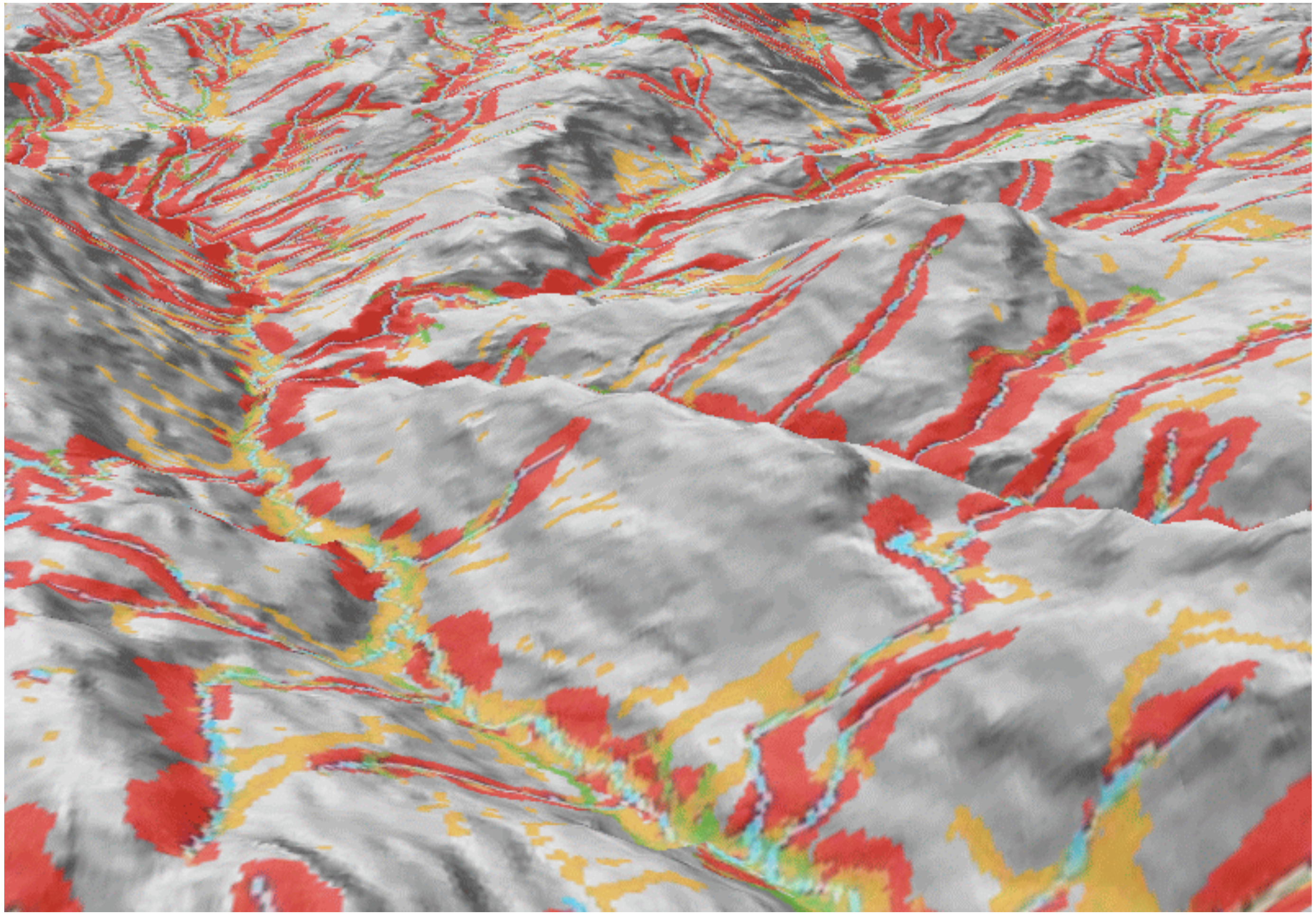
Source Area Connectivity in Parsimonious Model Structures

Klemens Rosin, Markus Weiler, Georg Jost

Starting Point

- Connectivity of dominant runoff generation areas to the channel network?



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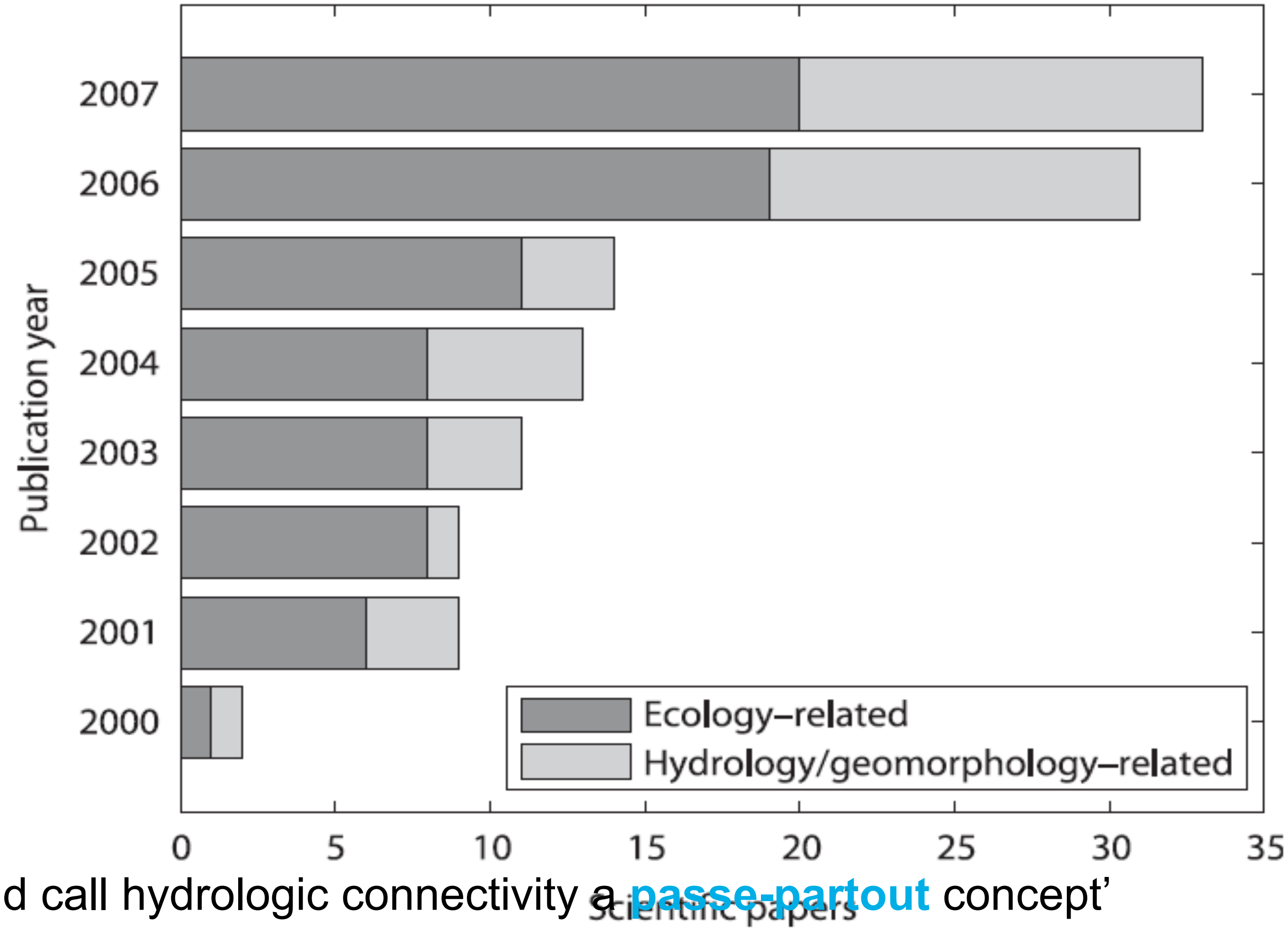
Connectivity: Previous Research

- Ali and Roy (2009):



- 'we could call hydrologic connectivity a **passe-partout** concept'

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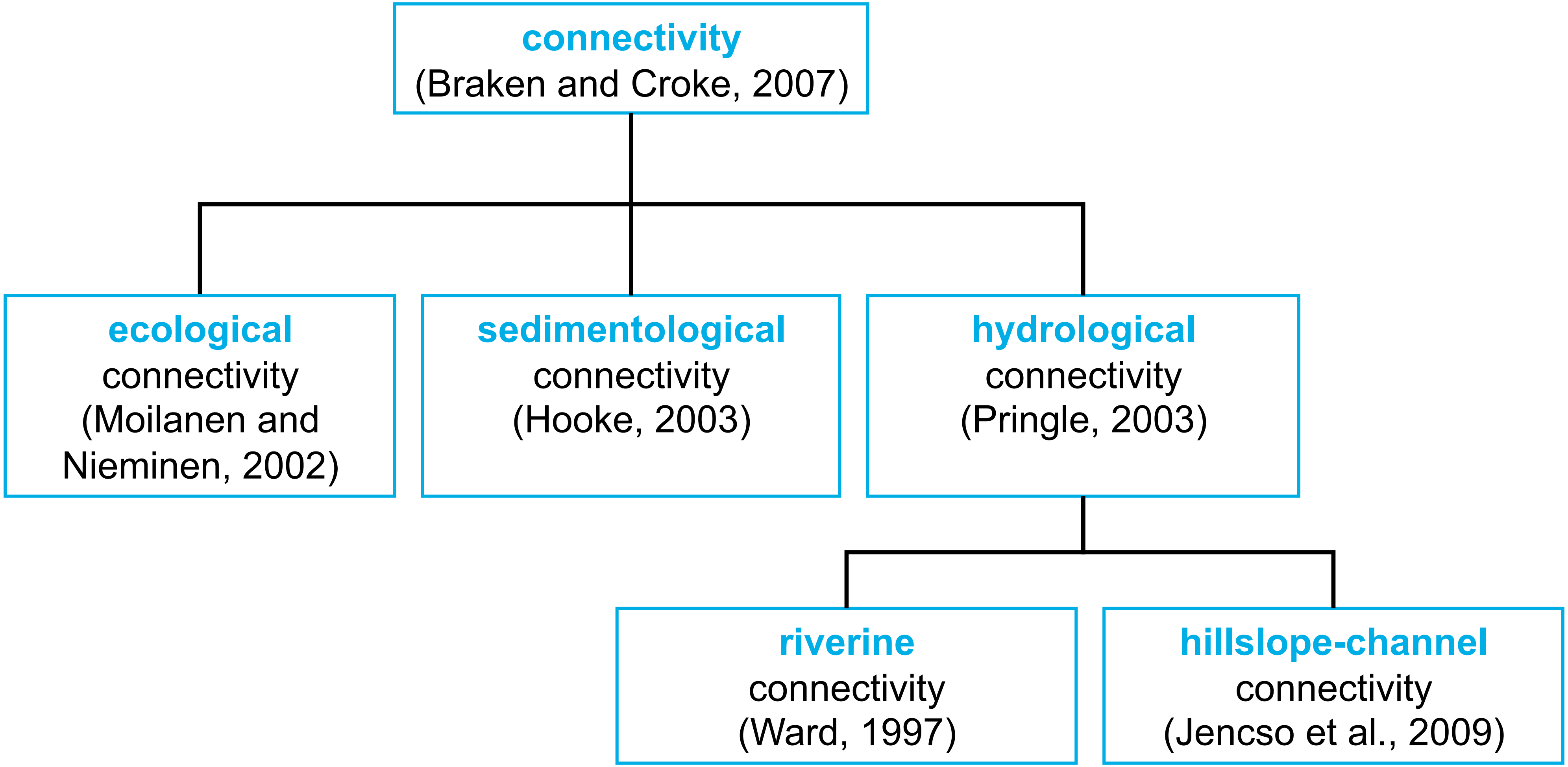

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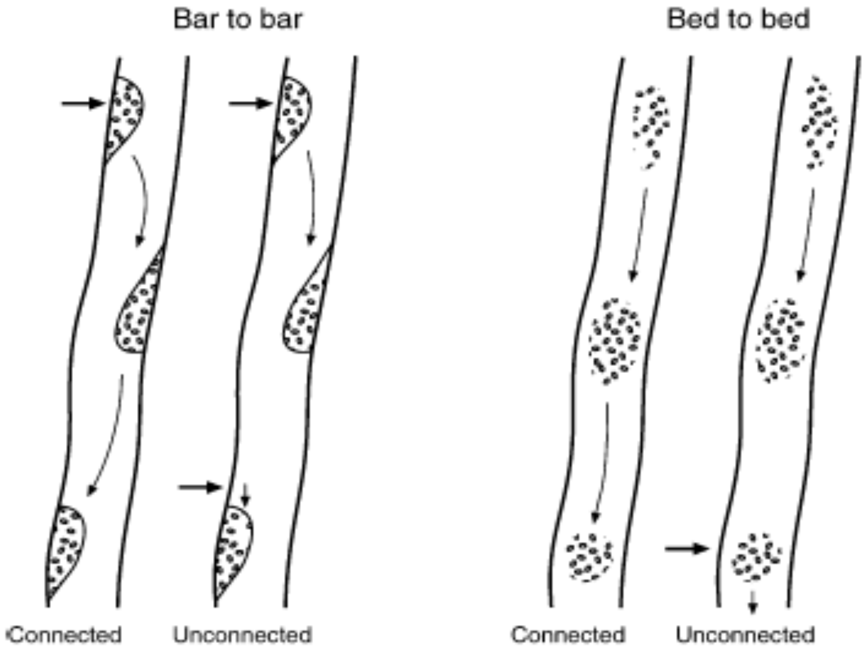
Ecological Connectivity

