Topography and the Spatial Distribution of Groundwater Recharge and Evapotranspiration:

A Need to Revisit Distributed Water Budget Analysis when Assessing Impacts to Ecological Systems.

By
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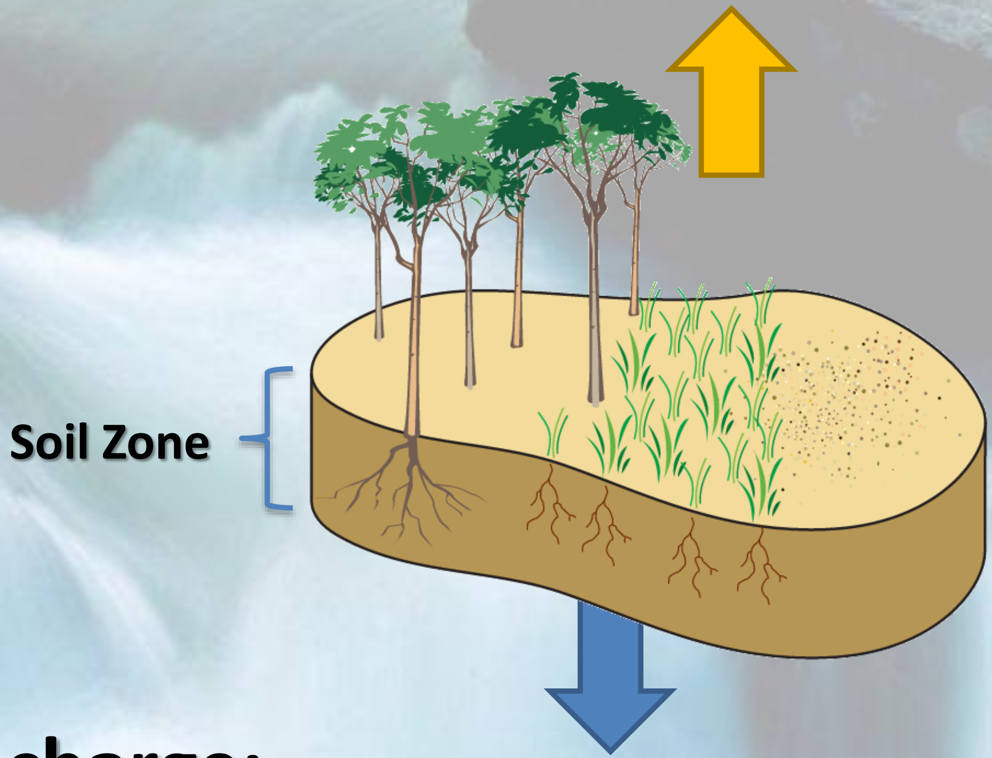
Evapotranspiration:

The combination of evaporation from all surfaces and any additional water loss from the physiological processes of vegetation.



Groundwater Recharge:

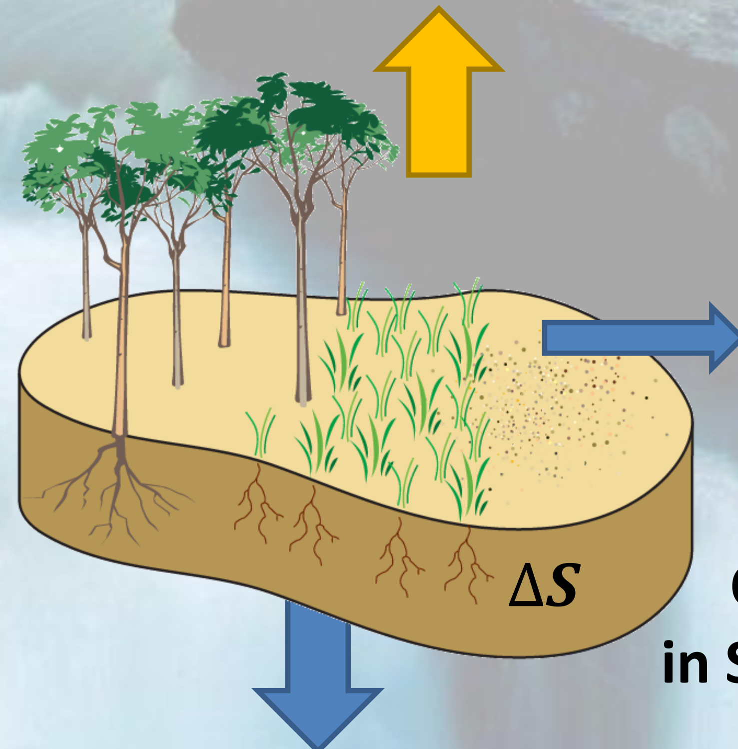
The rate at which water is added to the groundwater system

Simple Waterbalance

$$P = ET + Q + G + \Delta S$$

Precipitation (P)

Evapotranspiration (ET)

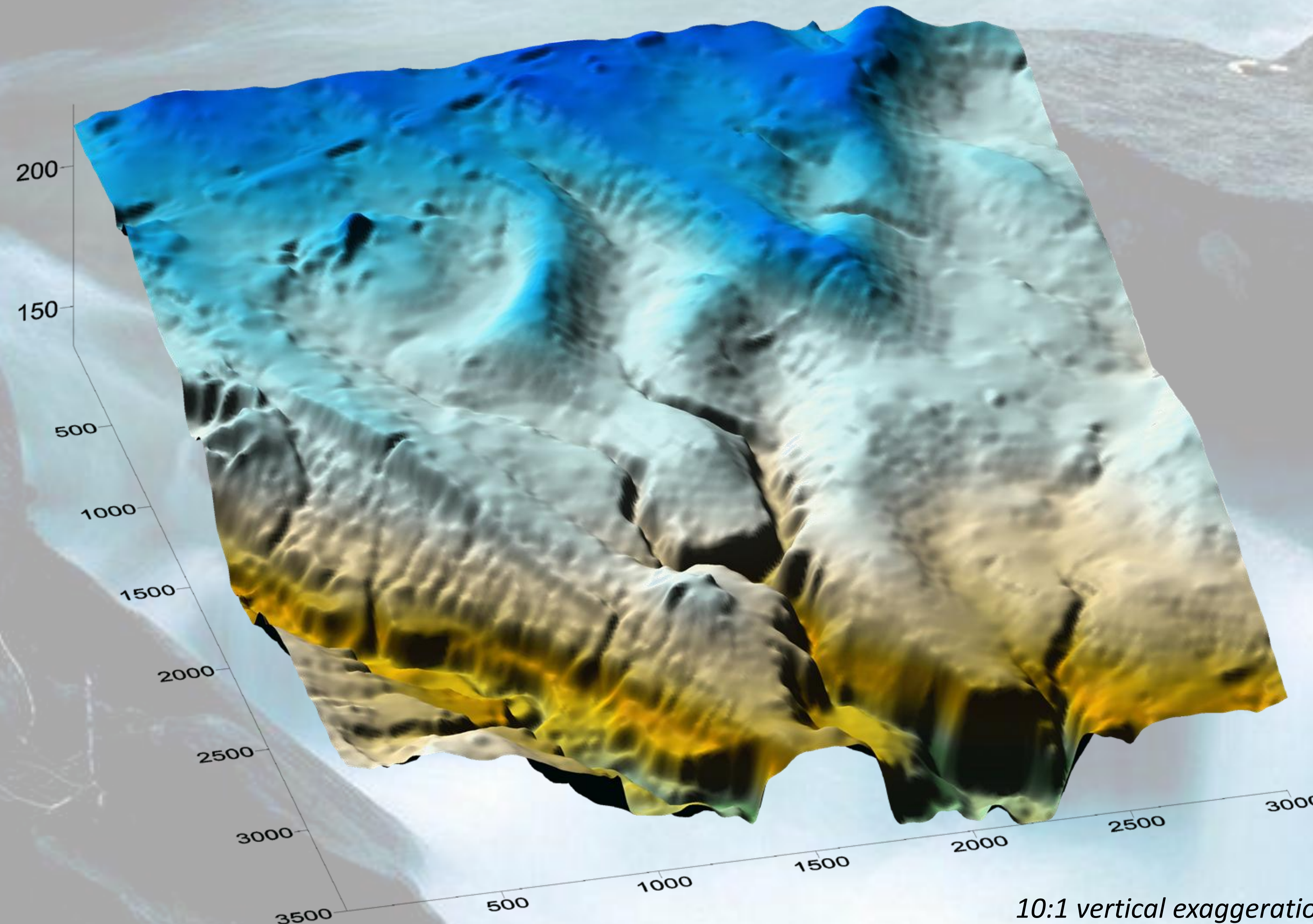


Runoff (Q)

Change in Storage

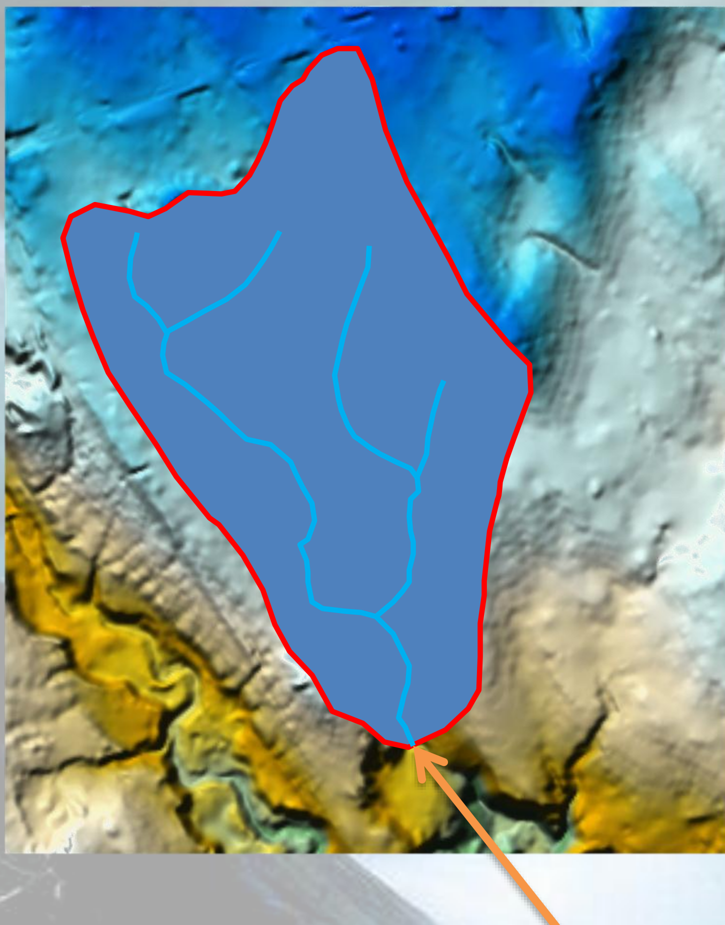
Groundwater Recharge (G)

