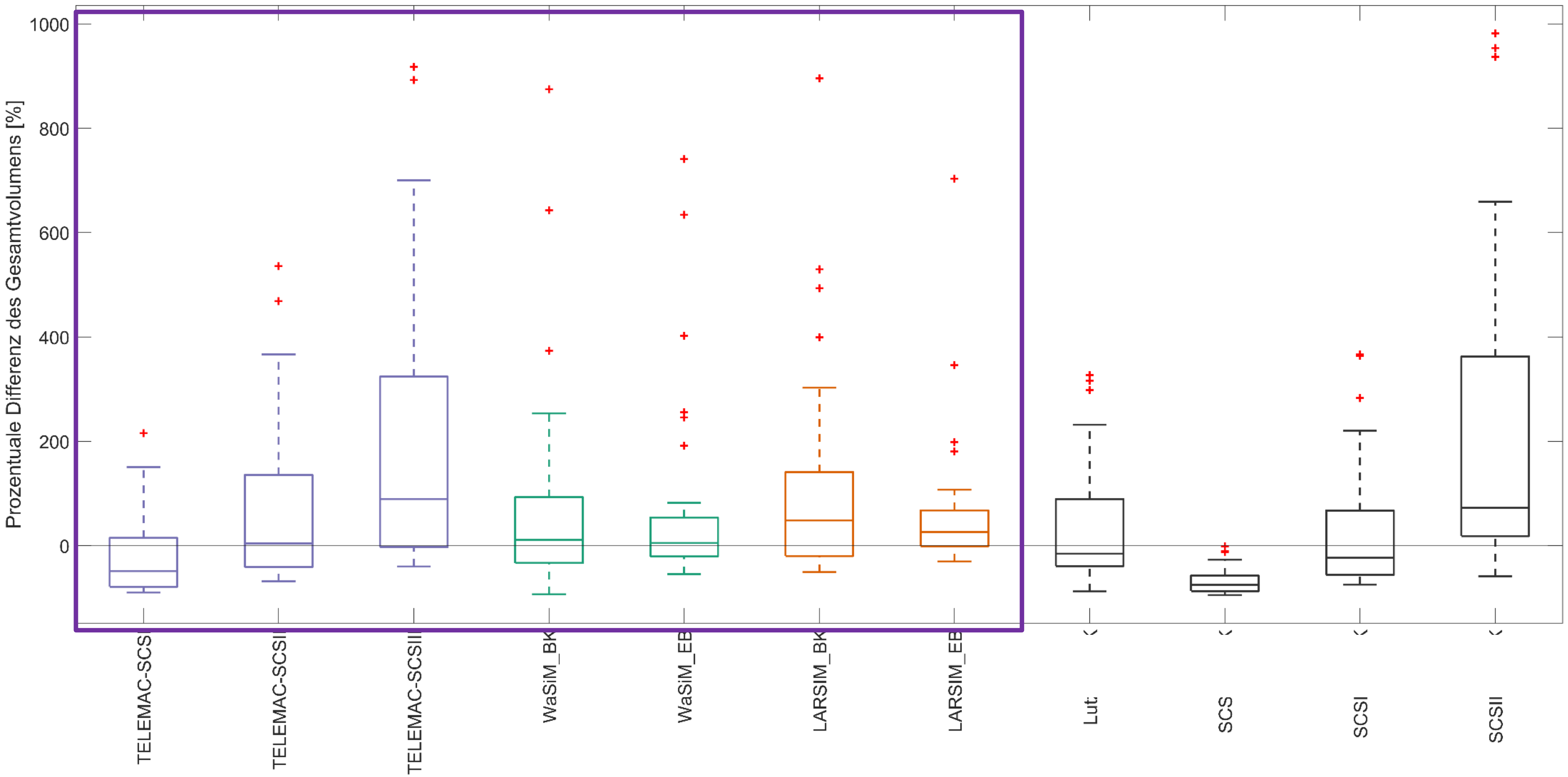
→ **56 locations** for „exemplary“ calculation of hazard map simulation work flow