- Conceptual models
  - Habitat-corridor connectivity (Andreassen et al., 1998)
  - Pathd between nodes (linear connectivity, Urban and Keitt, 2001)
  - Mosaic-stepping stones (Bennett, 2003)
  - **Patch-matrix** model (Toeyra & Pietroniro, 2005)
  - **Legacy effect** (=delayed reaction; Helm et al., 2006)
- Functional characteristics: Connectivity is often
  - **Directed** (upstream/downstream; Glatzel, 2009)
  - **Species/process specific** (Habel, 2006)

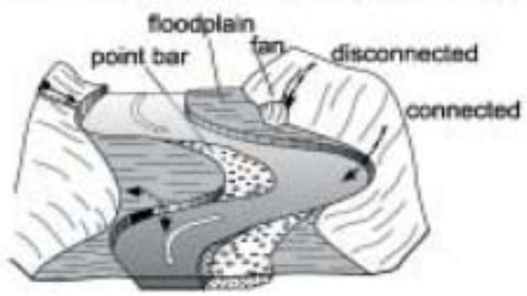
Sedimentological Connectivity

- Concepts
  - Mobilization/transport of solutes/dissolved matter (Hooke, 2003)
  - Spatial/temporal dynamics across **scales** (Brierley et al., 2006)
  - Flow dynamics/**grain size** dependence (Fryirs et al., 2007)
  - **Legacy** effect (between storms; connect/react; Thiel and Heckmann, 2009)


©Thiel,Heckmann (2009)



©Hooke (2003)



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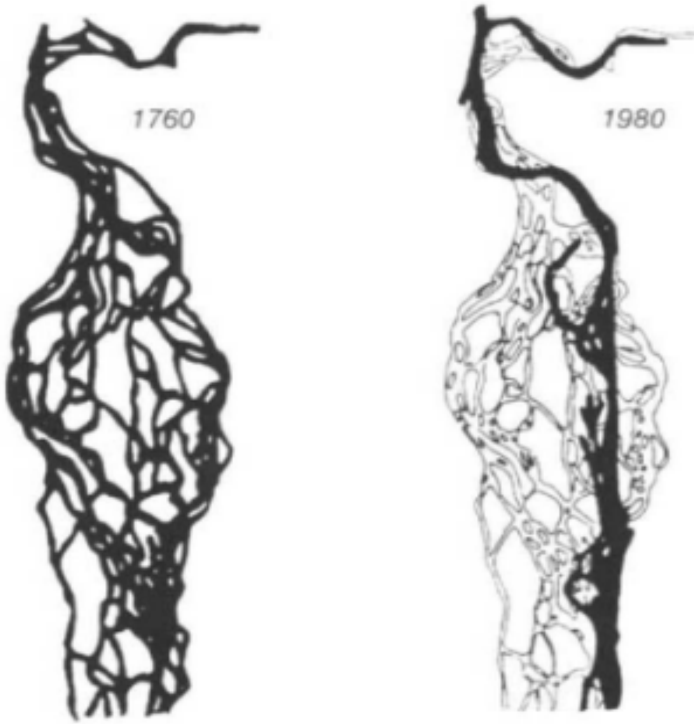
Riverine Connectivity

- Riverine connectivity
  - Water, solutes, organisms (Wiens, 2002)
  - Connectivity **proxies** (alkalinity, temperature; Tetzlaff et al., 2007)
  - Impact of **flood dynamics** on **ecology** (Danube; Hohensinner et al., 2005)



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Hillslope-Channel Connectivity: Recent Studies

- Ali and Roy (2009): **experimental designs** to detect connectivity patterns
- Bachmair and Weiler (2010): **Connect/react** concept
- Tetzlaff et al. (2007): Runoff **contributing area** connectivity (proxy = **alkalinity**)
- Jencso et al. (2009): **Duration** of **hillslope-riparian-stream** connectivity

Connect/React

- Concept analogy to **fill/spill** (Tromp-van Meerveld and McDonnell, 2006)
- Initiation of **hydrologically active** areas
  - **Surface** flow areas (rainfall intensity exceeding the infiltration capacity, surface sealing, hydrophobicity, structural features,…)
  - **Saturated** soil patches (surface and bedrock topography variation, microtopography, vegetation funnelling above-and below-ground,…)
  - High permeability **subsurface** features (decayed roots, or animal burrows,…)
- Interconnection of **hydrologically active** areas
  - **Internal network** flow (Sidle et al., 2000; Uchida et al., 2001)
  - Connection of **different types** of hydrologically-active areas (e.g. flow in high-permeability features interconnected via saturated soil patches (Anderson et al., 2008)
- Stream flow **contribution** reaction **after connection**
  - **Legacy**: Established active areas and network reoccur in next storms (finger-flow, Ritsema and Dekker, 2000; soil water content, Western et al., 2001)

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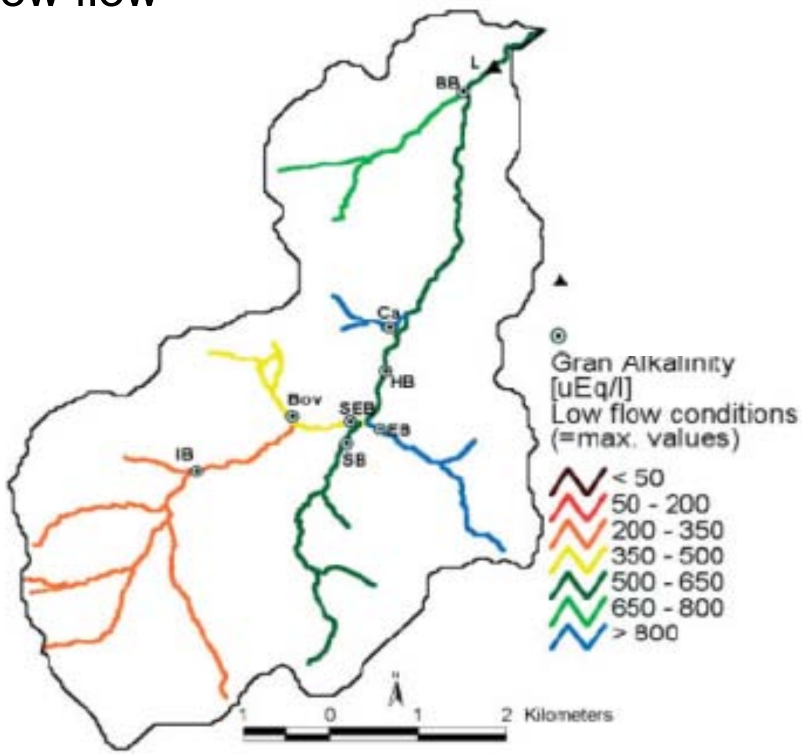
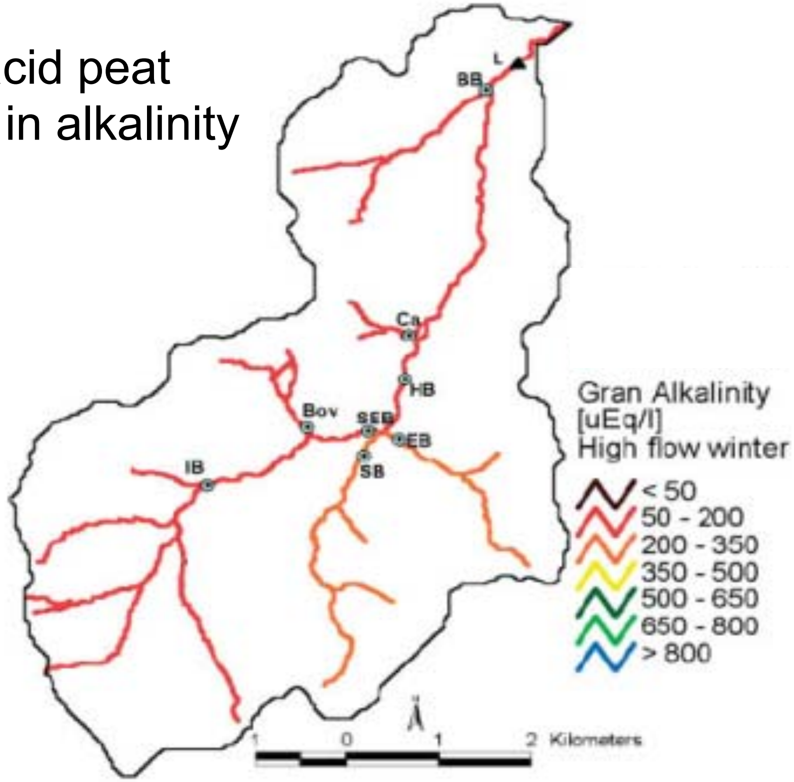
low flow



high flow:
connected acid peat
areas result in alkalinity
reductions



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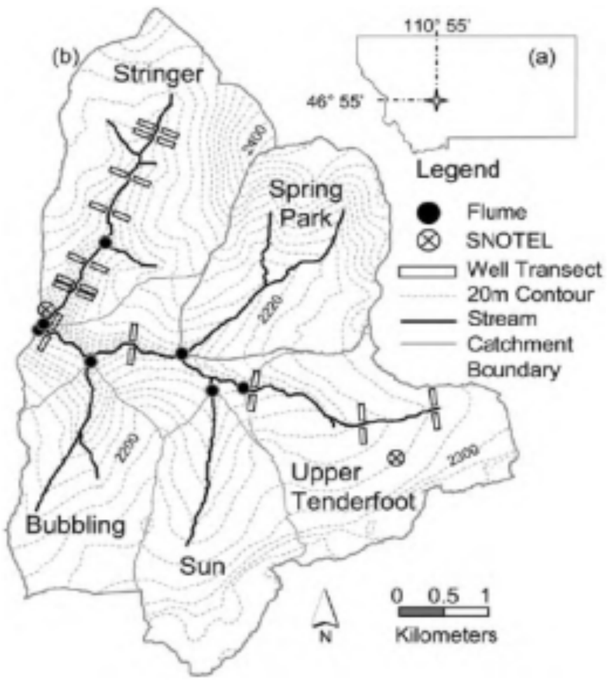
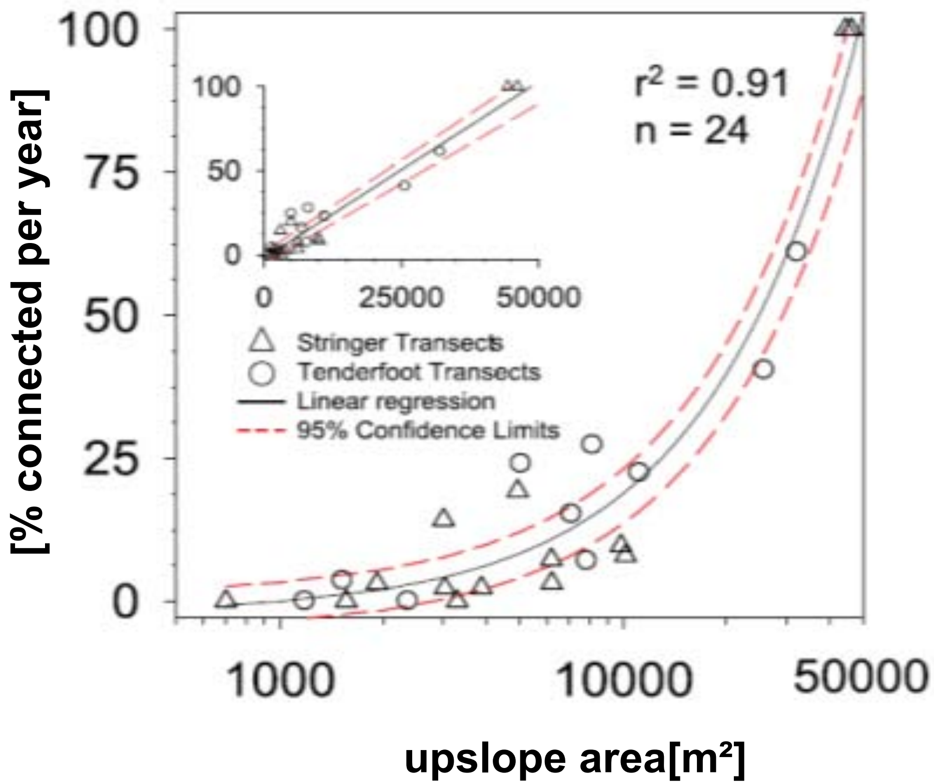
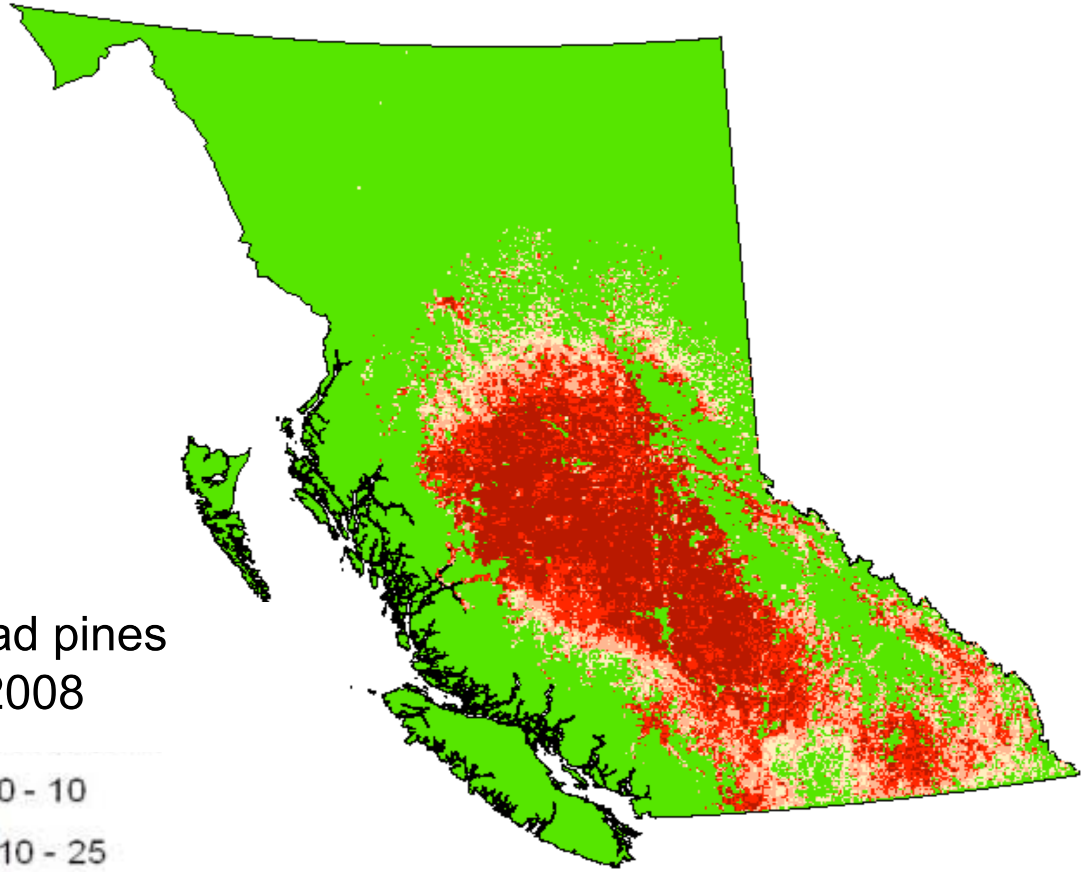