Surface Water Modeling Strategies



10:1 vertical exaggeration

Surface Water Modeling Strategies



Streamflow monitoring location

Lumped Model

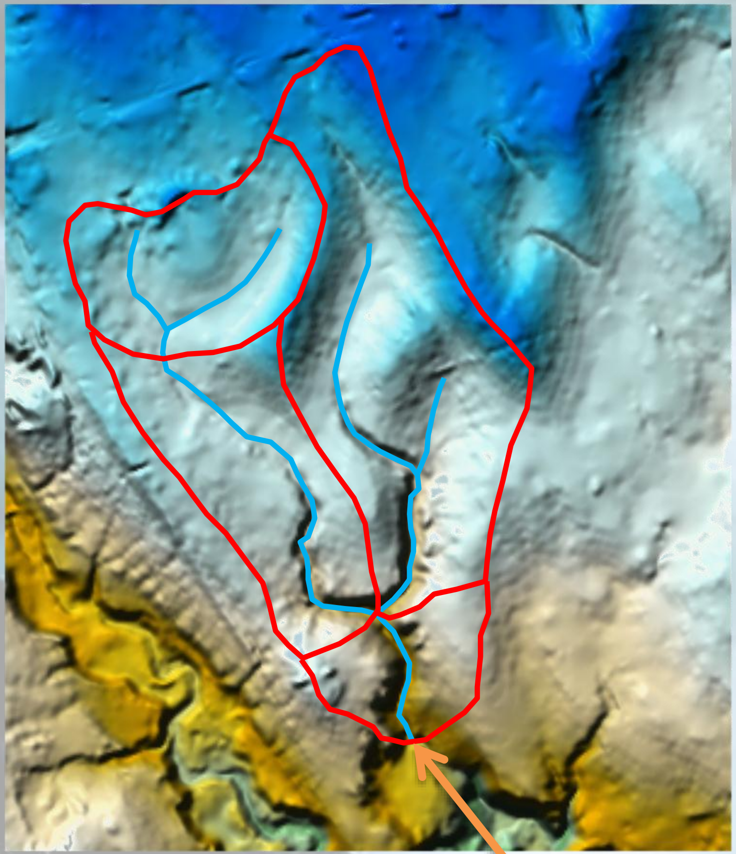
By assuming homogeneity, model parameters are effectively “lumped” together.

Works very well at predicting outflows from the catchment.

Computationally efficient.

Need to consider timing.

Surface Water Modeling Strategies



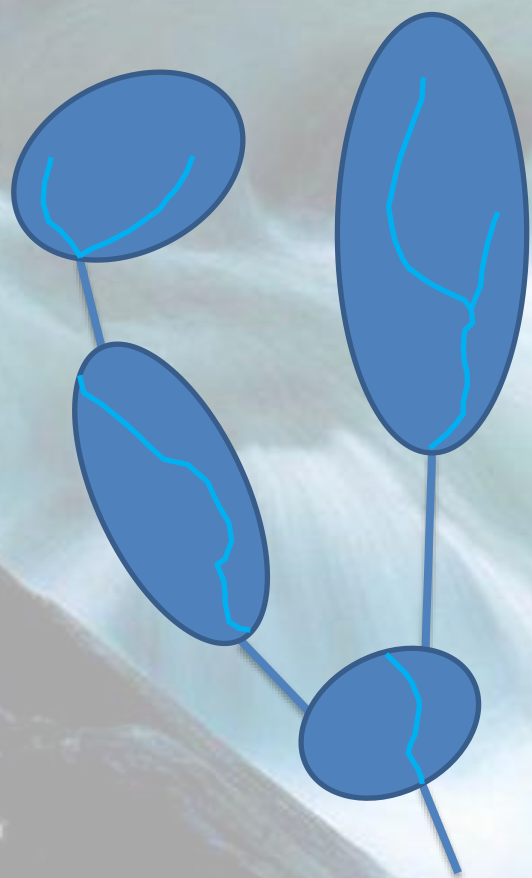
Streamflow monitoring location

Semi-Distributed Model

Adds a degree of heterogeneity, lumping model parameters in a distributed fashion.

Works very well at predicting outflows from the catchment where some catchment heterogeneity is present.

Surface Water Modeling Strategies



Semi-Distributed Model

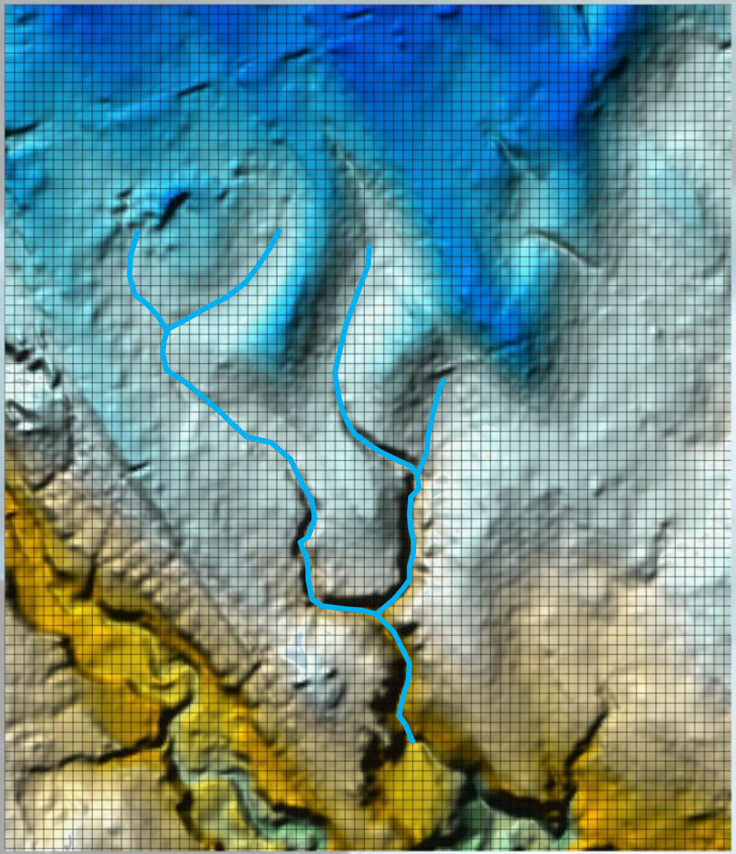
Adds a degree of heterogeneity, lumping model parameters in a distributed fashion.

Works very well at predicting outflows from the catchment where catchment heterogeneity is present.

Multiple lumped models in series and parallel.

Still need to consider timing.

Surface Water Modeling Strategies



Distributed Model

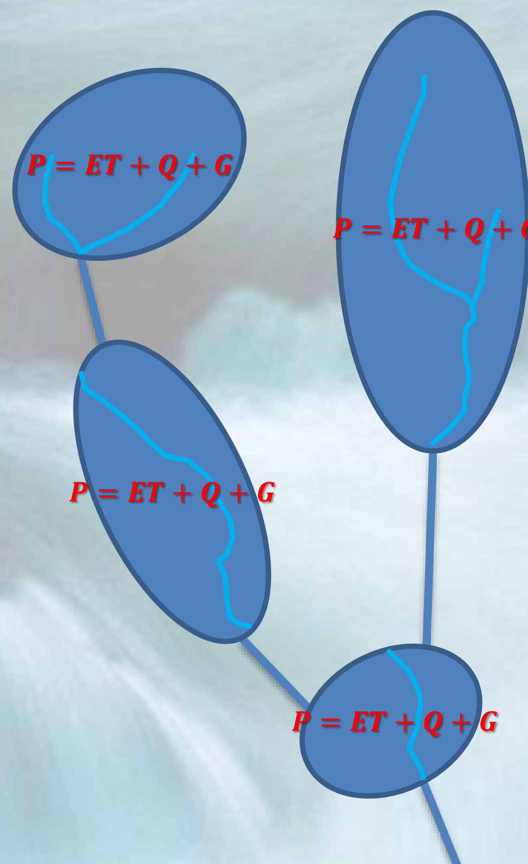
Considers heterogeneity, model parameters are distributed in a gridded fashion.

Computes a water balance *at every point* within the catchment.

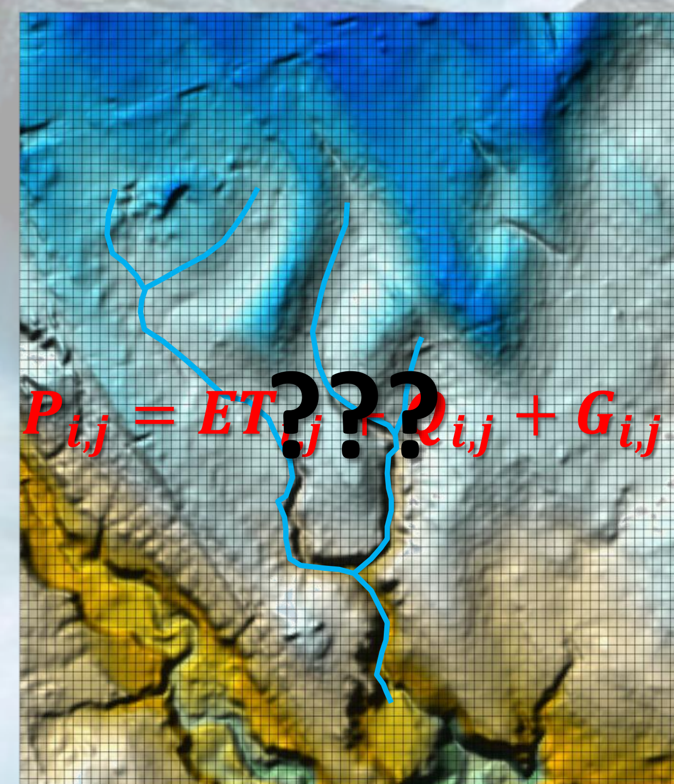
Less computationally efficient, greater data demands.