Results – Representative analysis for catchment Triftern



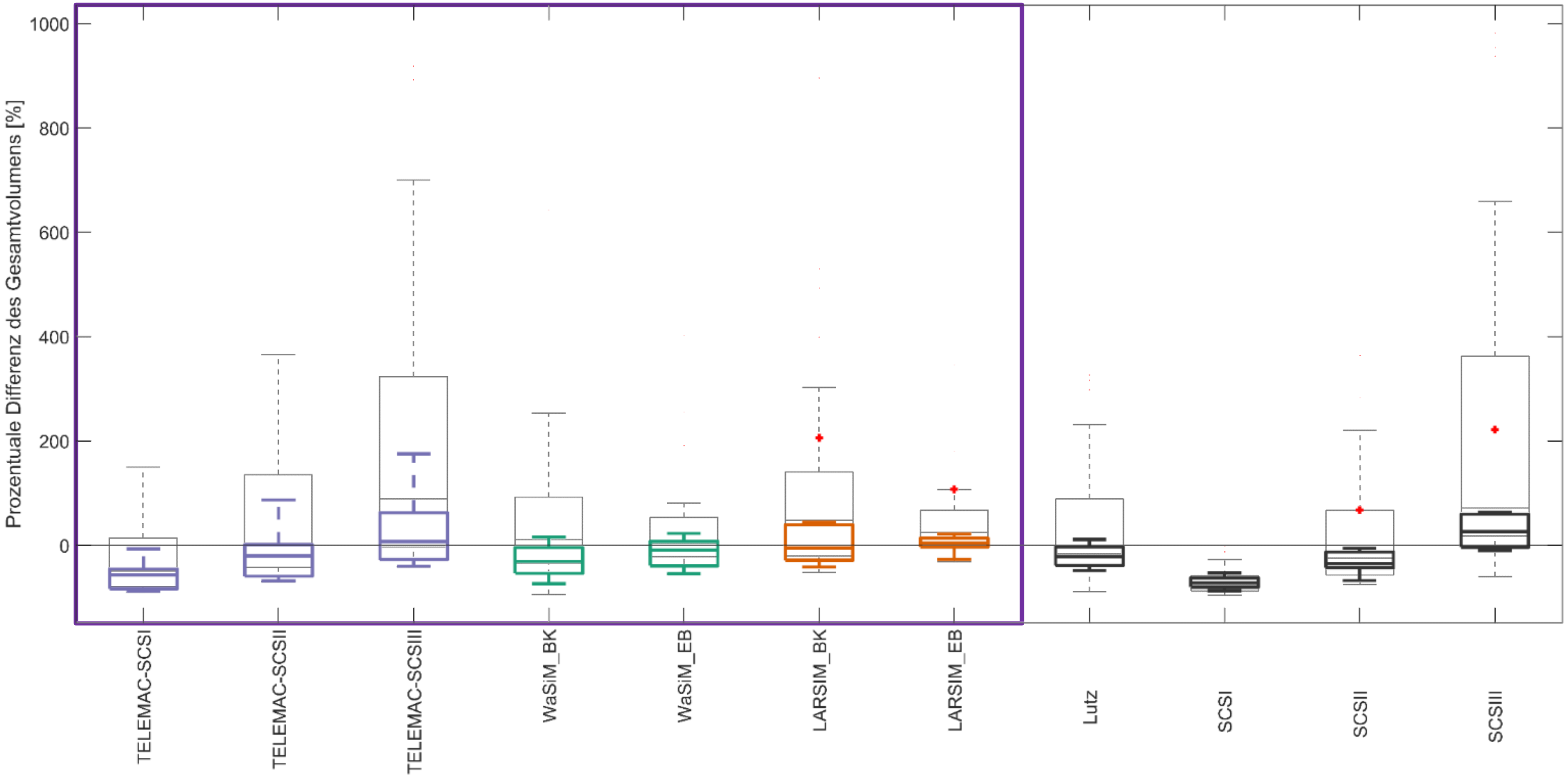
Results – Total volume difference [%]