24 transects (6 wells per transect)
subsurface flow dominated watershed
fairly impermeable bedrock



Example: Connectivity Simulations

- Project background: Mountain Pine Beetle Infestation in British Columbia



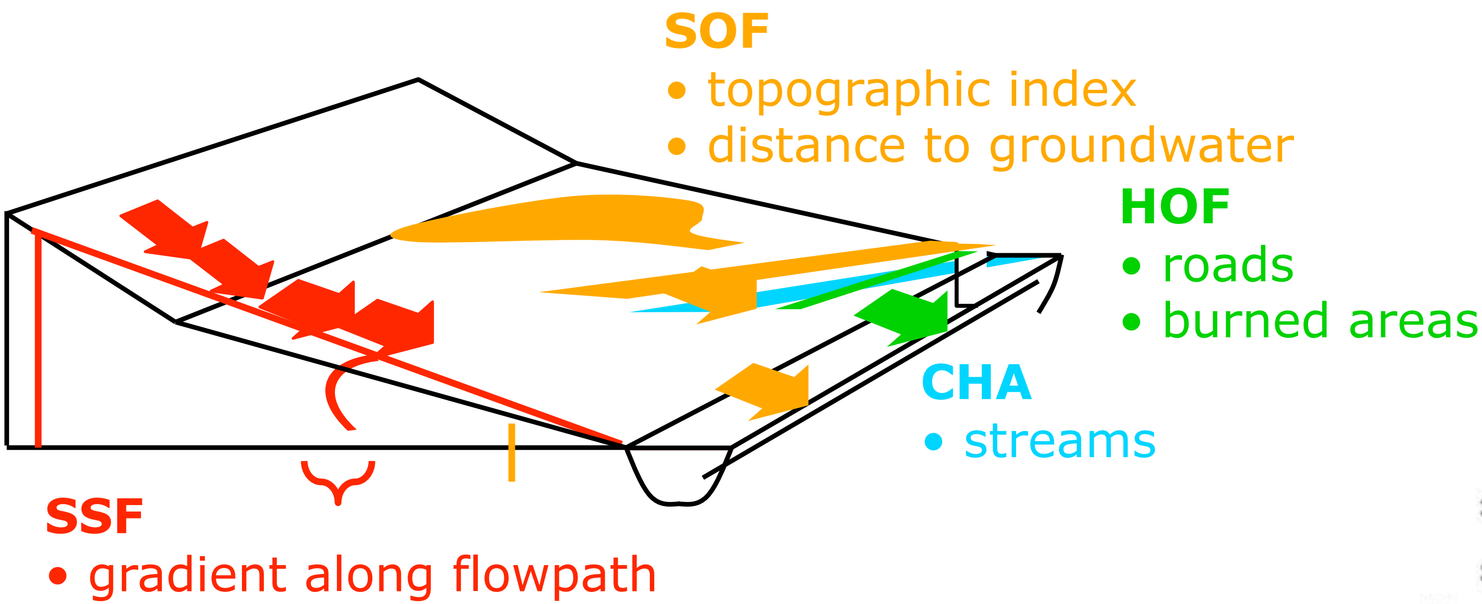
% dead pines
until 2008

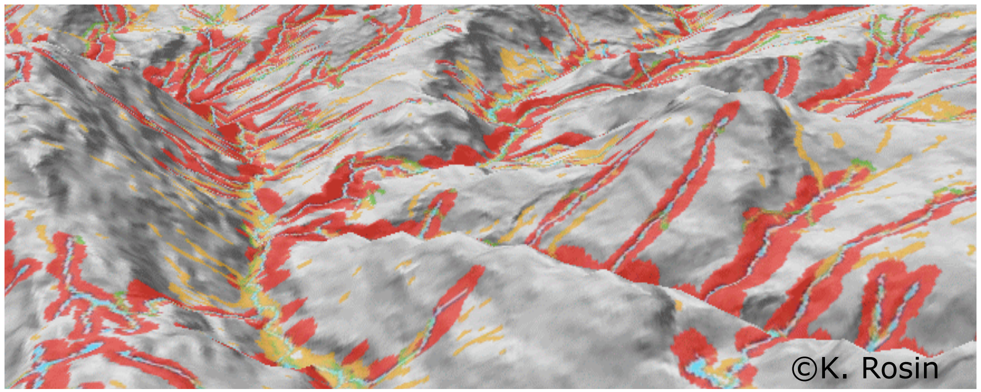
	0 - 10
	10 - 25
	25 - 50
	50 - 75
	75 - 100

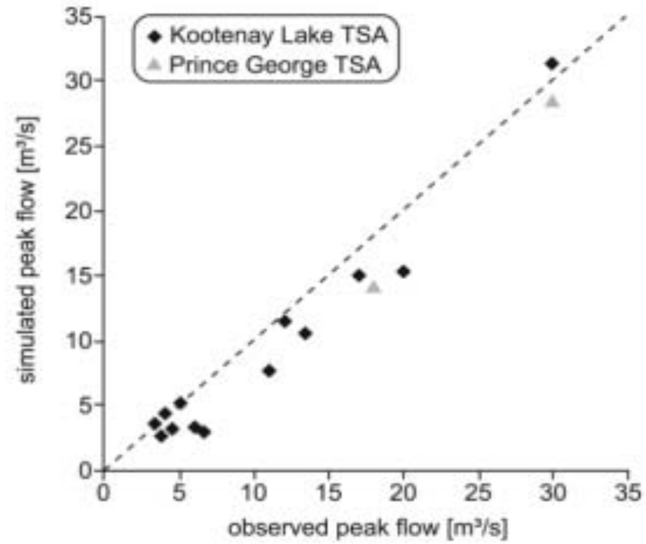
for comparison 

Area Delineation

- Parsimonious DRP area delineation criteria (due to lack of soil data)
- Evaluation with over 400 soil samples, indicator plant and morphology analyses







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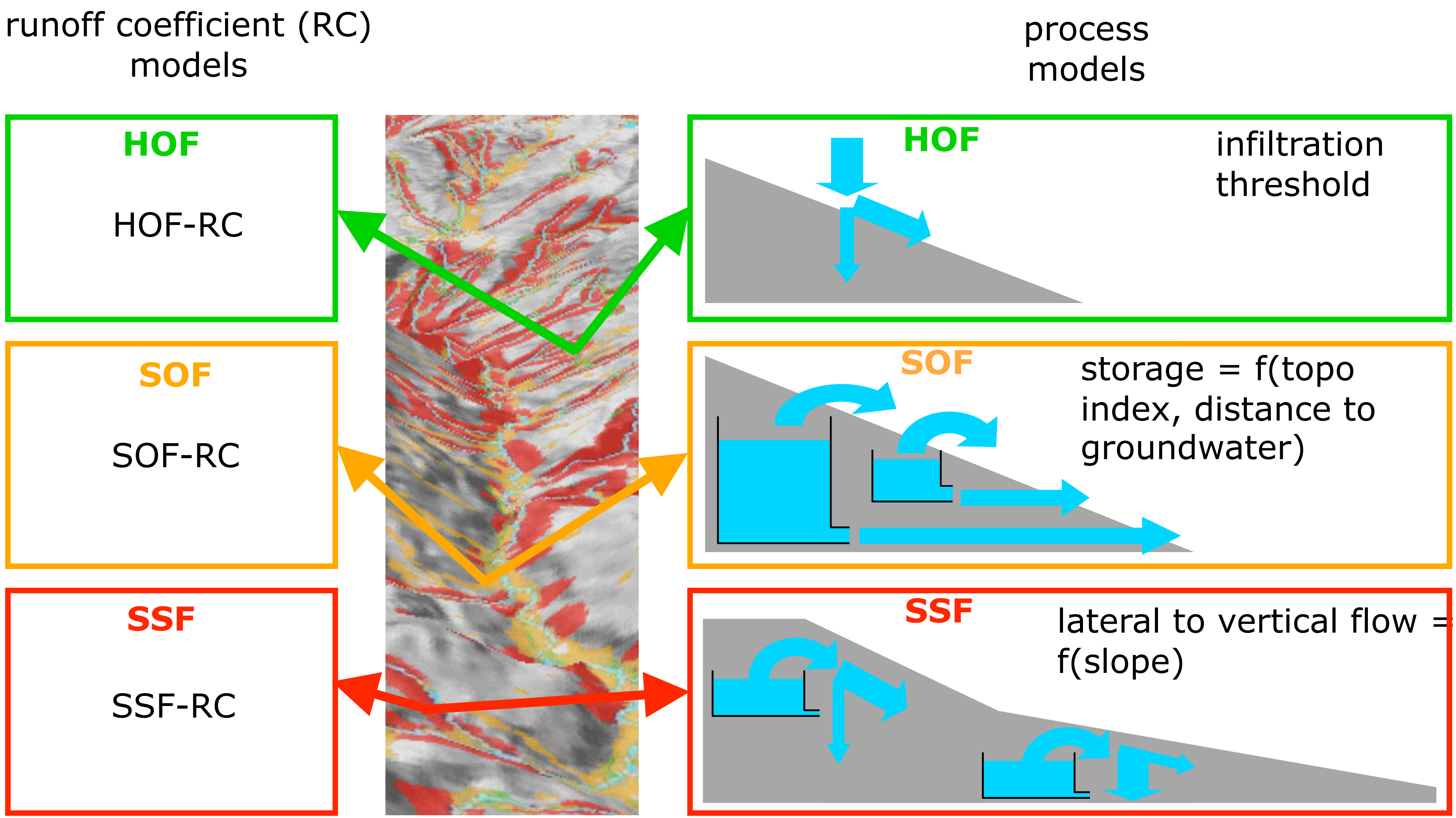
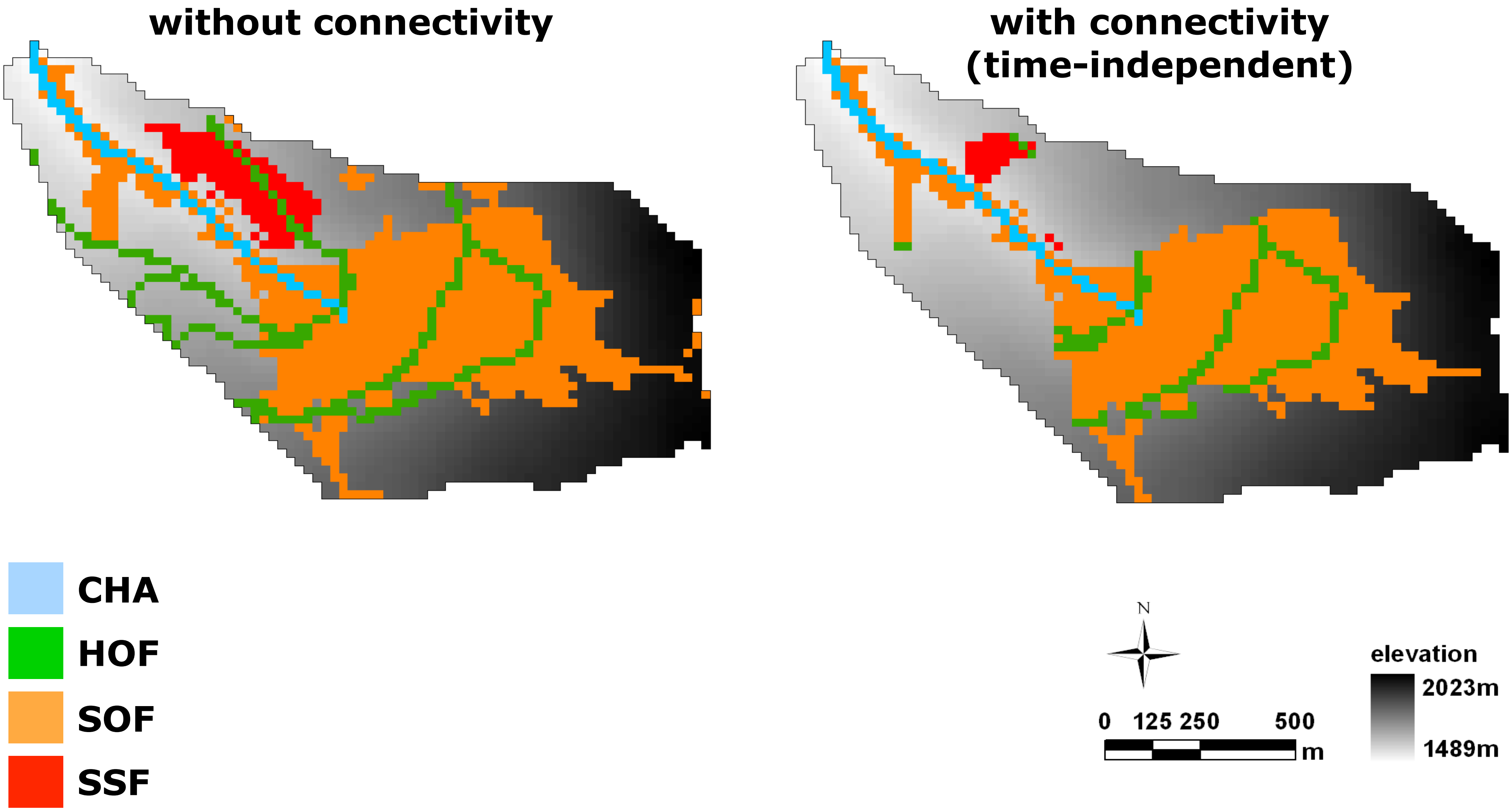
Process Predictions