Surface Water Modeling Strategies

Lumped

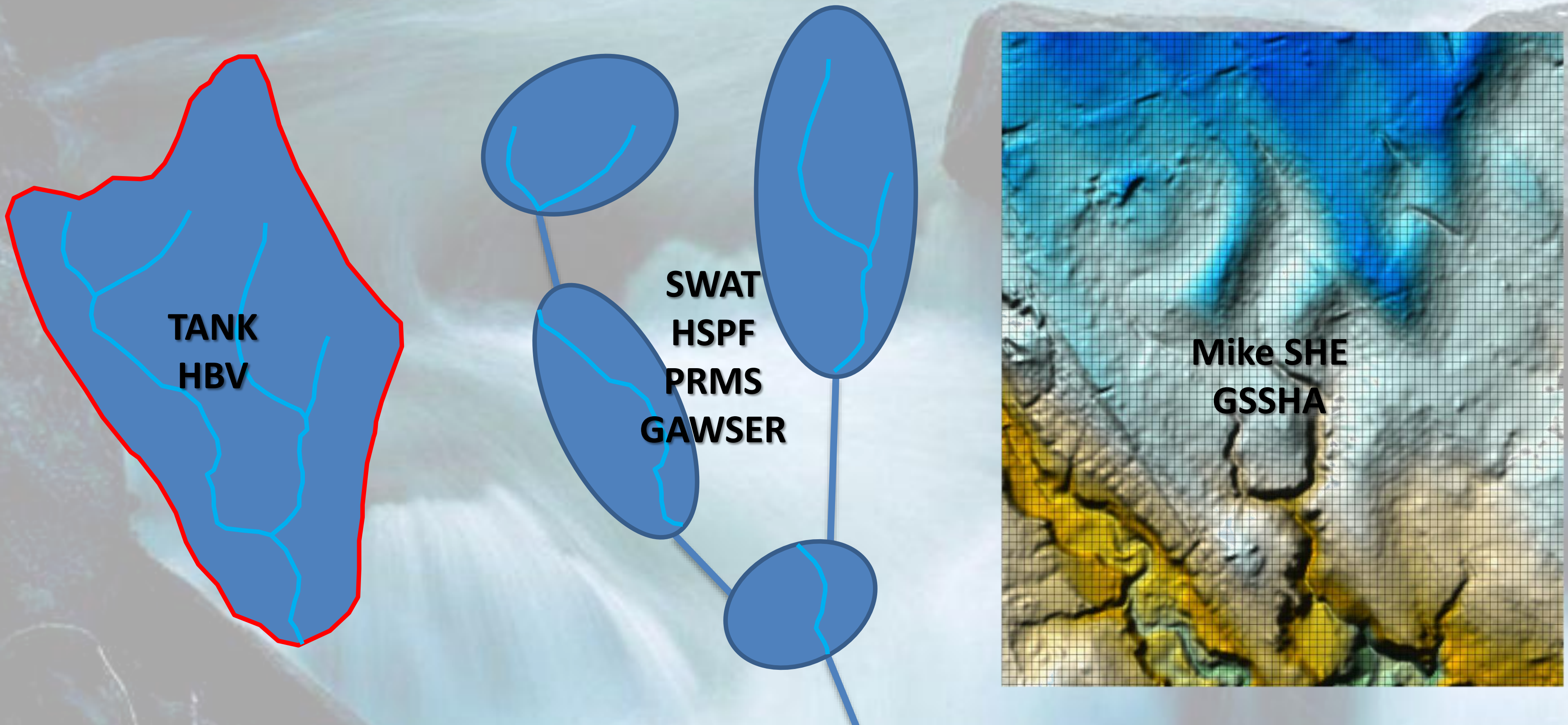


Semi-Distributed



(Fully-) Distributed

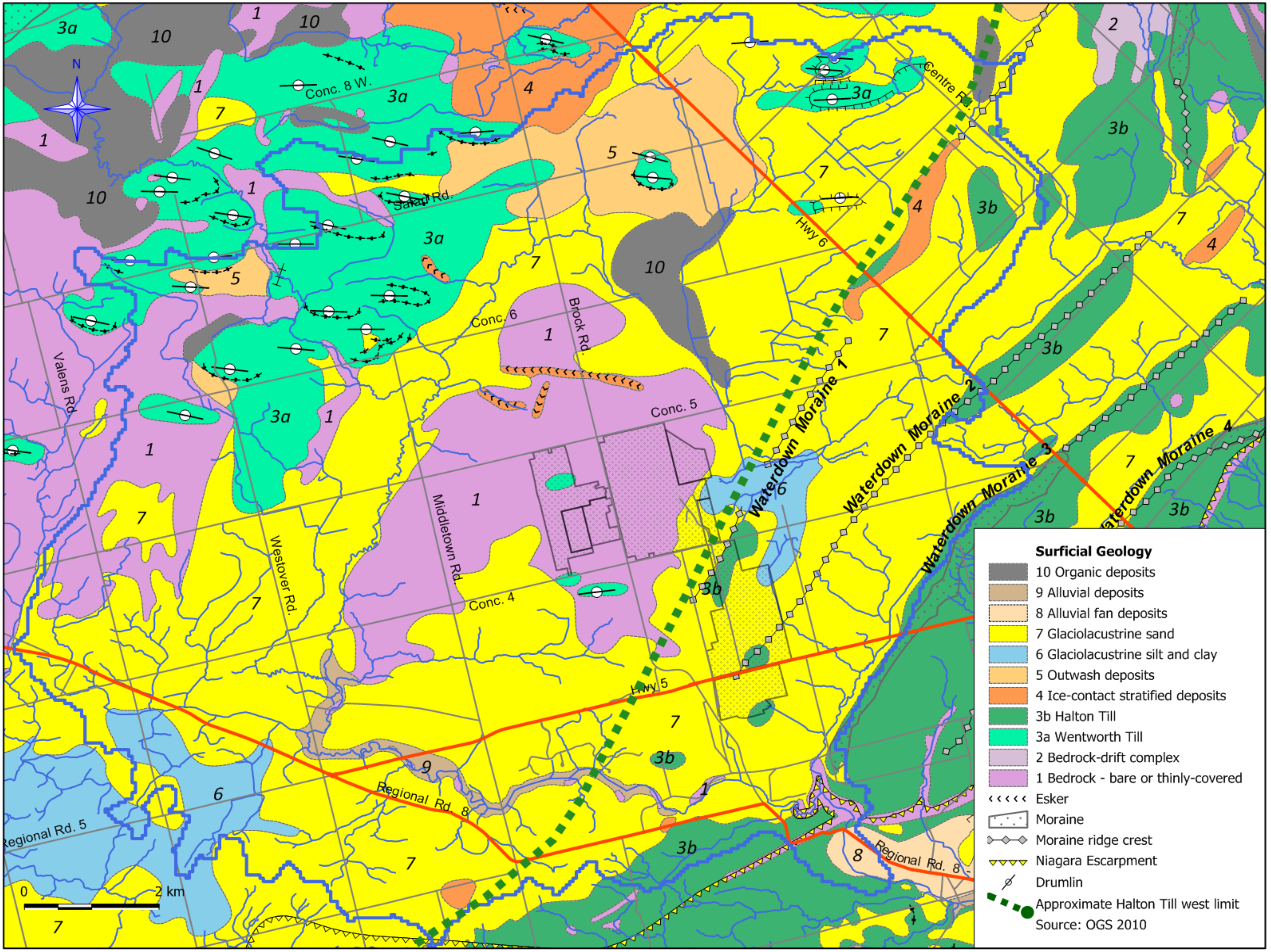
Surface Water Modeling Strategies



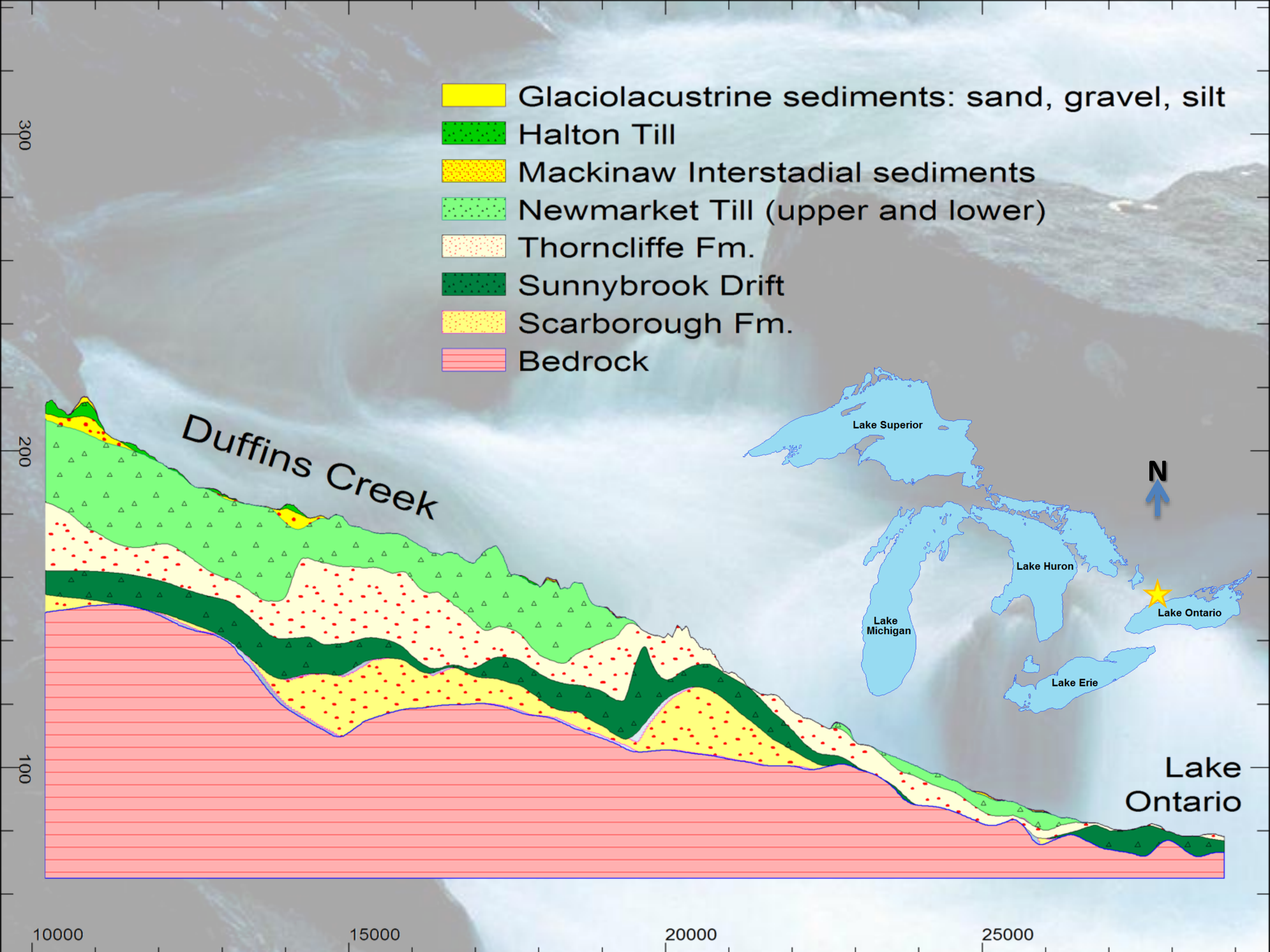
Lumped | **Semi-Distributed** | **(Fully-) Distributed**