n = 34, all events



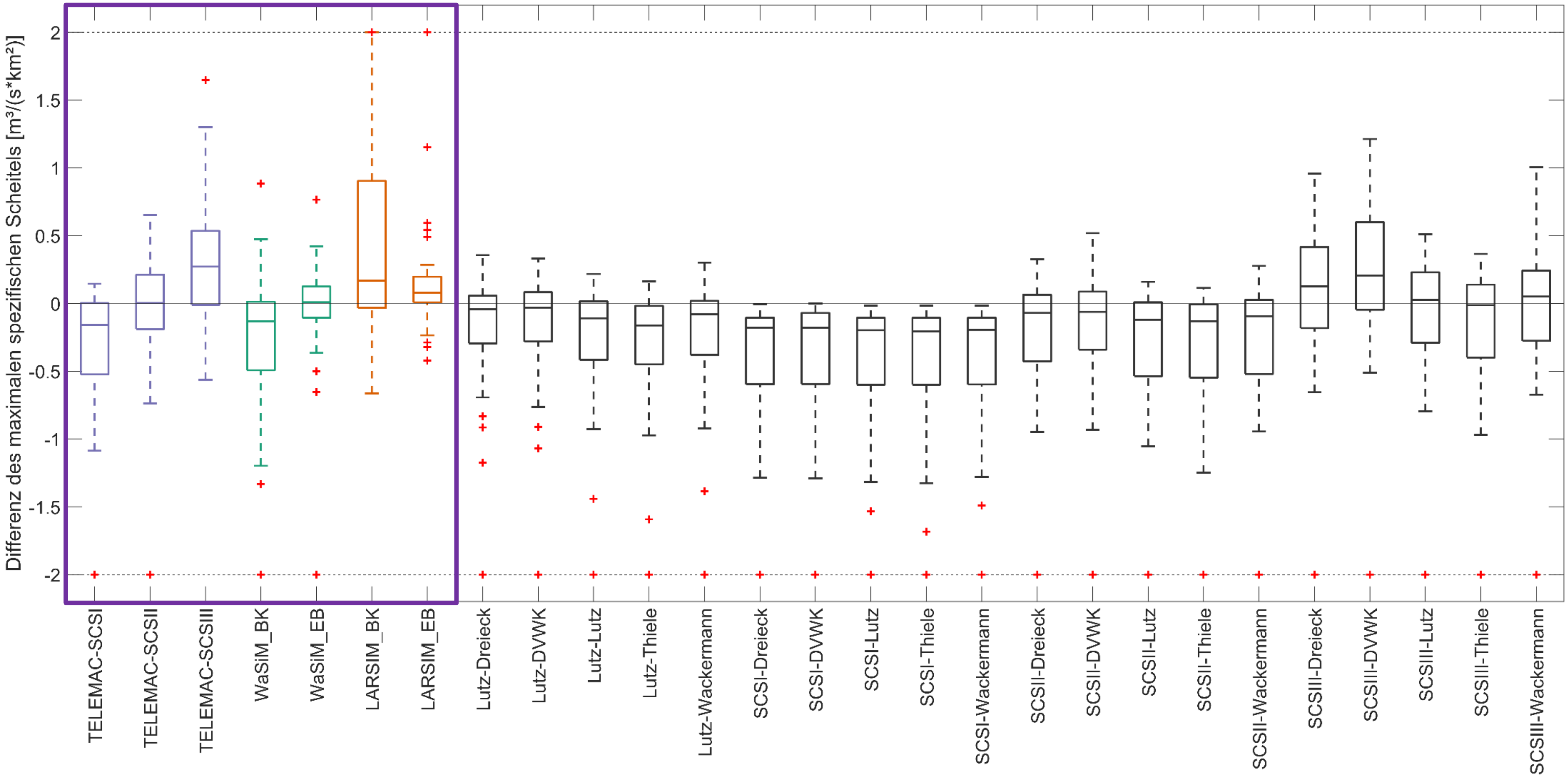
Results – Total volume difference [%]

n = 34, all events, grey
n = 8, events > HQ50, bold



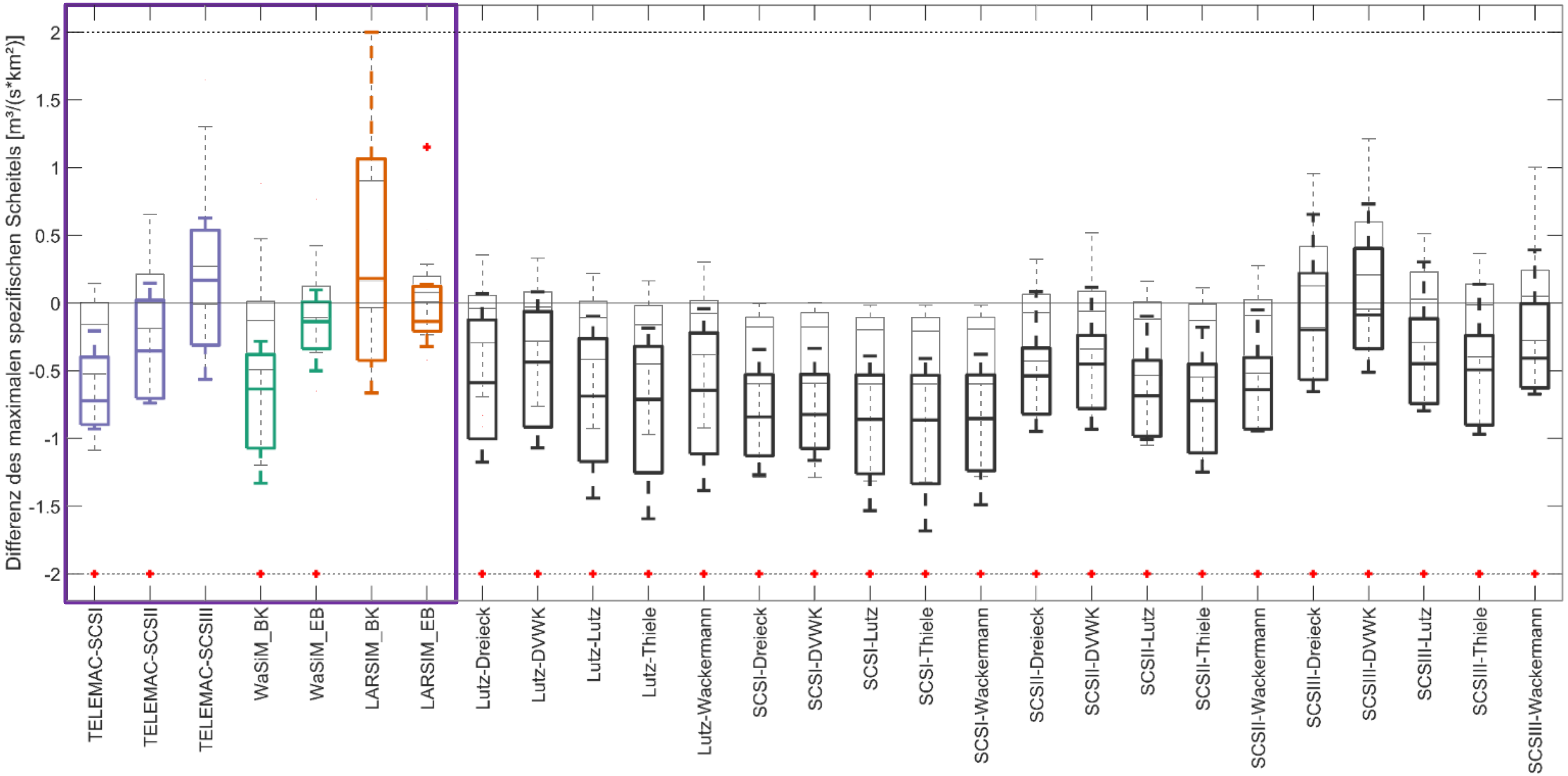
Results – Peak difference [m³/(s*km²)]