Source Area Connectivity

- Time **independent** connectivity (along flow paths)



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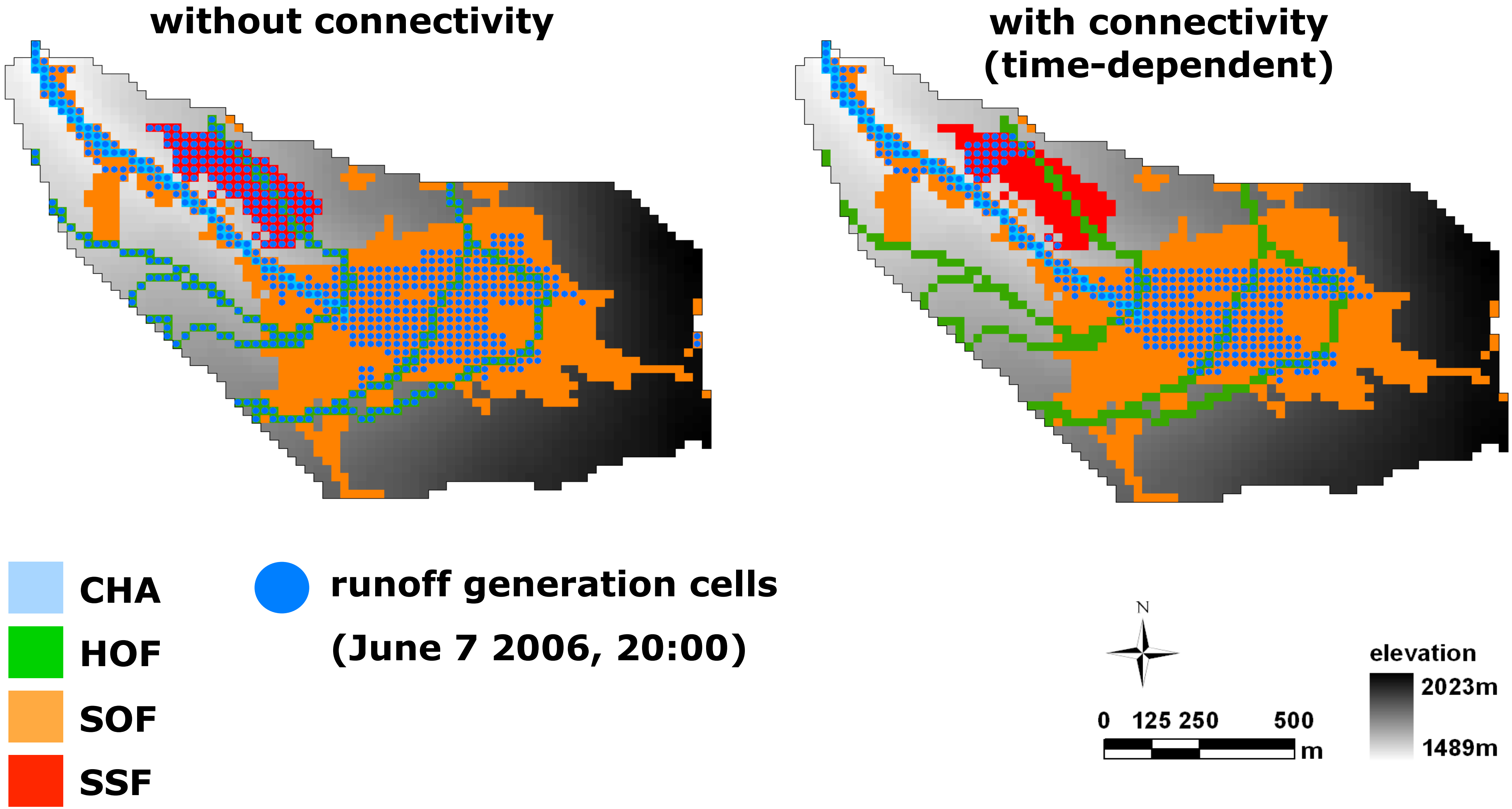

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Model Structures

model	model structure		connectivity		
	runoff coefficients	process models	no	time -independent	time -dependent
M1					
M3					
M5					
M2					
M4					
M6					

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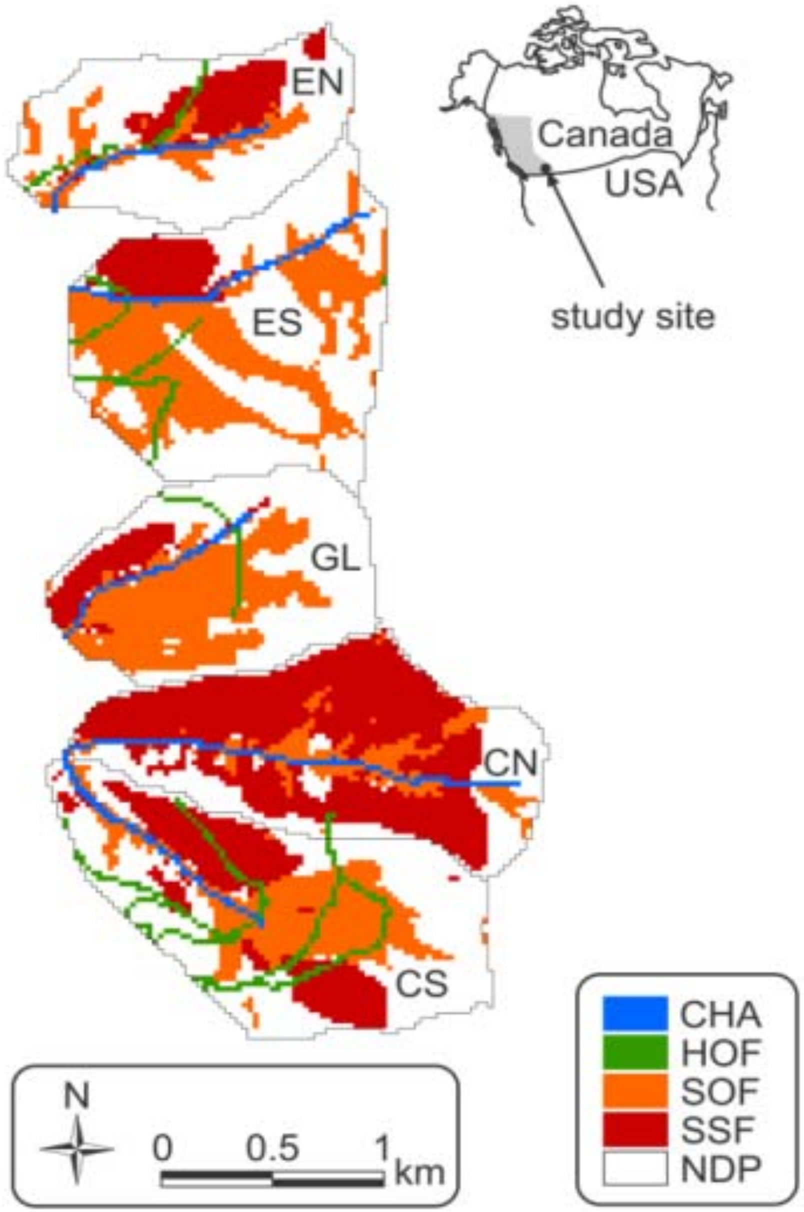
Research Questions

- Considering connectivity: what is the effect on **contributing areas**?
- Does the **model improve** when connectivity is incorporated?
- Are some runoff generation **processes** more **affected** by considering connectivity than others?
- What are the computational **costs** of including connectivity?