Low resolution → High resolution

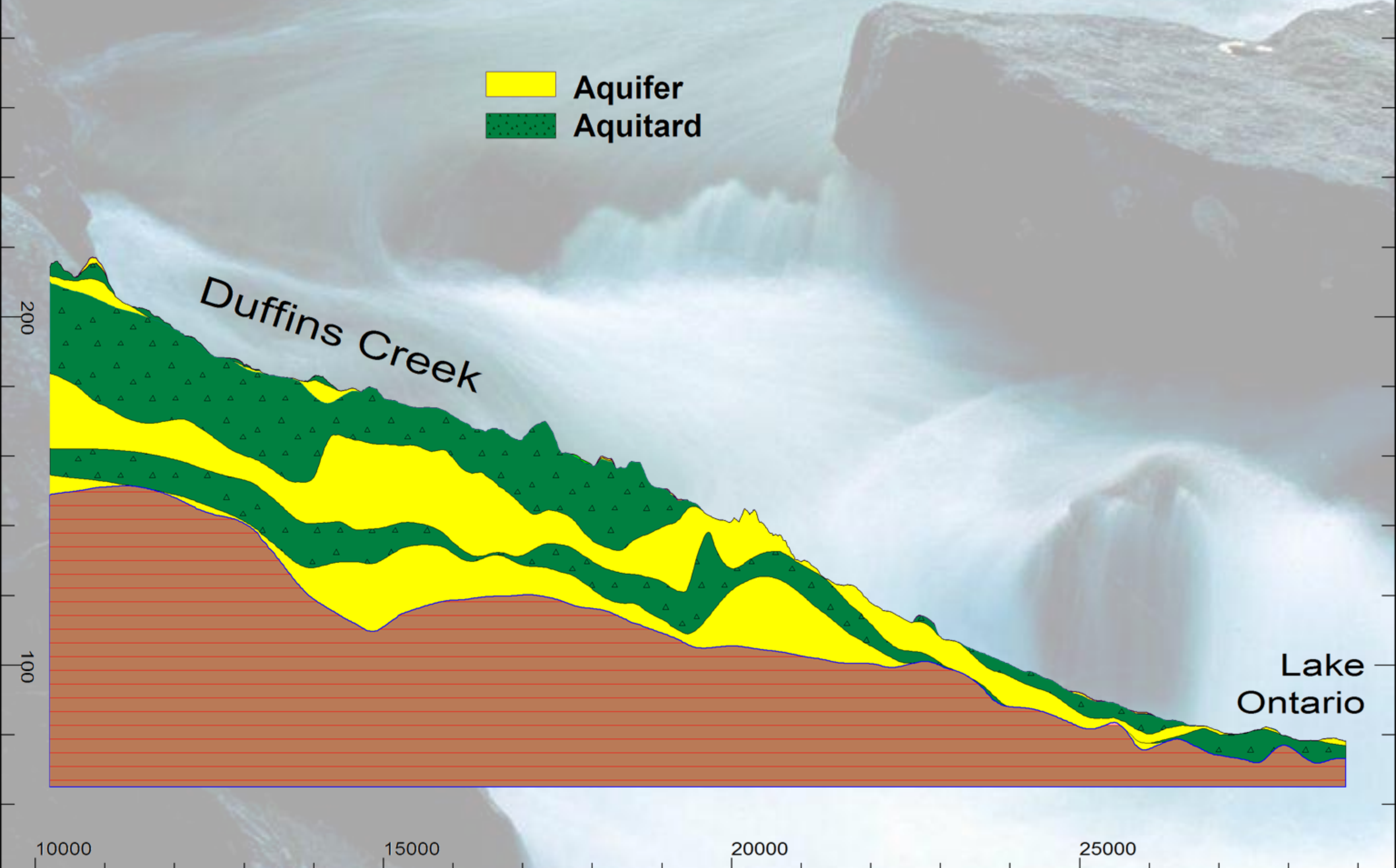
Increased computation time
Increased data demands
Increased heterogeneity



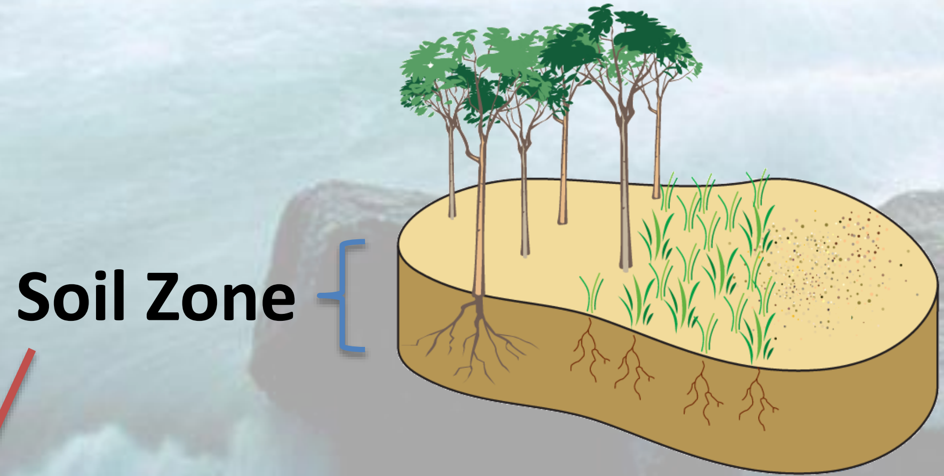
Surficial Geology
10 Organic deposits
9 Alluvial deposits
8 Alluvial fan deposits
7 Glaciolacustrine sand
6 Glaciolacustrine silt and clay
5 Outwash deposits
4 Ice-contact stratified deposits
3b Halton Till
3a Wentworth Till
2 Bedrock-drift complex
1 Bedrock - bare or thinly-covered
Esker
Moraine
Moraine ridge crest
Niagara Escarpment
Drumlin
Approximate Halton Till west limit
Source: OGS 2010
N
0
2 km
Conc. 8 W.
Safari Rd.
Conc. 6
Conc. 5
Conc. 4
Brock Rd.
Valens Rd.
Westover Rd.
Middletown Rd.
Centre Rd.
Hwy 6
Hwy 5
Regional Rd. 5
Regional Rd. 8
Waterdown Moraine 1
Waterdown Moraine 2
Waterdown Moraine 3
Waterdown Moraine 4

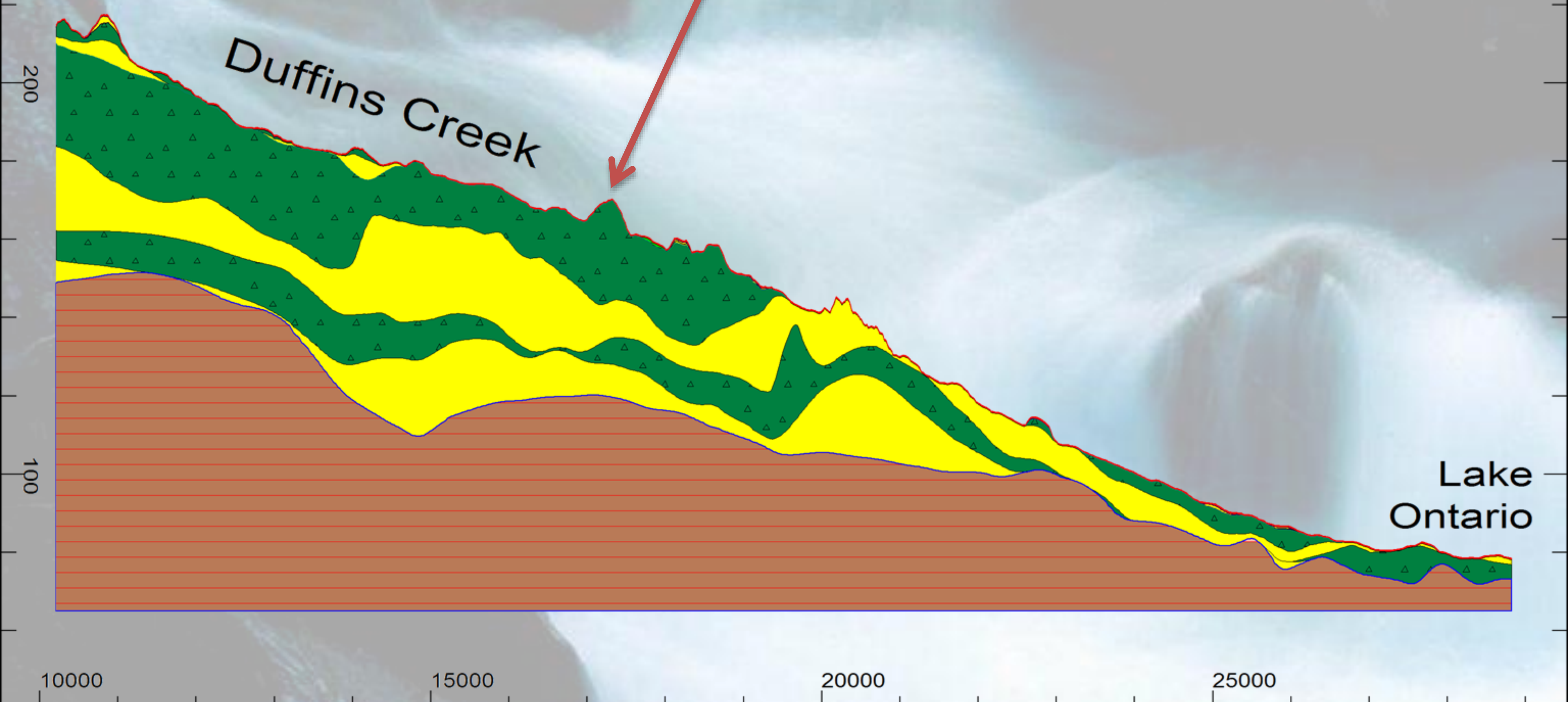

Glaciolacustrine sediments: sand, gravel, silt
Halton Till
Mackinaw Interstadial sediments
Newmarket Till (upper and lower)
Thorncliffe Fm.
Sunnybrook Drift
Scarborough Fm.
Bedrock
Duffins Creek
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
N
Lake Ontario
300
200
100
10000
15000
20000
25000