n = 34, all events



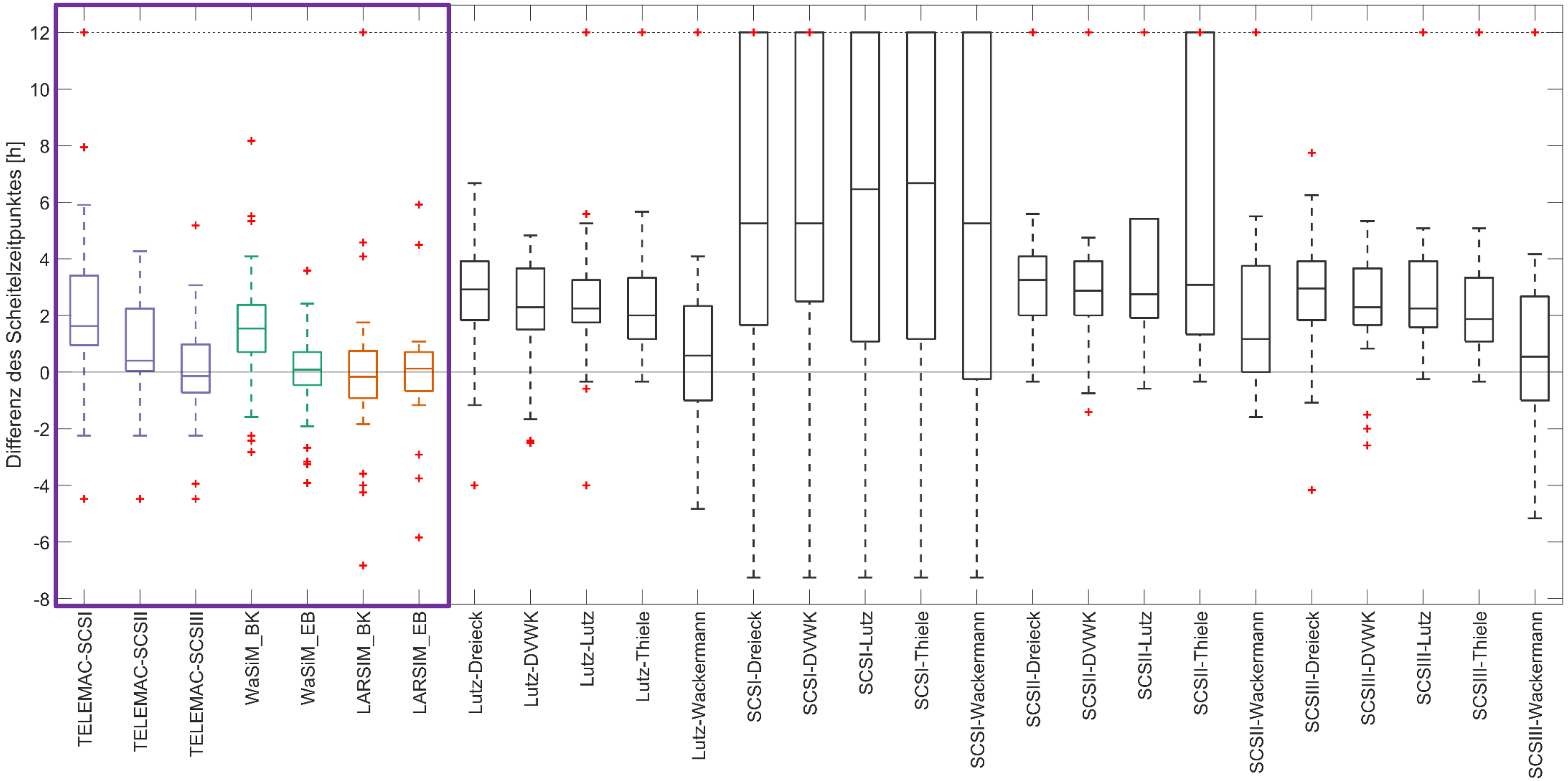
Results – Peak difference [m³/(s*km²)]