- Evaluation for different
  - model structures
  - watersheds
  - storm types (rain on snow, snow melt, rain)

Methods: Study Area

	area [km²]	median flow path gradient [-]	median flow path length [m]
EN	1.03	0.23	337
ES	1.64	0.20	482
GL	1.13	0.22	562
CN	1.46	0.31	314
CS	1.57	0.27	505



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Study Area: Previous Simulations

- Simulation with a distributed hydrologic model (**DHSVM**, 2004 – 2008, hourly)
- Calibrated and validated to spatial **snow surveys** (19 snow sampling transects)
- Jost et al. 2007. The influence of forest and topography on snow accumulation and melt at the watershed-scale. Journal of Hydrology.
- Fairly accurate **spatial-temporal** input pattern

Methods

- Storm types
  - rain
  - snow melt
  - rain on snow
  - unforced runoff

Mar Apr May Jun Jul Aug Sep Oct

- Optimization: GENOUD (GENetic Optimization Using Derivatives)
- Regional sensitivity analysis: Sobol, Morris
- Uncertainty analysis: GLUE
- 25m x 25m grid cells, 4h time step, year 2006

Results

- Considering connectivity: what is the effect on **contributing areas**?
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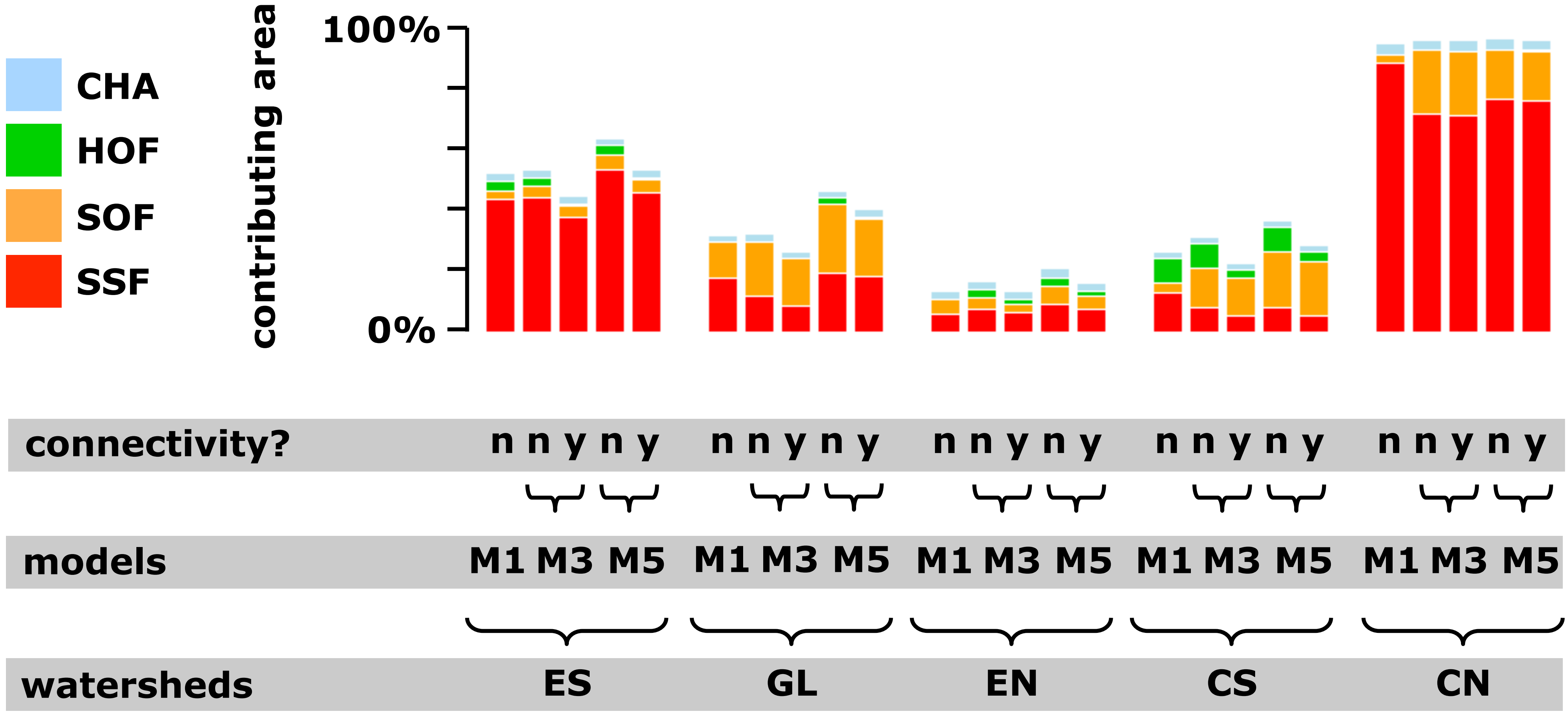
Effect on Contributing Areas



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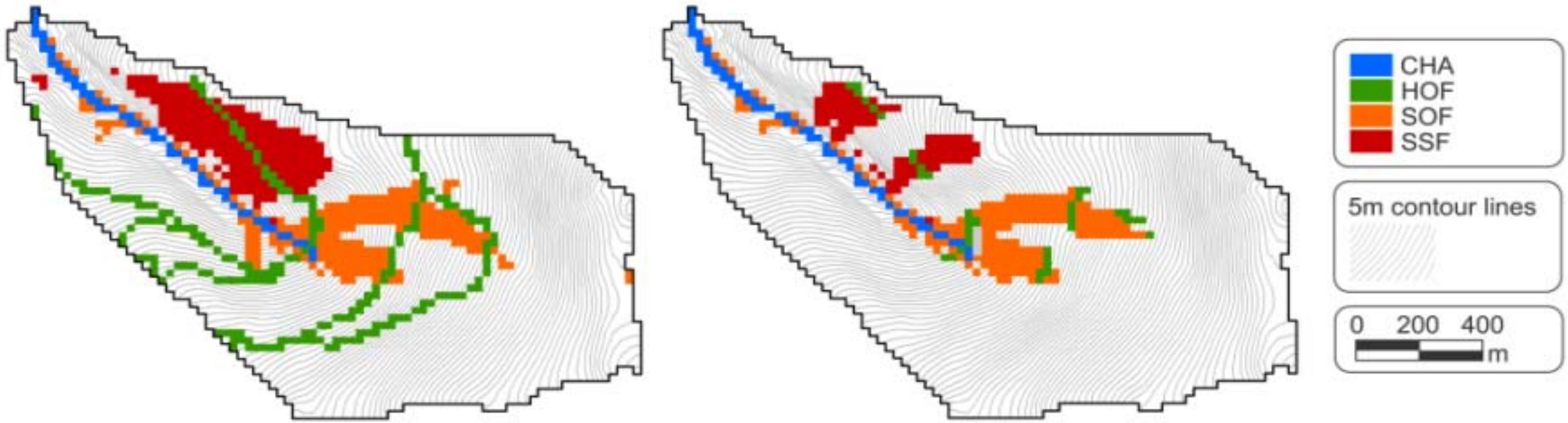
Effect on Contributing Areas

- Redistribution toward locations along flowpaths
- Example: CS watershed, NSE/rain on snow-optimized parameters of model M4



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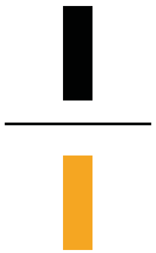
Model Improvement with Connectivity?

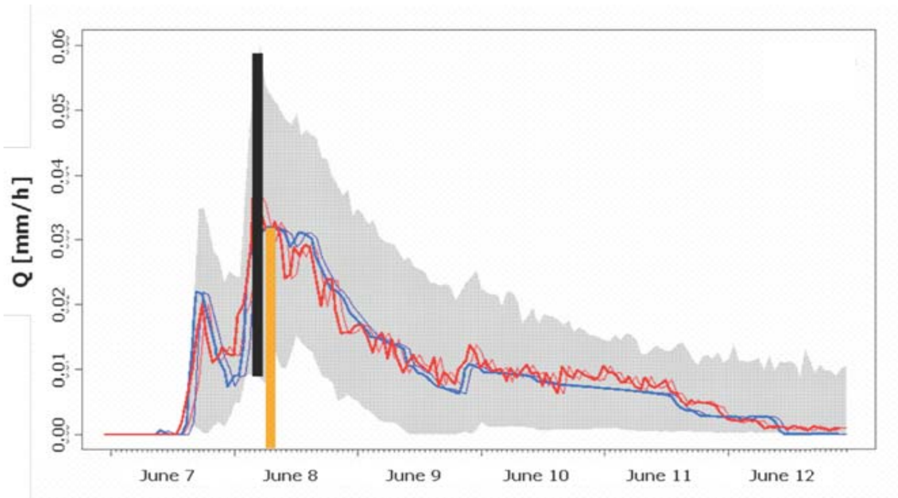
- **Fit** of simulated and observed runoff?

$$NSE = 1 - \frac{\sum_{t=1}^{n}\left(Q_{obs,t} - Q_{sim,t}\right)^2}{\sum_{t=1}^{n}\left(Q_{obs,t} - \overline{Q_{obs}}\right)^2} \qquad MAM = \frac{\frac{1}{n}\sum_{i=1}^{n}\left|Q_{obs,t} - Q_{sim,t}\right|}{Q_{obs,\max}}$$

- Model **prediction uncertainty**

relative range at peak =





- Feasible **parameter ranges** (comparison with previous defined parameter ranges; sensitive parameters only)

Model Fit

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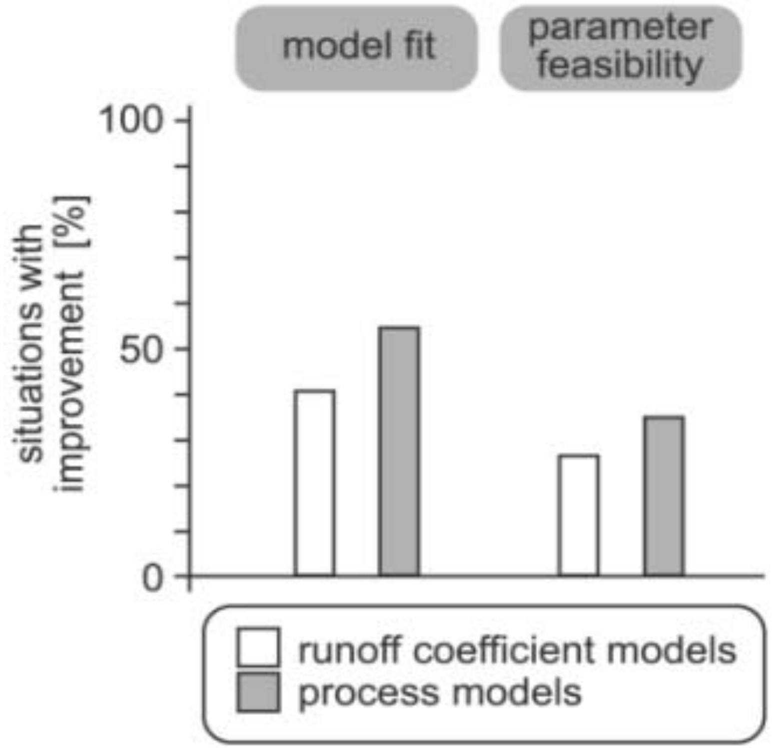
Model Improvement with Connectivity?

- Effects between **model structures**:



- No effects among:
  - **watersheds**
  - **storm types**
  - **objective functions**

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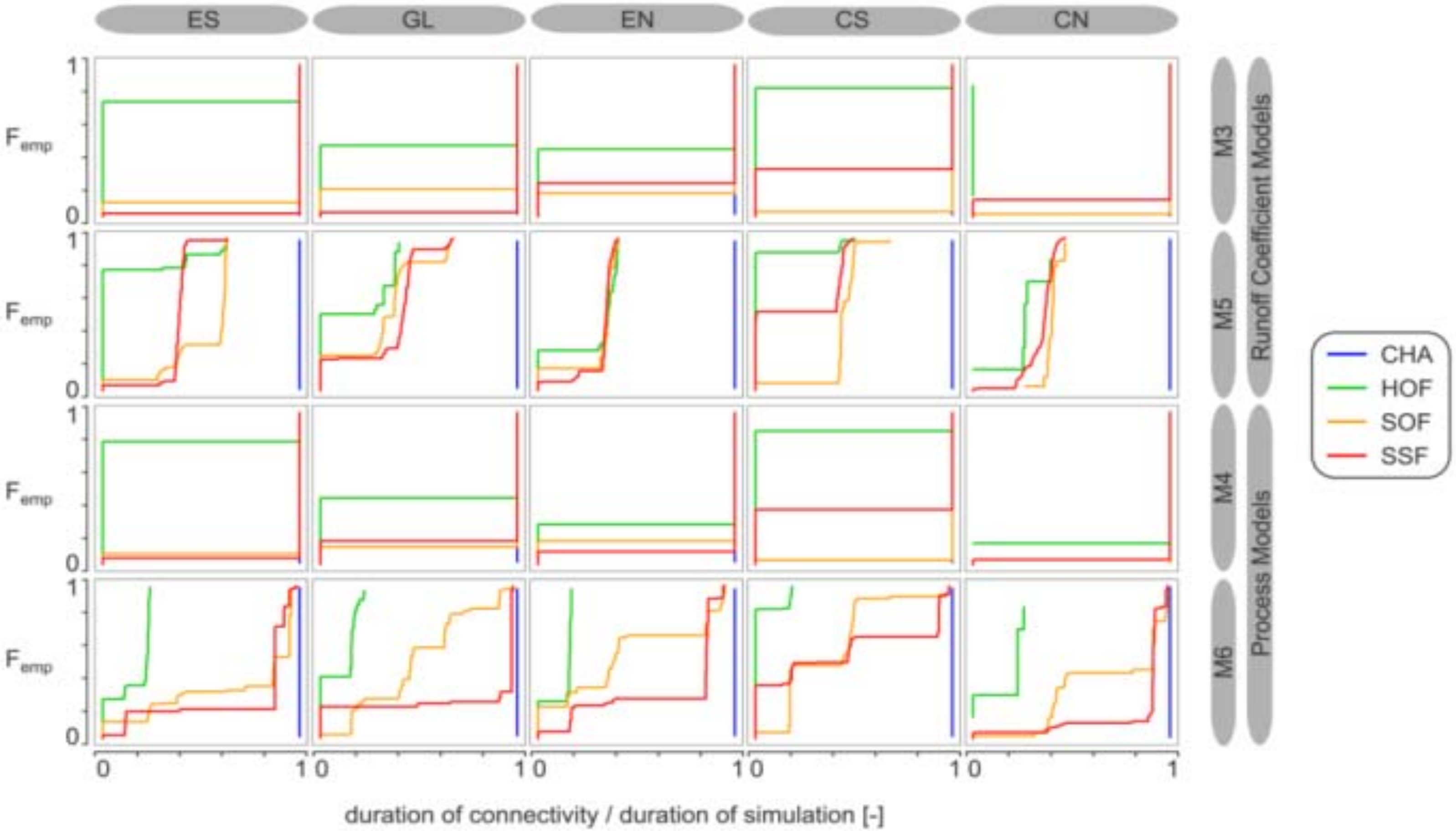
Temporal Connectivity