Hydrostratigraphy

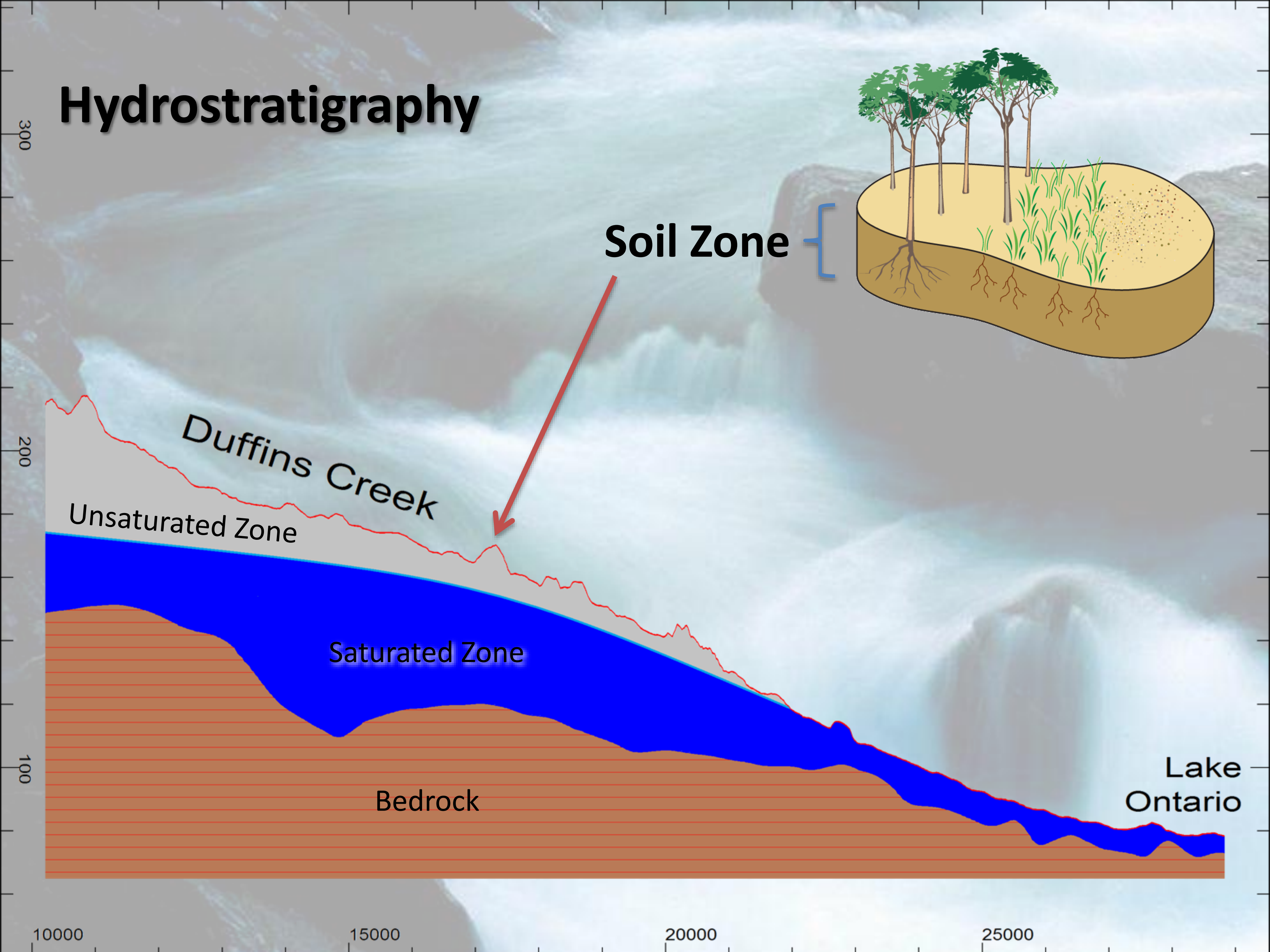


Hydrostratigraphy



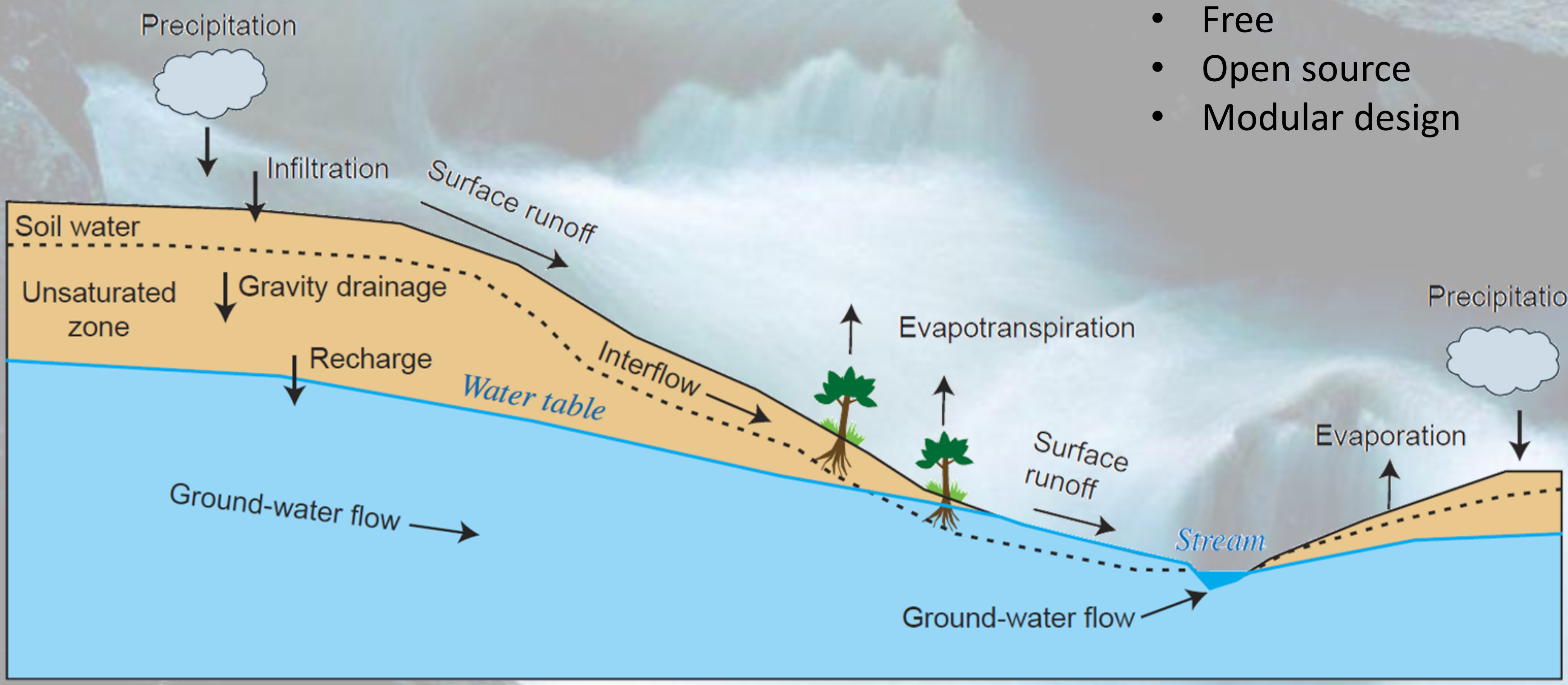


Hydrostratigraphy



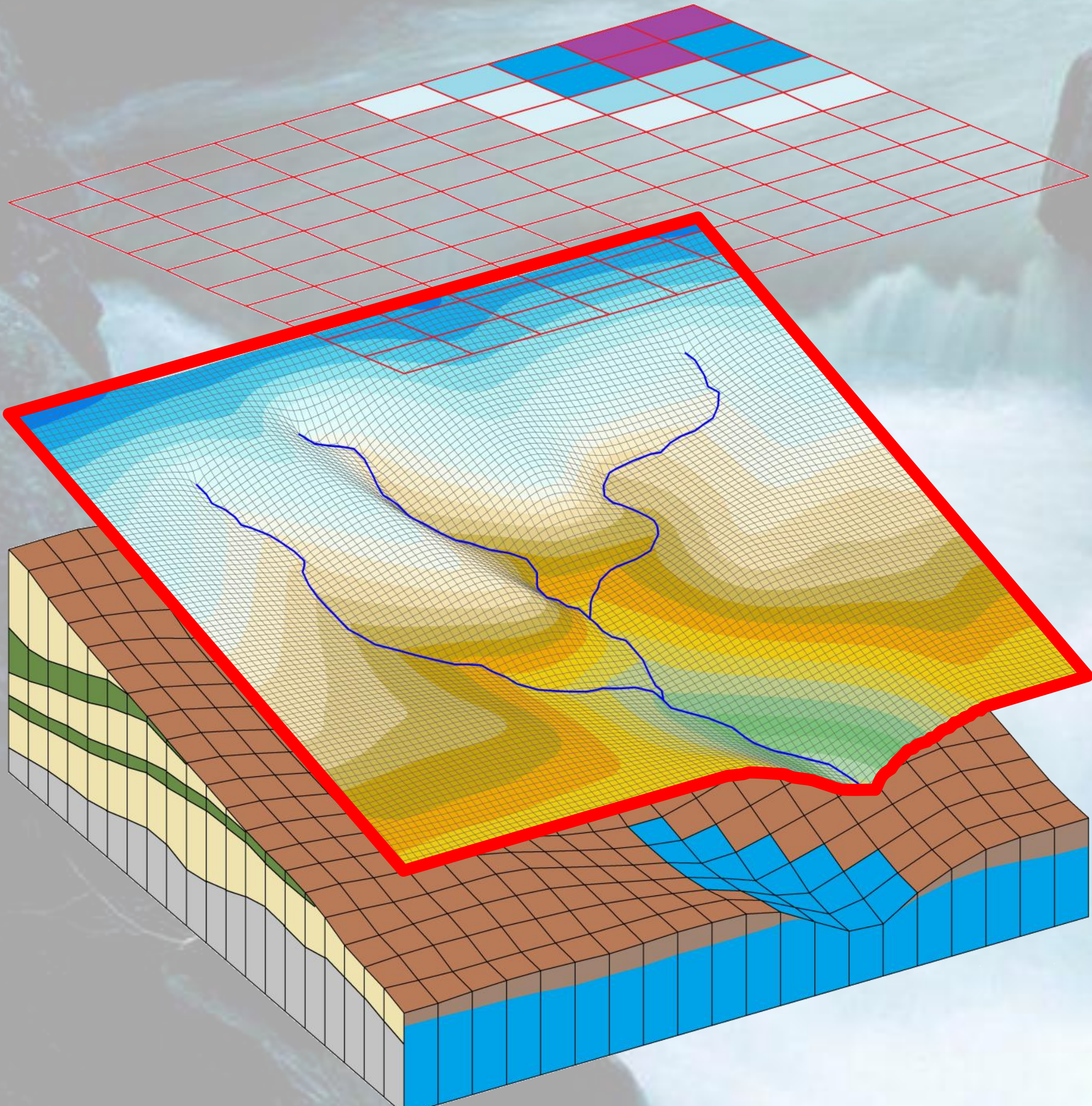
GSFLOW — Coupled Ground-Water and Surface-Water Flow Model Based on the Integration of the Precipitation-Runoff Modeling System (**PRMS**) and the Modular Ground-Water Flow Model (**MODFLOW**)

- Free
- Open source
- Modular design



(Markstrom et.al., 2008)