n = 34, all events, grey
n = 8, events > HQ50, bold



Results – Time to peak difference [h]

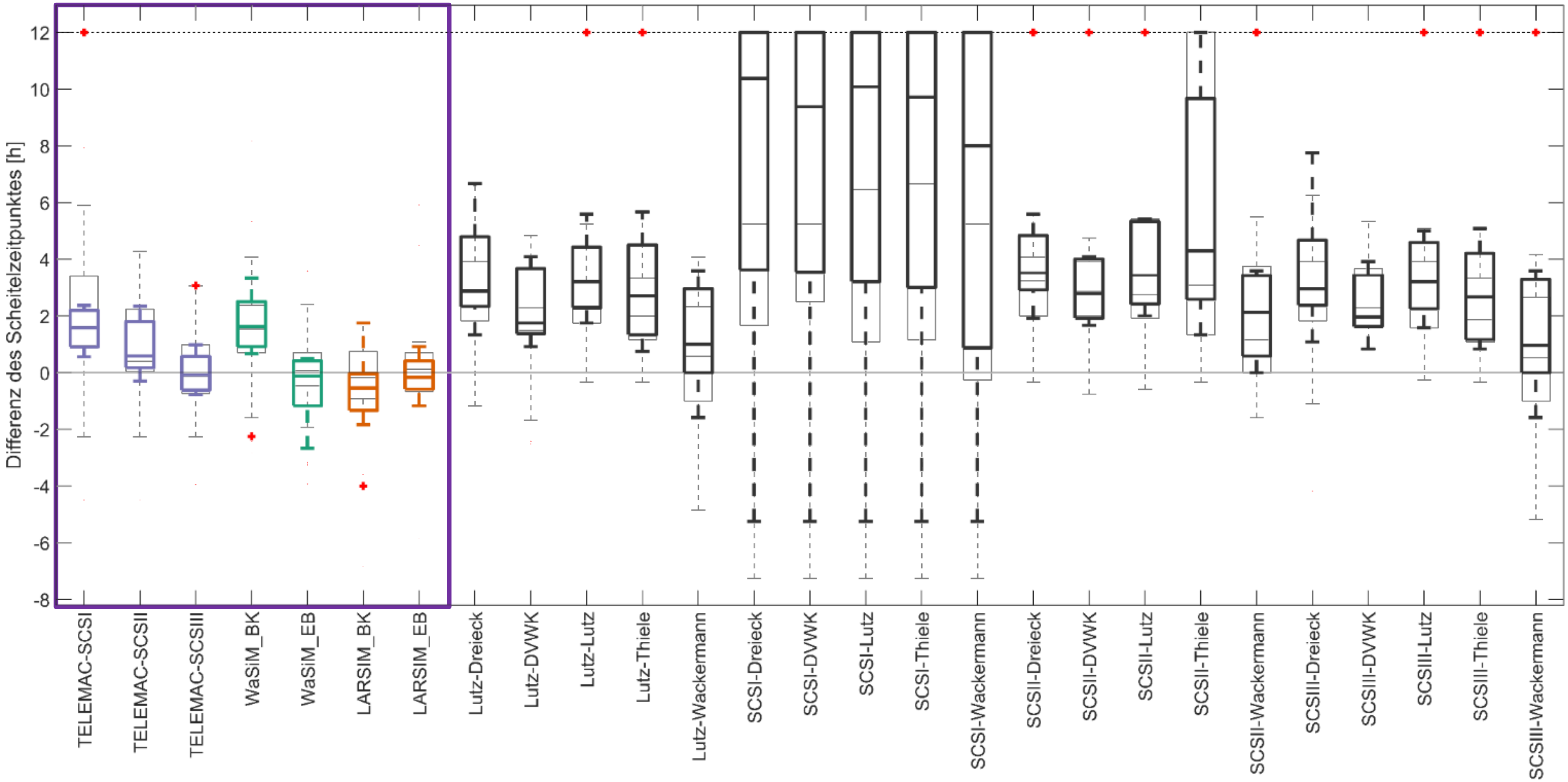
n = 34, all events



Results – Time to peak difference [h]