- Empirical distribution F_{emp} of the average duration of connectivity for each grid cell



- **HOF m**
- More **gradual** temporal distributions (e.g. for SOF) with model M6 compared to M5

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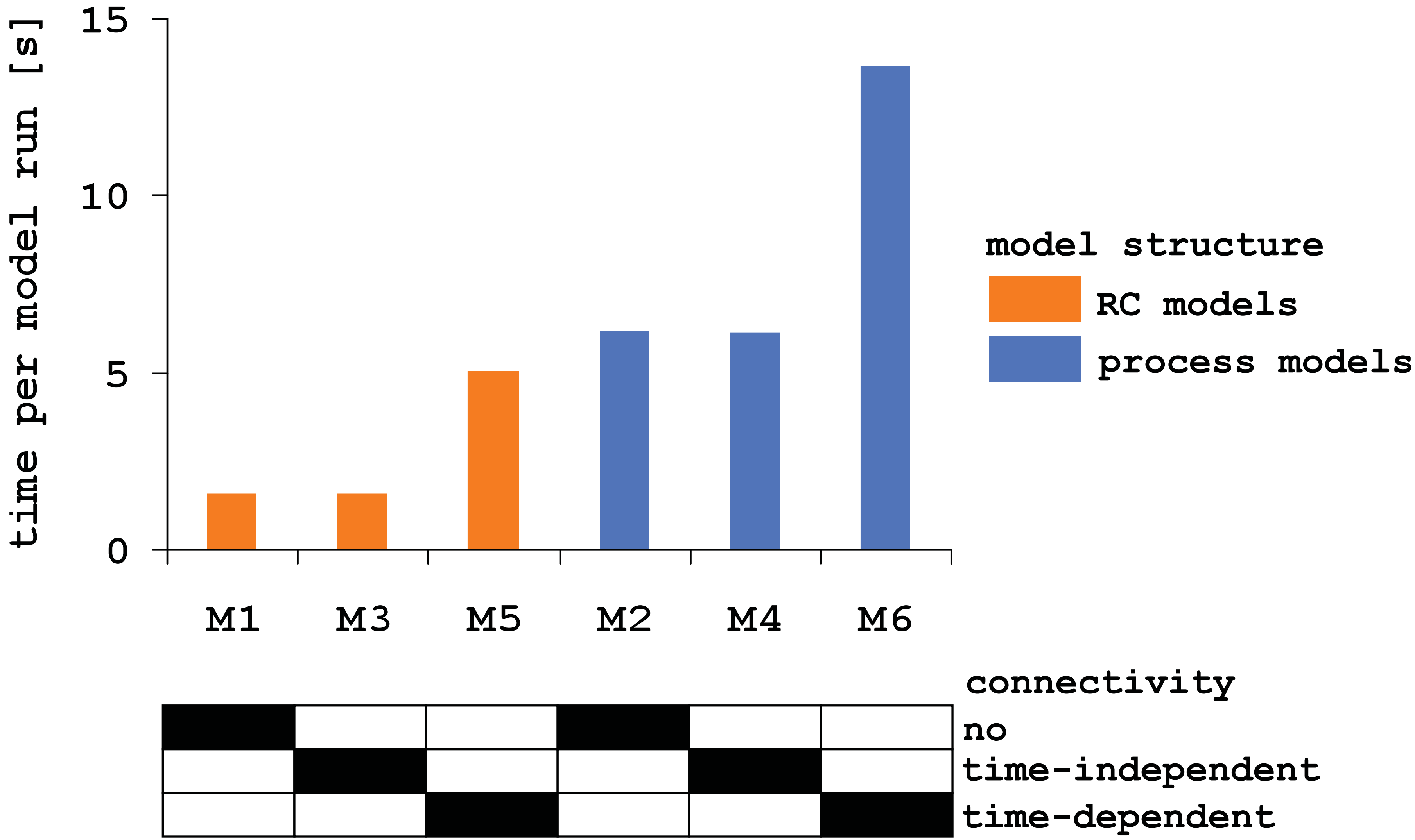
Computational Costs



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Conclusions

- 1) **Redistribution** of contributing areas along flowpaths
- 2) **HOF** is **more affected** by introducing connectivity than SOF and SSF
- 3) With connectivity: **No** consistent **trends** for different
  - storm types
  - watersheds
  - objective functions
- 4) Introducing connectivity makes more sense for **process models** than for runoff coefficient models.

Thank you!

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Future Work, Open Questions

- Process understanding:
  - Interconnection of **different types** of hydrologically active areas?
  - **Legacy/memory** of interconnections?
  - Connectivity **impediments/barriers**?

- Connectivity simulation:
  - Model **evaluation**?
  - Input/parameter/model structure **uncertainty**?
  - **parsimony vs. complexity:** Cell-to-cell algorithms? Process specific connectivity predictions? Dynamic DRP area delineation toward VSA?

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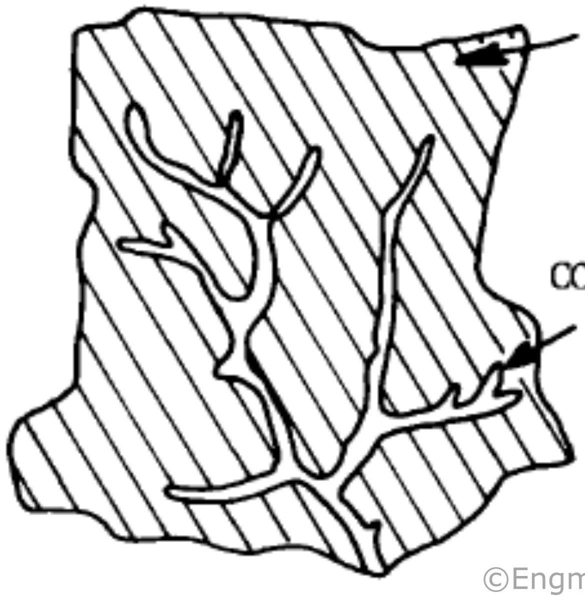
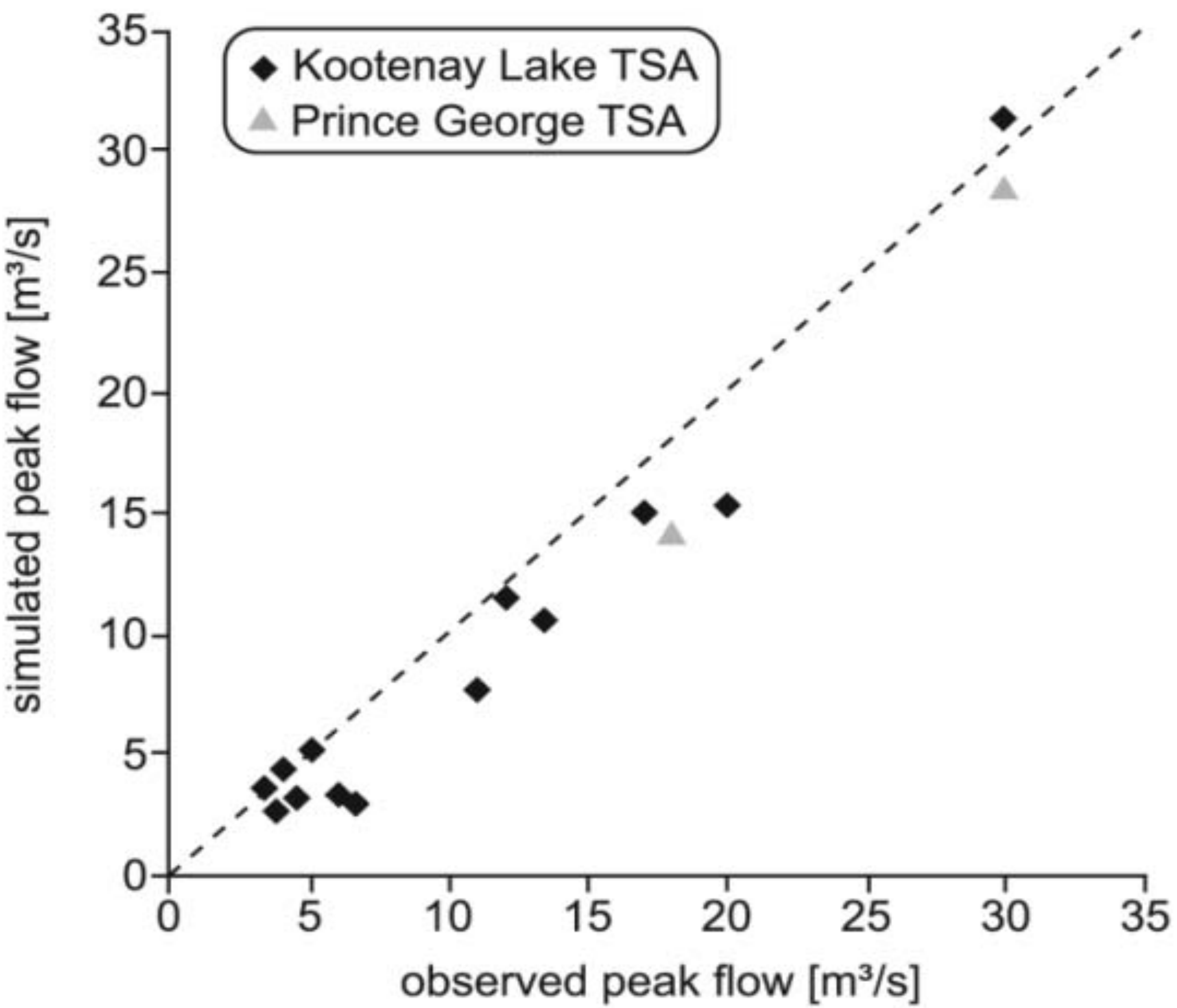
Fundamental Concepts

- Cappus (1960)
  - ‘ruissellement superficiel’, ‘ruissellement hypodermique’, ‘écoulement souterrain de crue’ (**overland**, near **surface**, **subsurface** storm flow)
- Betson (1964)
  - runoff contribution only from certain areas in a watershed
  - **partial contributing area concept**
- Hewlett and Hibbert (1967)
  - contributing areas in a watershed vary during and among storms
  - **variable source area concept (VSA)**
- Engman (1974)
  - **hydrologically active** and **passive** areas within a watershed



©Engman (1974)



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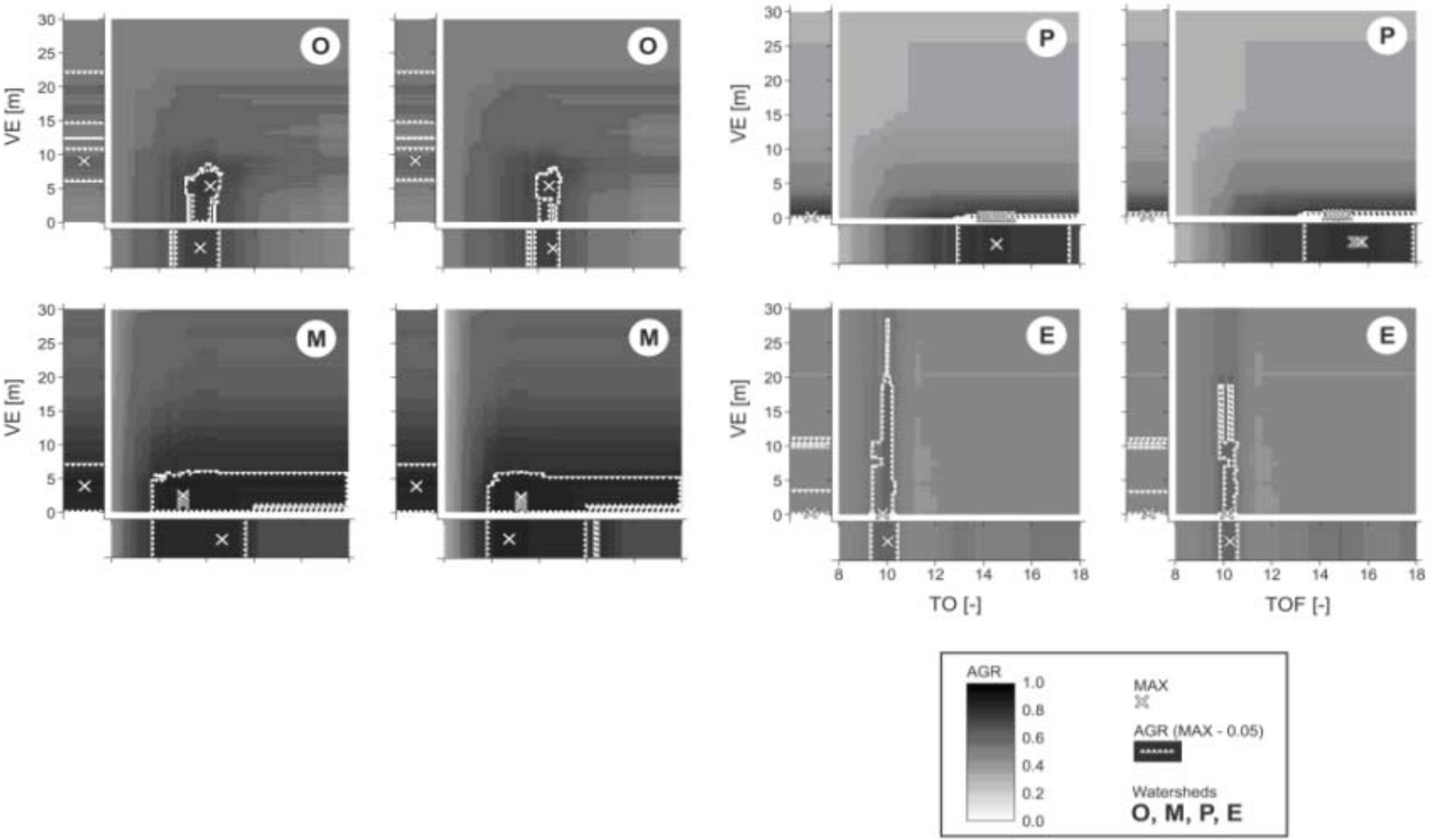