GSFLOW: Multi-Resolution



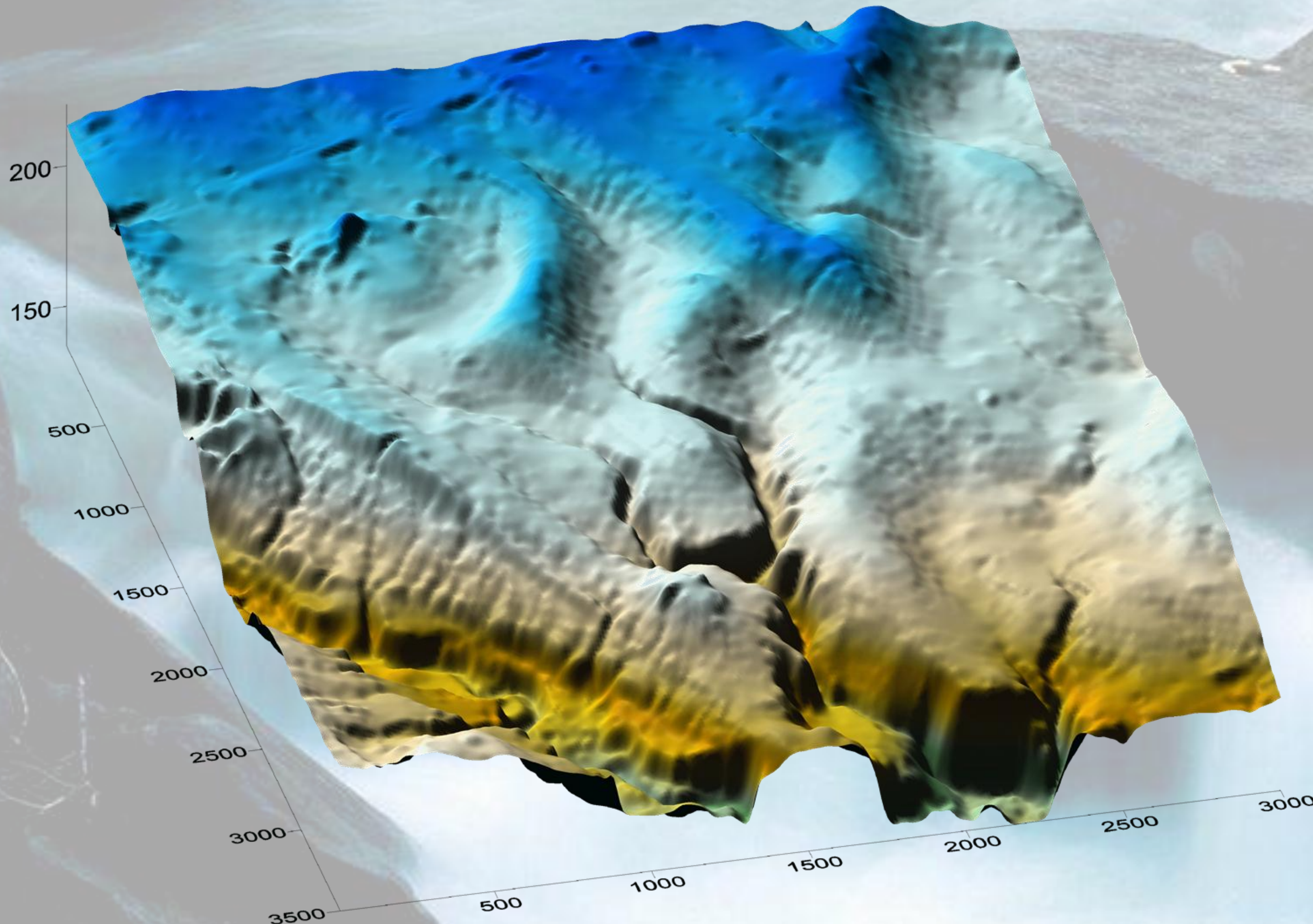
Climate variables 10:1

Stream networks
Treated as linear segments independent of grid resolution

Surface hydrology 1:1

Sub-surface hydrogeology 5:1

GSFLOW: Cascade flowpaths

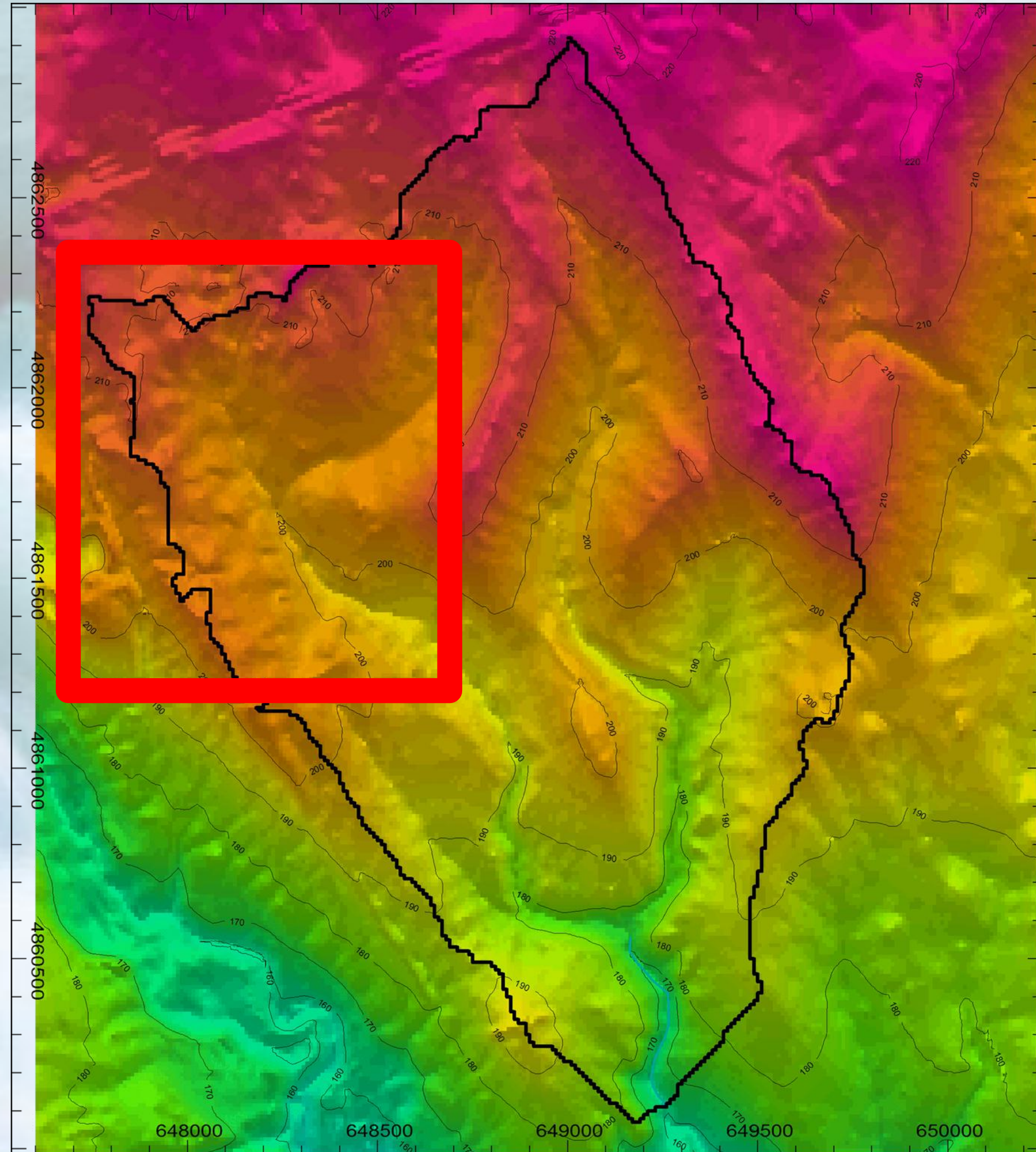


GSFLOW: Cascade flowpaths

5m LIDAR digital elevation model down-scaled to a 10m DEM.

Elevation range 160-220 masl.

50% of the catchment have slopes <3%.

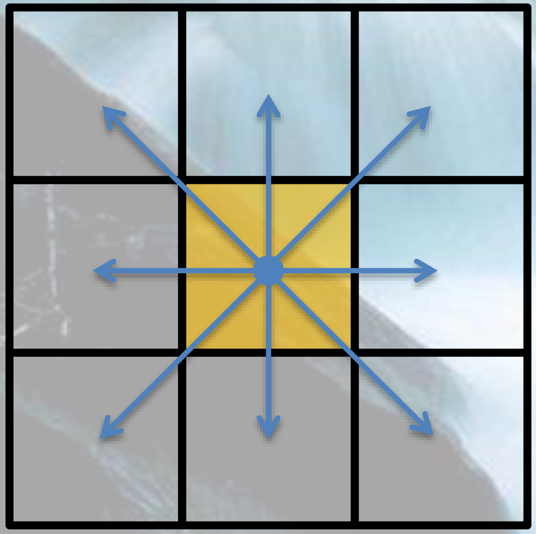


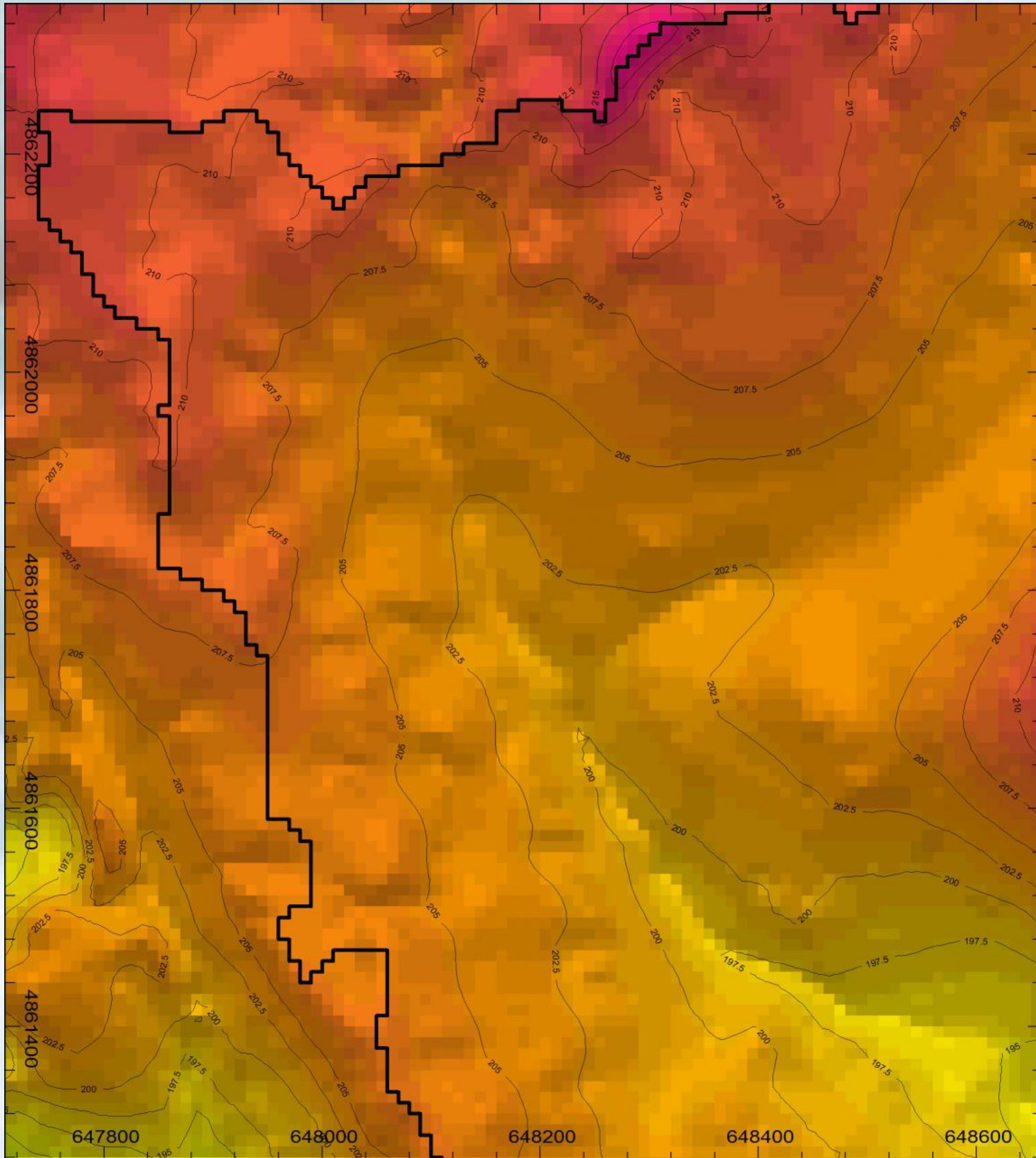
GSFLOW: Cascade flowpaths

Elevation range 160-220 masl.