n = 34, all events, grey

n = 8, events > HQ50, bold



Model-based hazard map

Max. water depth

Pluviales Szenario
100 mm in 1 h
Fluviale Szenarien
N 100 / 1000

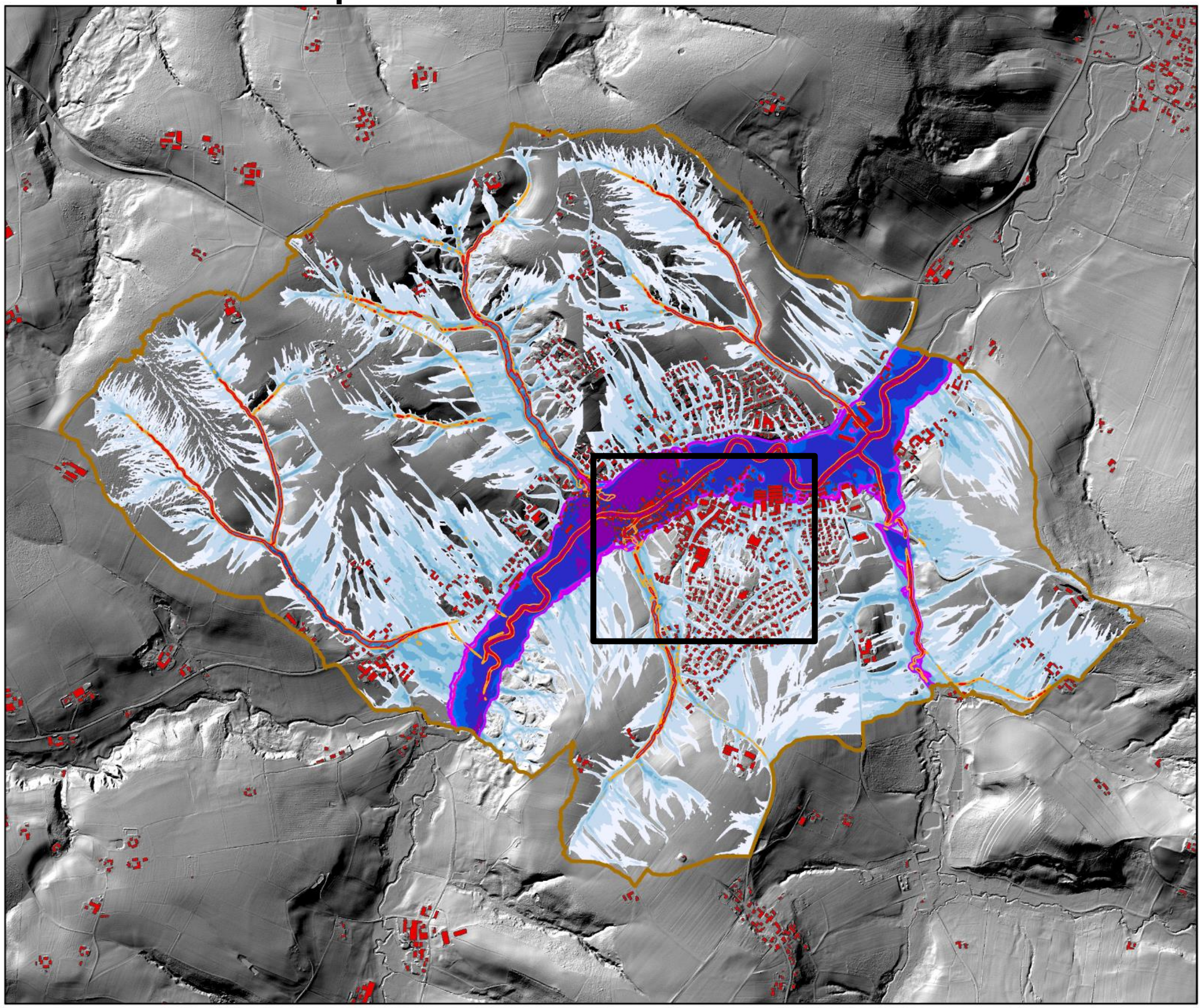
Max. water depth pluvial
- 0,10 - 0,25 m
- 0,25 - 0,50 m
- 0,50 - 1,00 m
- 1,00 - 2,00 m
- > 2,00 m