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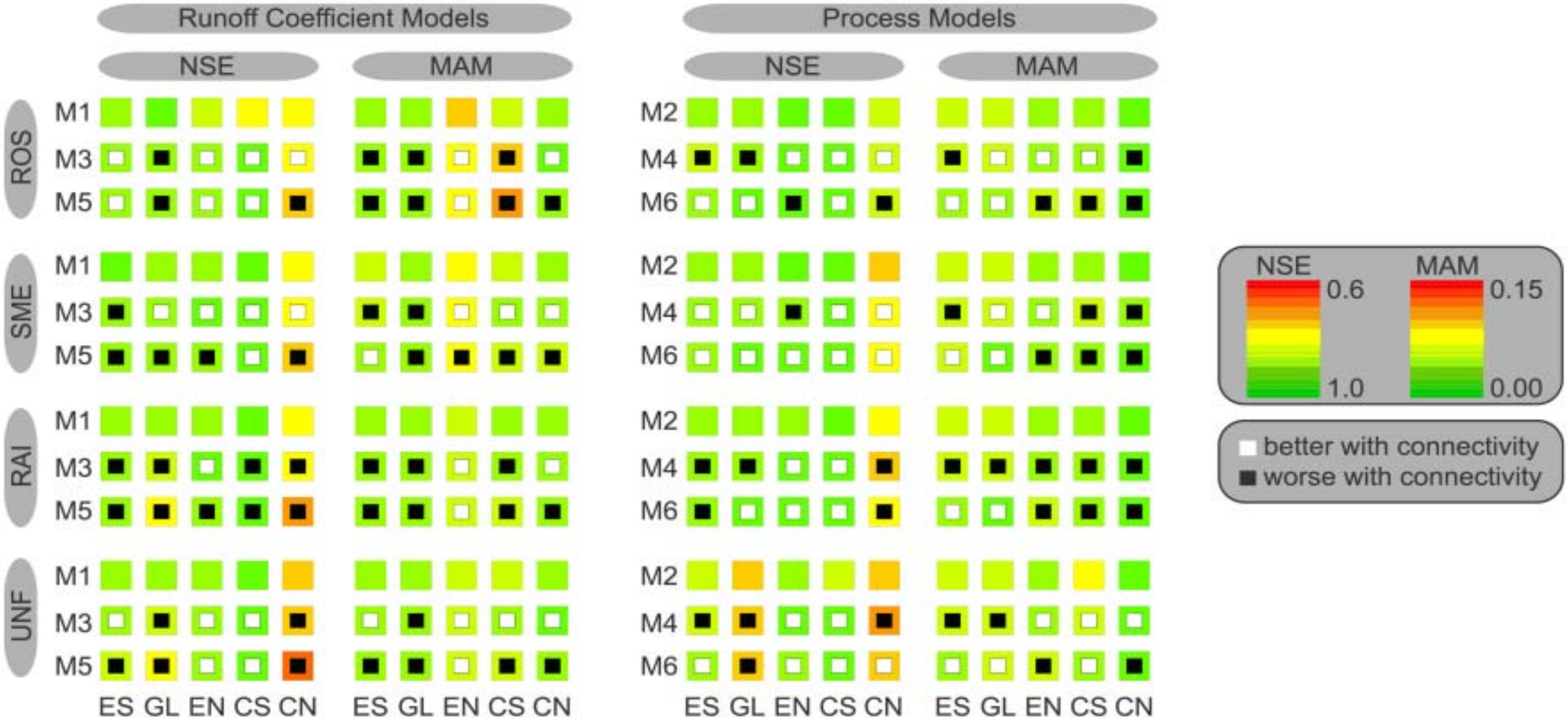
Prediction Uncertainty



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Sensitivity Analysis

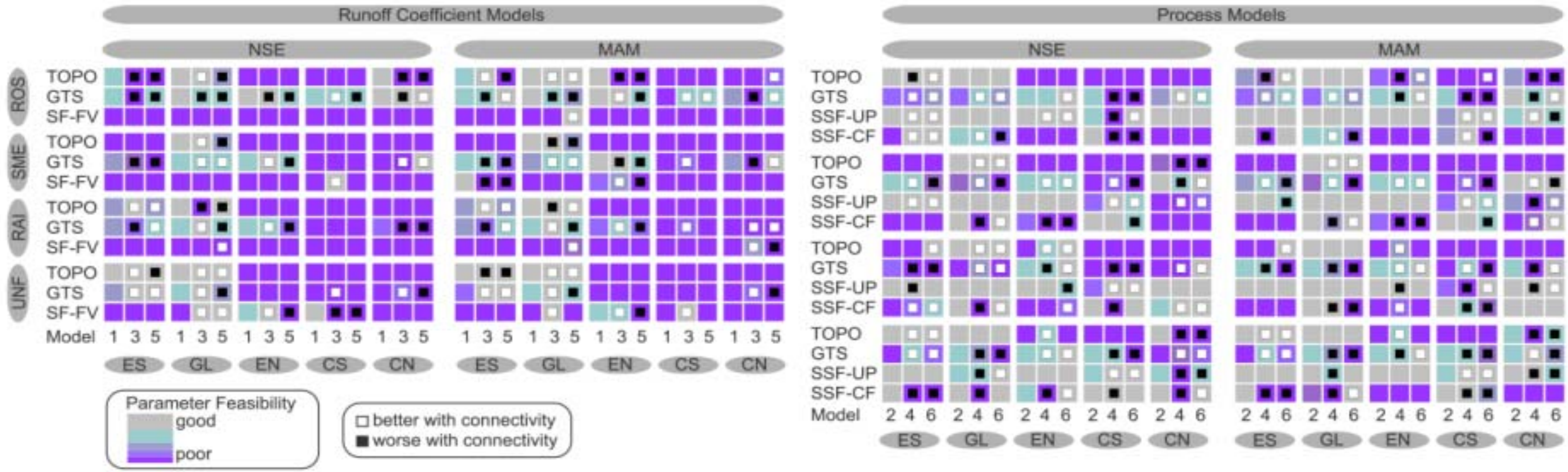
runoff coefficient models (each cell: Morris, Sobol)

	ES M1	ES M3	ES M5	GL M1	GL M3	GL M5	EN M1	EN M3	EN M5	CS M1	CS M3	CS M5	CN M1	CN M3	CN M5
TOPO	● ●	● ●	● ●	● ○	● ○	● ○	○ ●	○ ○	○ ○	● ●	● ●	● ●	○ ●	○ ○	○ ○
VERT	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ●	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
GTS	● ○	● ○	● ○	○ ○	○ ○	○ ○	● ●	● ○	● ○	● ●	● ●	● ●	● ○	● ●	● ●
CHA-RC	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
HOF-RC	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
SOF-RC	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
SSF-RC	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
OF-FV	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
SF-FV	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	● ●	● ○	● ●	● ○	○ ○	○ ○	● ●	● ○	● ○

process models (each cell: Morris, Sobol)

	ES M2	ES M4	ES M6	GL M2	GL M4	GL M6	EN M2	EN M4	EN M6	CS M2	CS M4	CS M6	CN M2	CN M4	CN M6
TOPO	● ●	● ●	● ●	● ○	● ○	● ○	○ ○	○ ○	○ ○	● ●	● ●	● ●	○ ○	○ ○	○ ○
VERT	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
GTS	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	● ○	● ●	● ○	● ○	● ○	● ○	○ ●	● ●	○ ○
CHA-RC	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
HOF-TH	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ●	○ ○	○ ○	○ ○	○ ○	○ ○
SOF-UP	○ ●	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
SSF-UP	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	● ●	● ●	● ○
SSF-CF	○ ○	○ ○	○ ○	○ ●	○ ○	○ ○	● ●	● ○	● ●	● ●	● ●	● ○	● ○	● ○	● ○
K-DRP	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ●	○ ○	○ ○
OF-FV	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
SF-FV	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ●	○ ○	○ ○	● ○	○ ○	● ○

Parameter Feasibility

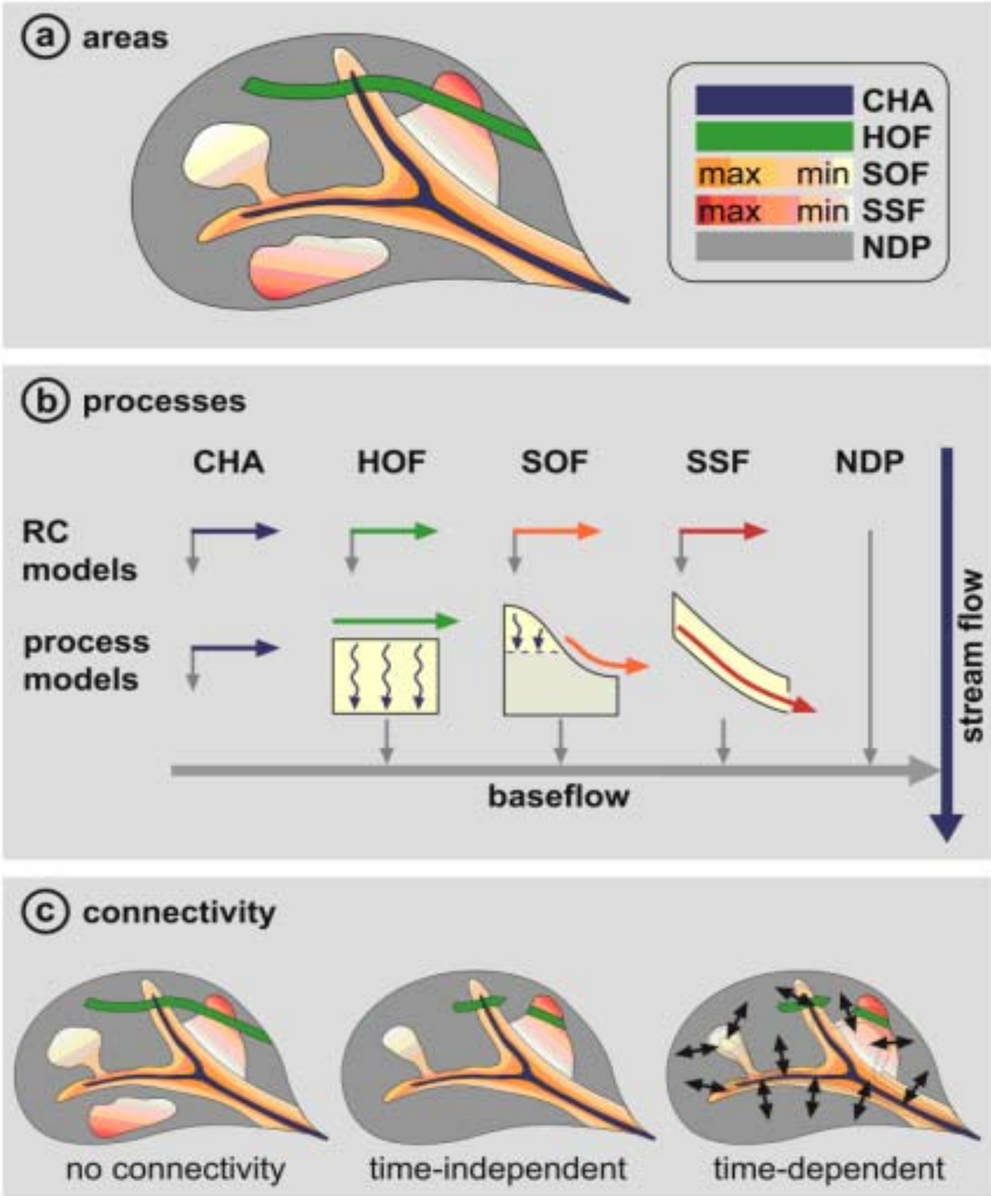


Concepts

- **Fill / spill** (Tromp-van Meerveld and McDonnell, 2006)
  - Bedrock depressions fill up during a rainfall event
  - Water spills over the bedrock ridges and contributes to hillslope outflow
  - Steeper overall gradient results in lower bedrock pool volume
  - Non-linear response characteristics: timing/spatial distribution of water flow altered (Hopp and McDonnell, 2009)
- **Connect / react** (Bachmair and Weiler, 2010)
  - Speculation: Non-linear hillslope response characteristics due to connectivity?
  - Potential interconnection of hydrologically active areas.