5m LIDAR digital elevation model down-scaled to a 10m DEM.

Flowpaths defined using an 8-directional, steepest decent algorithm.





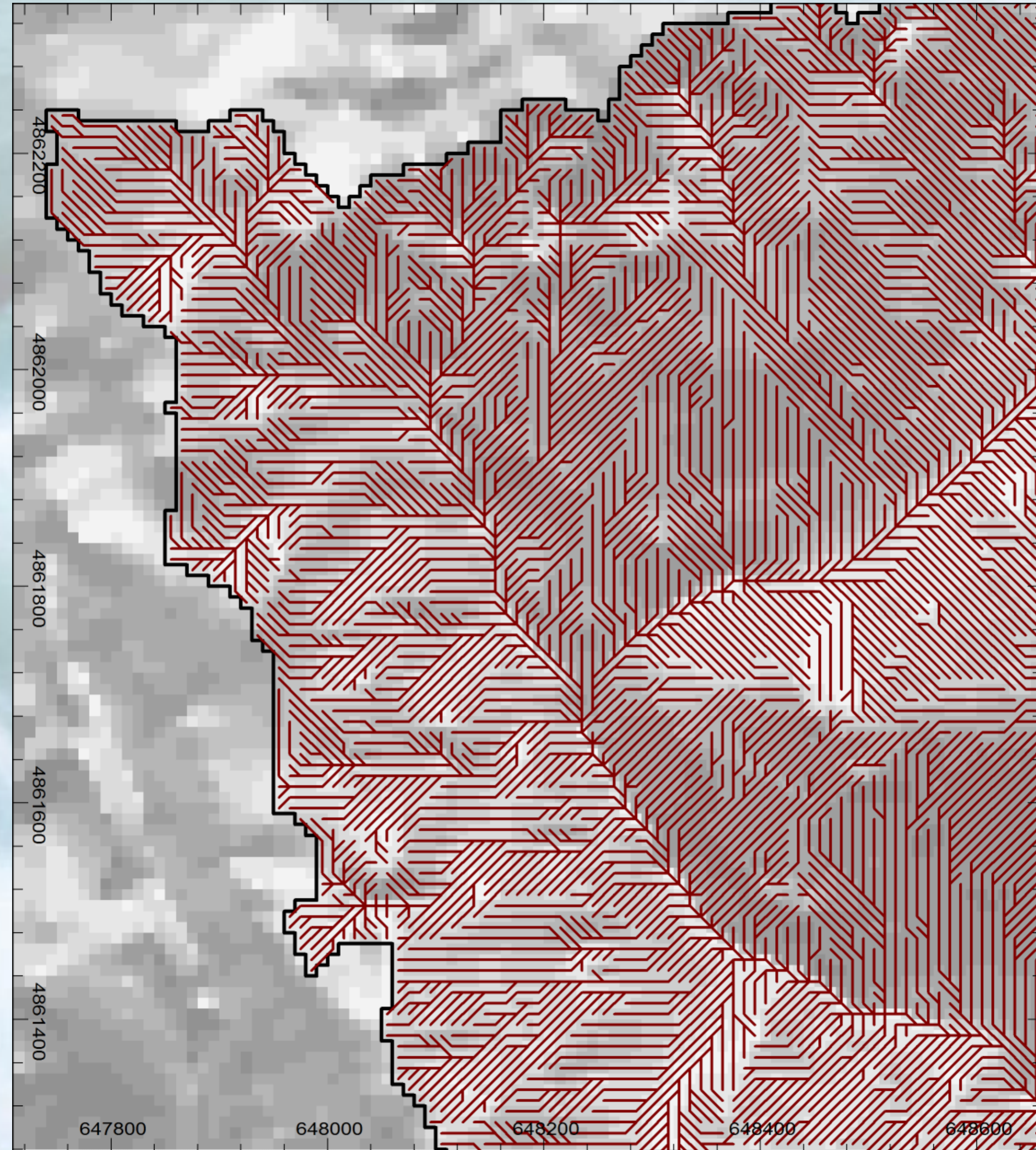
GSFLOW: Cascade flowpaths

Timing is treated explicitly.

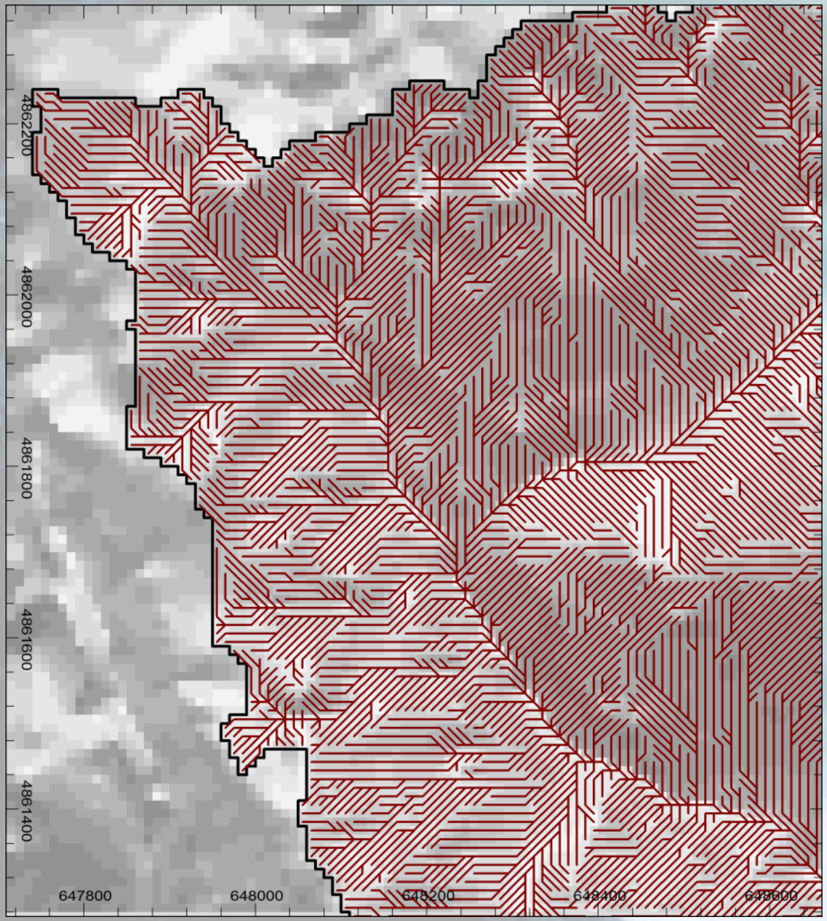
Runoff generated from one grid cell can infiltrate in an adjacent cell. (i.e., ***Run-on***).

Infiltration into the soil zone of one cell is routed to an adjacent cell (***interflow***) and can emerge as surface runoff (***exfiltration***).

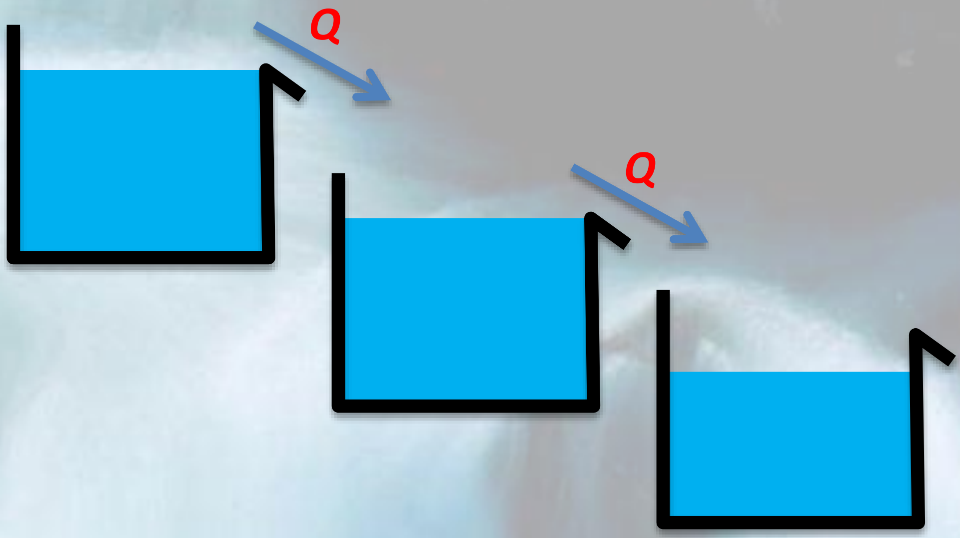
Assumption: water runs downhill.