Max. water depth fluvial
- 0,05 - 0,10 m
- 0,10 - 0,25 m
- 0,25 - 0,50 m
- 0,50 - 1,00 m
- 1,00 - 2,00 m
- > 2,00 m

Hazard in flood flows
- 0,70 - 1,30 m*m/s
- > 1,30 m*m/s
- Gebäude
- Modellrand
- Ü-Grenze N100
- Ü-Grenze N1000

0 225 450 m

N



Model-based hazard map

Max. water depth

Pluviales Szenario
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N 100 / 1000

Max. water depth pluvial
- 0,05 - 0,10 m
- 0,10 - 0,25 m
- 0,25 - 0,50 m
- 0,50 - 1,00 m
- 1,00 - 2,00 m
- > 2,00 m

Max. water depth fluvial
- 0,00 - 0,05 m
- 0,05 - 0,10 m
- 0,10 - 0,25 m
- 0,25 - 0,50 m
- 0,50 - 1,00 m
- 1,00 - 2,00 m
- > 2,00 m

Hazard in flood flows
- 0,70 - 1,30 m*m/s
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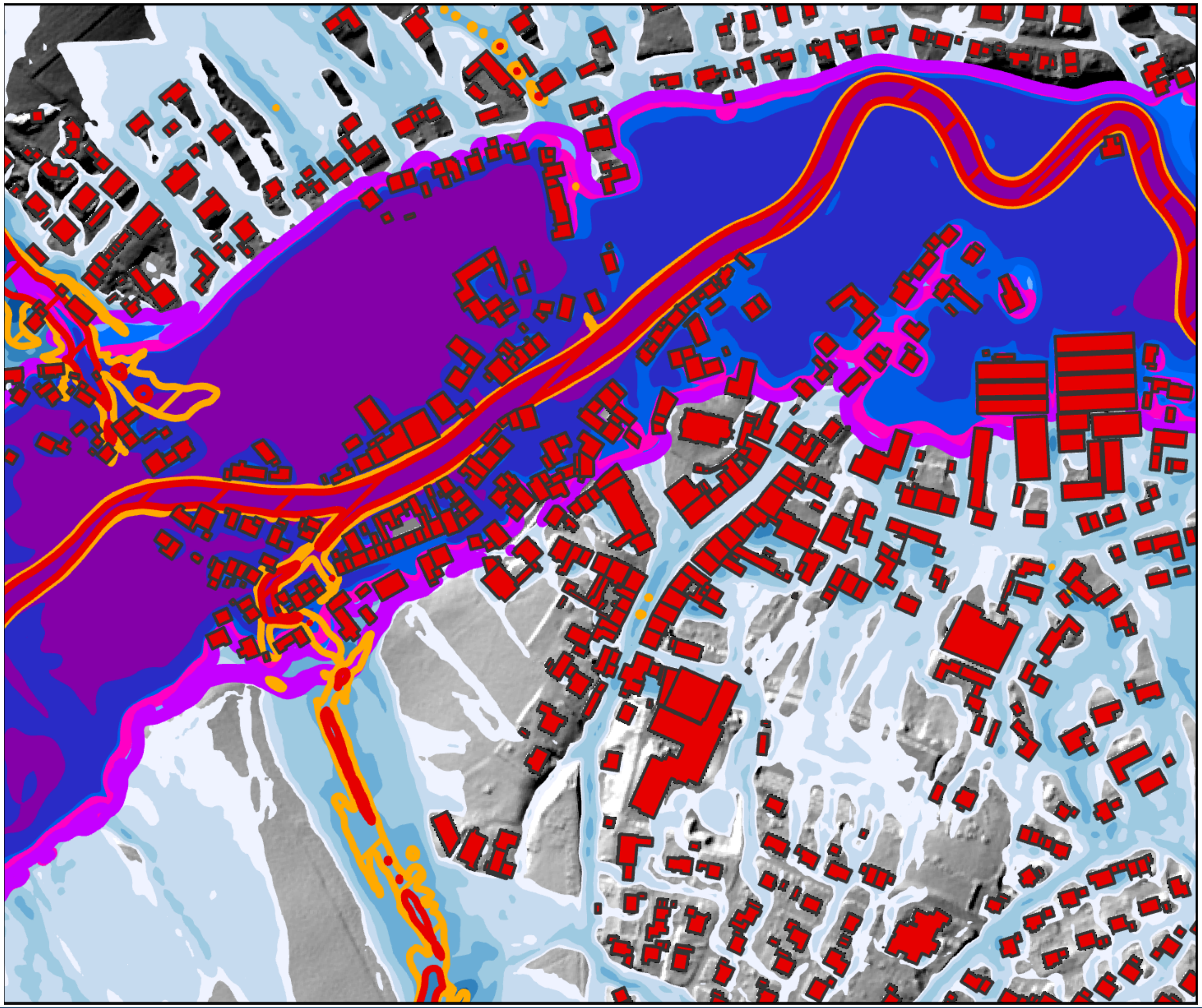
- Modellrand
- Ü-Grenze N100
- Ü-Grenze N1000

0 225 450 m
N



4. Summary and Conclusion

Summary

Historical Events

Event characteristics

- Short but heavy precipitation events do not show significant clustering in Bavaria
- Precipitation characteristics of events are very diverse and show a high complexity in space and time
- Runoff coefficients show a large variability.