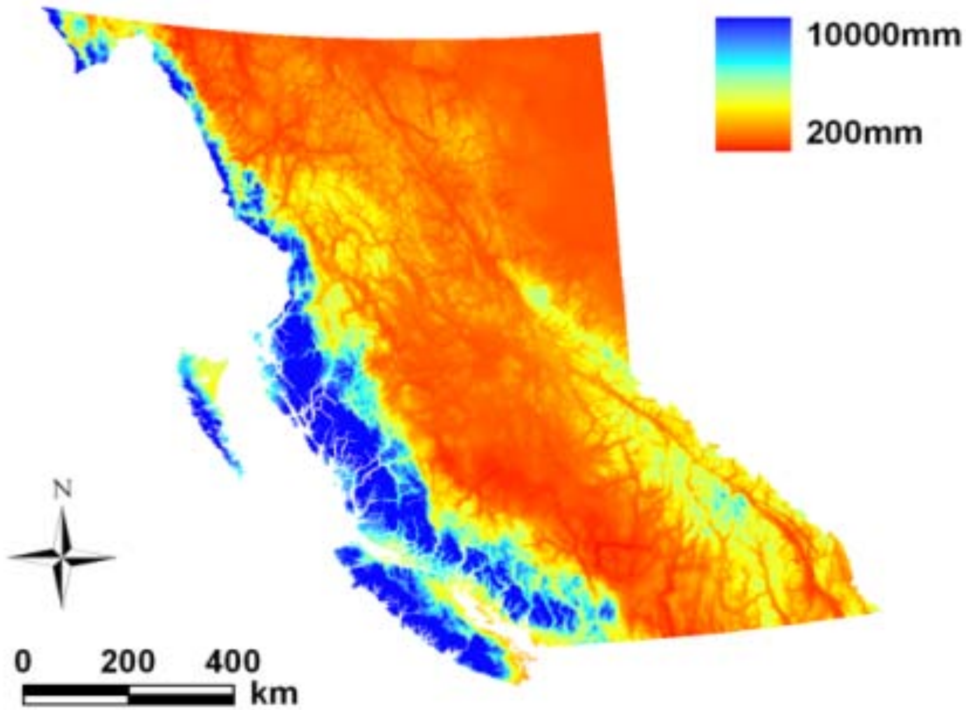
Konnektivität

- Methoden
  - Flächenausscheidung
  - Prozesse
  - Konnektivität



Climate Effects

mean annual precipitation
(1961-1990)



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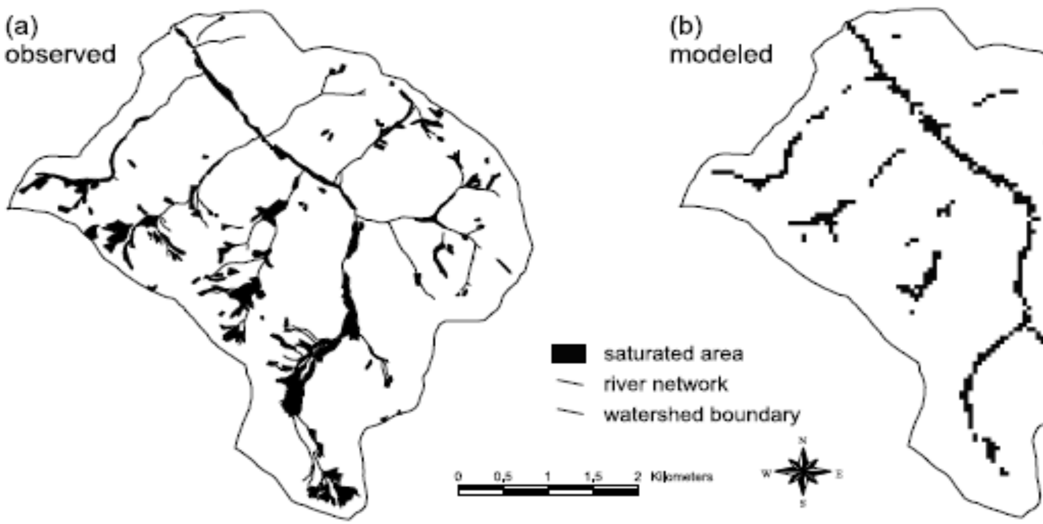
Recent Research

iHf HYDROLOGIE FREIBURG

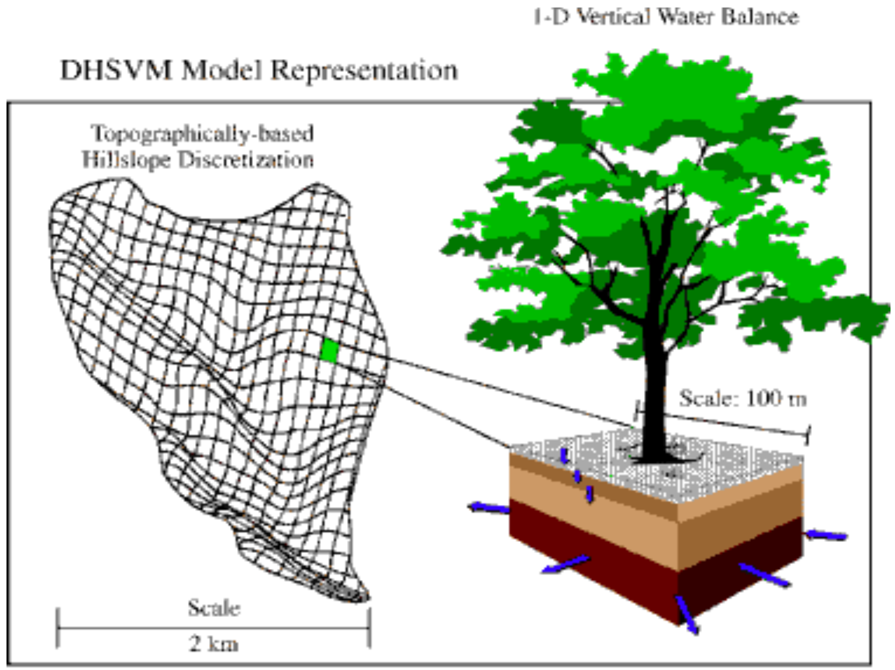
- Scherrer and Naef (2003): Dominant process identification with **decision trees**
- Markart et al. (2004): Field guidance for **surface coefficient** estimation
- Güntner et al. (2004): **Evaluation** of **predicted saturation** patterns



- Schmocker-Fackel et al. (2007): Process identification at **plot and basin scale**
- Chifflard et al. (2008): Relevance of periglacial **cover beds** for runoff generation
- Meissl et al. (2009): Runoff response guidelines for small, **alpine watersheds**
- Jencso et al. (2009): **Connectivity** between hillslopes, riparian areas, streams

DHSVM

- Distributed Hydrology Soil Vegetation Model
- Mark Wigmosta (University of Washington, early 1990s)
- Effects of topography and vegetation on water fluxes
- Often used for mountainous watersheds in the Pacific Northwest of the US



Lettenmaier, 2002

DHSVM: Output

101Evap.ETot	Evapotranspiration (Total)	m/timestep	Total amount of evapotranspiration
102Evap.EPot	Potential Evapotranspiration	m/timestep	Potential evaporation/transpiration
103Evap.EInt	Interception Evaporation	m/timestep	Evaporation from interception
104Evap.ESoil	Not implemented yet	m/timestep	Not implemented yet
105Evap.EAct	Evaporation	m/timestep	Actual evaporation/transpiration
201Precip	Precipitation	m/timestep	Precipitation
202Precip.IntRain	Interception Storage (liquid)	m	Interception storage (liquid)
203Precip.IntSnow	Interception Storage (frozen)	m	Interception storage (frozen)
301Rad.Beam	Incoming Direct Radiation	W/m2	Direct beam solar radiation
302Rad.Diffuse	Incoming Diffuse Radiation	W/m2	Diffuse solar radiation
401Snow.HasSnow	Snow Presence/Absence	-	Snow cover flag
402Snow.SnowCoverOver	Overstory Snow Flag	-	Flag overstory can be covered
403Snow.LastSnow	Last Snowfall	days	Days since last snowfall
404Snow.Swq	Snow Water Equivalent	m	Snow water equivalent
405Snow.Melt	Snow Melt	m/timestep	Snow Melt

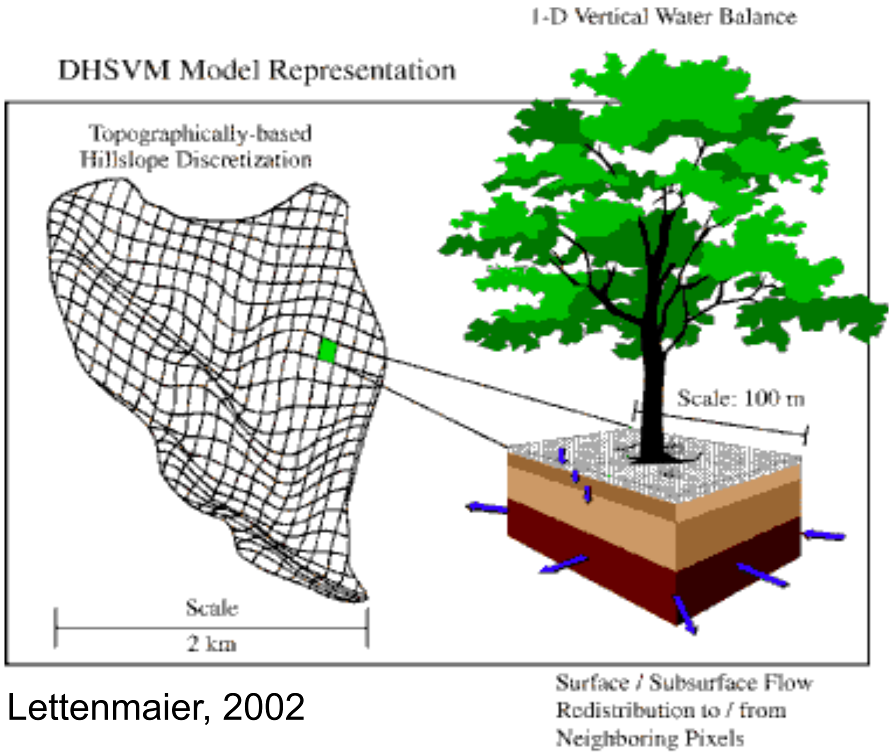
406Snow.PackWater	Liquid Water Content (Deep Layer)	m	Liquid water content of snow pack
407Snow.TPack	Snow Temperature (Deep Layer)	°C	Temperature of snow pack
408Snow.SurfWater	Liquid Water Content (Surface Layer)	m	Liquid water content of surface layer
409Snow.TSurf	Snow Temperature (Surface Layer)	°C	Temperature of snow pack surface layer
410Snow.ColdContent	Snow Cold Content	J	Cold content of snow pack
501Soil.Moist	Soil Moisture Content	-	Soil moisture for layer % d
502Soil.Perc	Percolation	m/timestep	Percolation
503Soil.TableDepth	Water Table Depth	m below surface	Depth of water table
504Soil.NetFlux	Net Water Flux	m/timestep	Net flux of water
505Soil.TSurf	Surface Temperature	°C	Soil surface temperature
506Soil.Qnet	Net Radiation	W/m2	Net radiation exchange at surface
507Soil.Qs	Sensible Heat Flux	W/m2	Sensible heat exchange
508Soil.Qe	Latent Heat Flux	W/m2	Latent heat exchange
509Soil.Qg	Ground Heat Flux	W/m2	Ground heat exchange

DHSVM: Input

- Sediment Model Configuration file
- Configuration file for DHSVM 2.0 and below
- Mask file   Note: 2-D data binary files are stored from NW->SE, incrementing across columns before down rows
- DEM file
- Soil type file
- Soil depth file
- Vegetation type file
- Meteorological station file
- Meteorological map files
- PRISM files
- Shading parameter files
- Wind model files
- Stream/road class files
- Stream/road network files
- Stream/road map files
- Travel time file
- Unit hydrograph file

To initialize the model, a number of model state files are required as well:

- Soil state file
- Snow state file
- Interception state file
- Channel state file
- Hydrograph state file



Lettenmaier, 2002