Simulation results

- The diversity of runoff generation results is huge dependent on event characteristics and model types.
- A two-dimensional hydrodynamic model is recommended to reproduce runoff concentration dynamics.
- As calibration is tendentially difficult for small potentially ungauged catchments, models without need for calibration are preferrable – as long as they reproduce major processes.
- Recently developed models use bidirectional coupling of in-/exfiltration and two-dimensional runoff concentration

Summary

Hydrological influencing factors

- **Precipitation** is an important but **not changeable influencing factor**.
  - Variables **duration, intensity and wetted share of catchment** dominate hydrographs of heavy precipitation.
  - **Intensity** and **presaturation** dominate **peak discharge** and **runoff volume**. **Duration** and - less important - temporal distribution influence the **peak lag time**.
- **Infiltration** is influenced by soil condition (e.g., soil moisture) as well as by precipitation intensity and with lower importance temporal distribution.
  - **Runoff volumes and peak discharge may be multiplied if soil conditions change**.
  - Soil conditions are hardly ever monitored and we could not reproduce them satisfactory using simulations (potential draw-backs from weak calibration).

Summary

Hydrodynamic influencing factors

- The **slope factor** has the greatest influence. The roughness has little influence on the percentage of maximum water levels.
- **Buildings** can block runoff and divert flow (e.g. dam effect of terraced houses across the direction of flow).
- **Culverts and Bridges** have low impact if they are well designed. They can have a significant impact if they are blocked during the flood event (clogging hazard*) or not modeled.
- The **sewer network** influences surface runoff . It usually has a low relieving effect for extreme floods. However, if the sewer network is overloaded, there can also be significant water flow from the sewer system.

*) Clogging is a so called cascading hazard like f.i. dam-break.

Summary

Model-based hazard map generation

Hazard maps – an important tool for risk communication

- ... provide indications of a possible risk of surface runoff and flash floods and thus serve to raise awareness of the topic of heavy rain hazards.
- … are an aid for interested citizens, municipalities, as well as specialized planners and ministries.
- … should encourage citizens and communities to assess their individual risk situation.

Conclusion



Problem


Activity

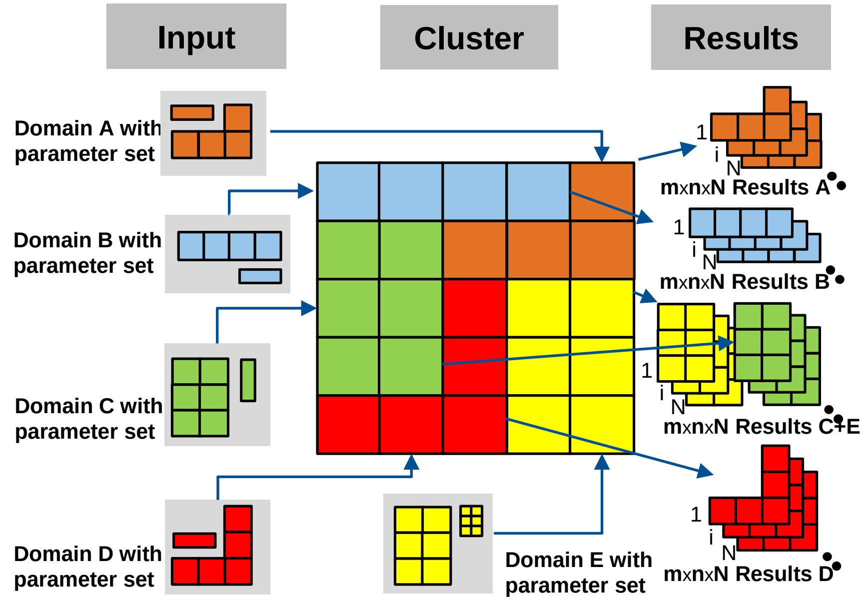
HPC-system

LRZ-Cluster CoolMUC2

- Number of nodes 384
- Cores 28 per node
- Prozessor 2.6 GHz

LRZ-Cluster SuperMuc-HW

- Number of nodes 3072
- Cores 28 per node
- Prozessor 2.6 GHz



HPC Scaling test

1 node = 28 cores

Optimal node number : 4
(= 112 cores)