GSFLOW: Cascade flowpaths



“Nash (1957) cascade”

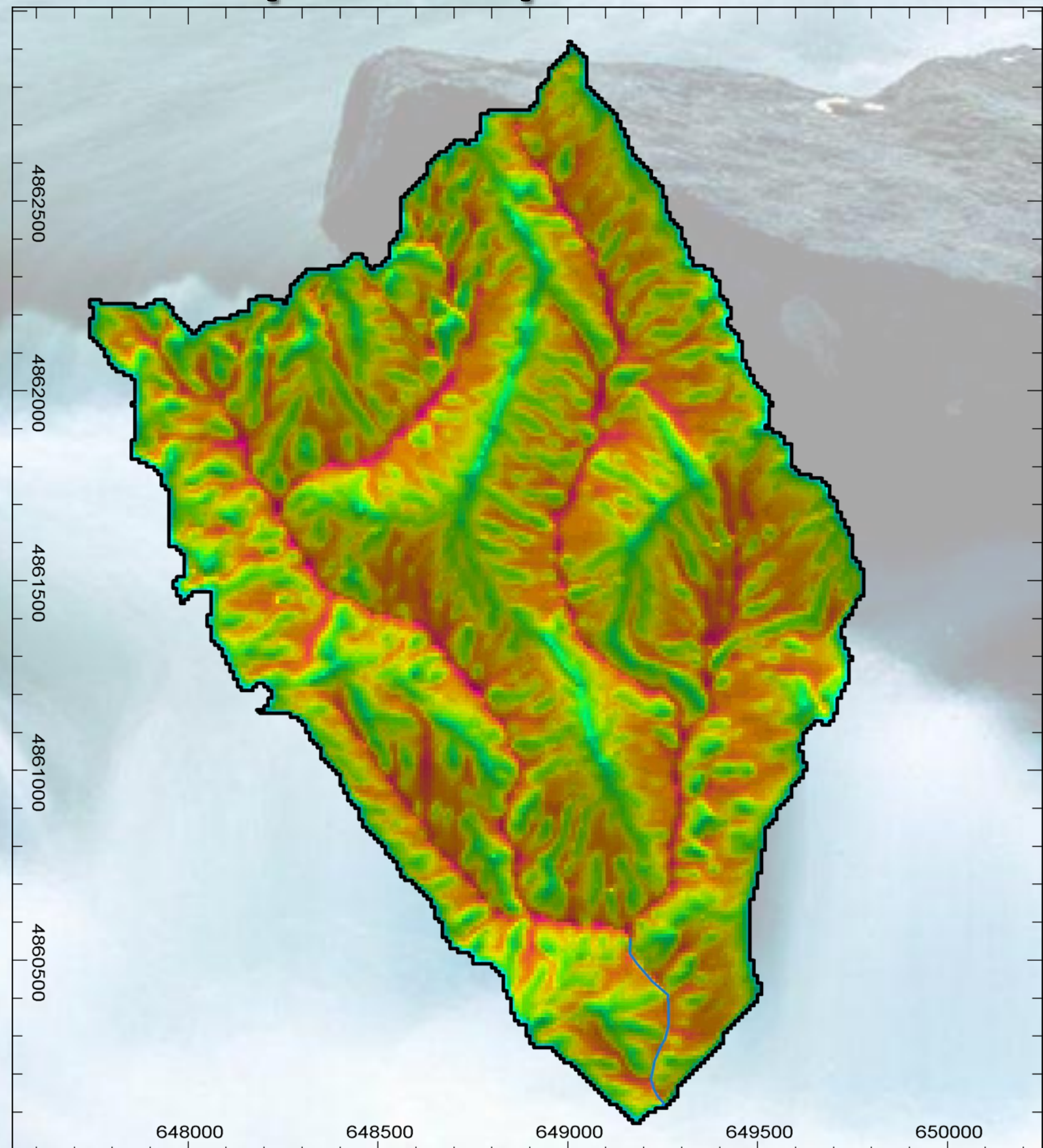


Cascade: Implications to Evapotranspiration

850 mm/yr precipitation

Evapotranspiration ranges from 300 mm/yr on the peaks to 480 mm/yr in the valleys.

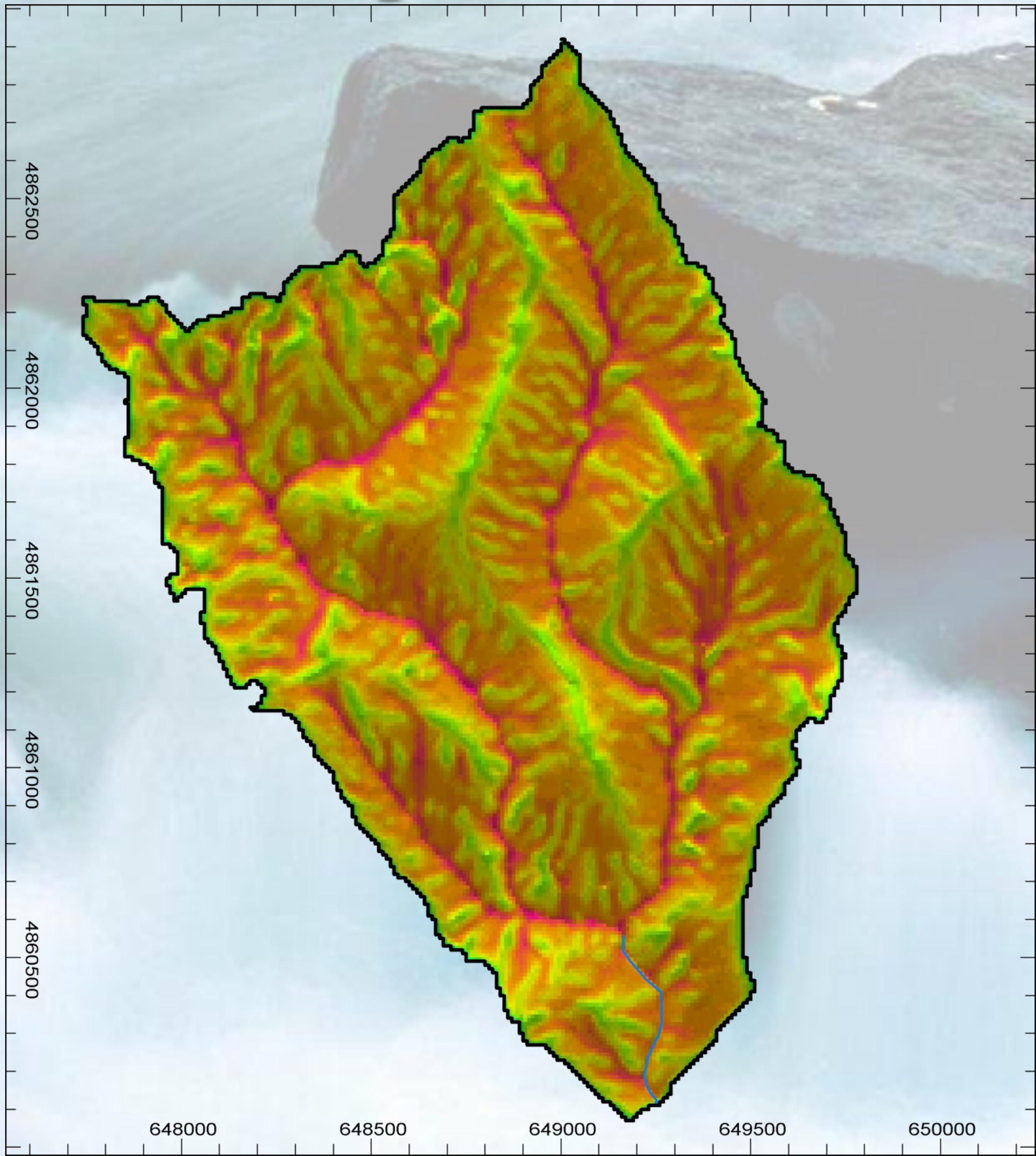
Strong spatial distribution emerges when accounting for topography



Cascade: Implications to Recharge

Groundwater recharge ranges from 380 mm/yr on the peaks to 760 mm/yr in the valleys ***(Percolation rate = 4x10^{-8} m/s).***

Distribution is again strongly related to topography.
i.e., the ***presence of water*** is dictated by the geo-morphological landscape features created by the ***presence of water***.

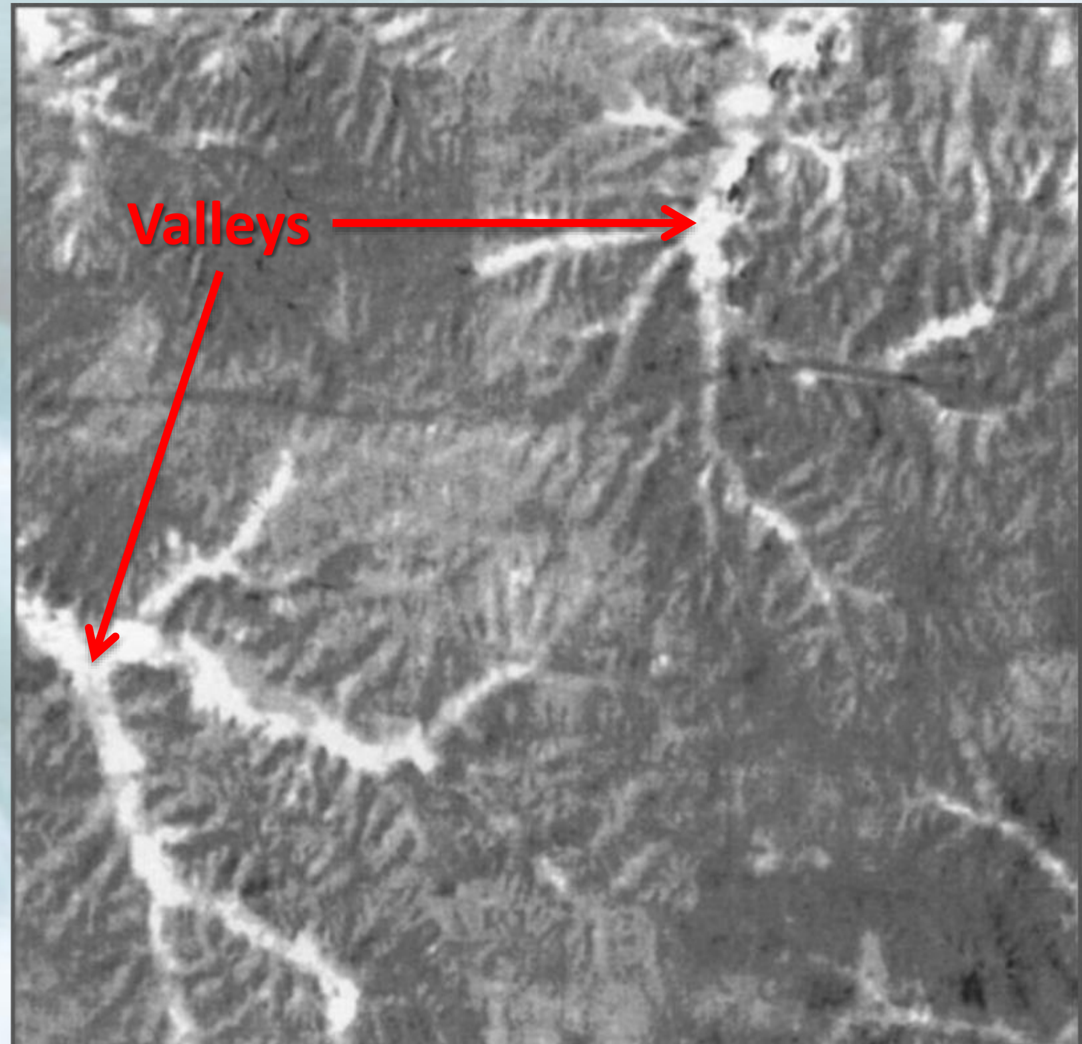


Latent Heat Flux

Latent Heat Flux = Energy consumed by evaporation

W/m²

- Above 500
- 460 - 500
- 420 - 460
- 380 - 420
- 340 - 380
- 300 - 340
- 260 - 300
- 220 - 260
- 180 - 220
- 140 - 180
- 100 - 140
- Below 100

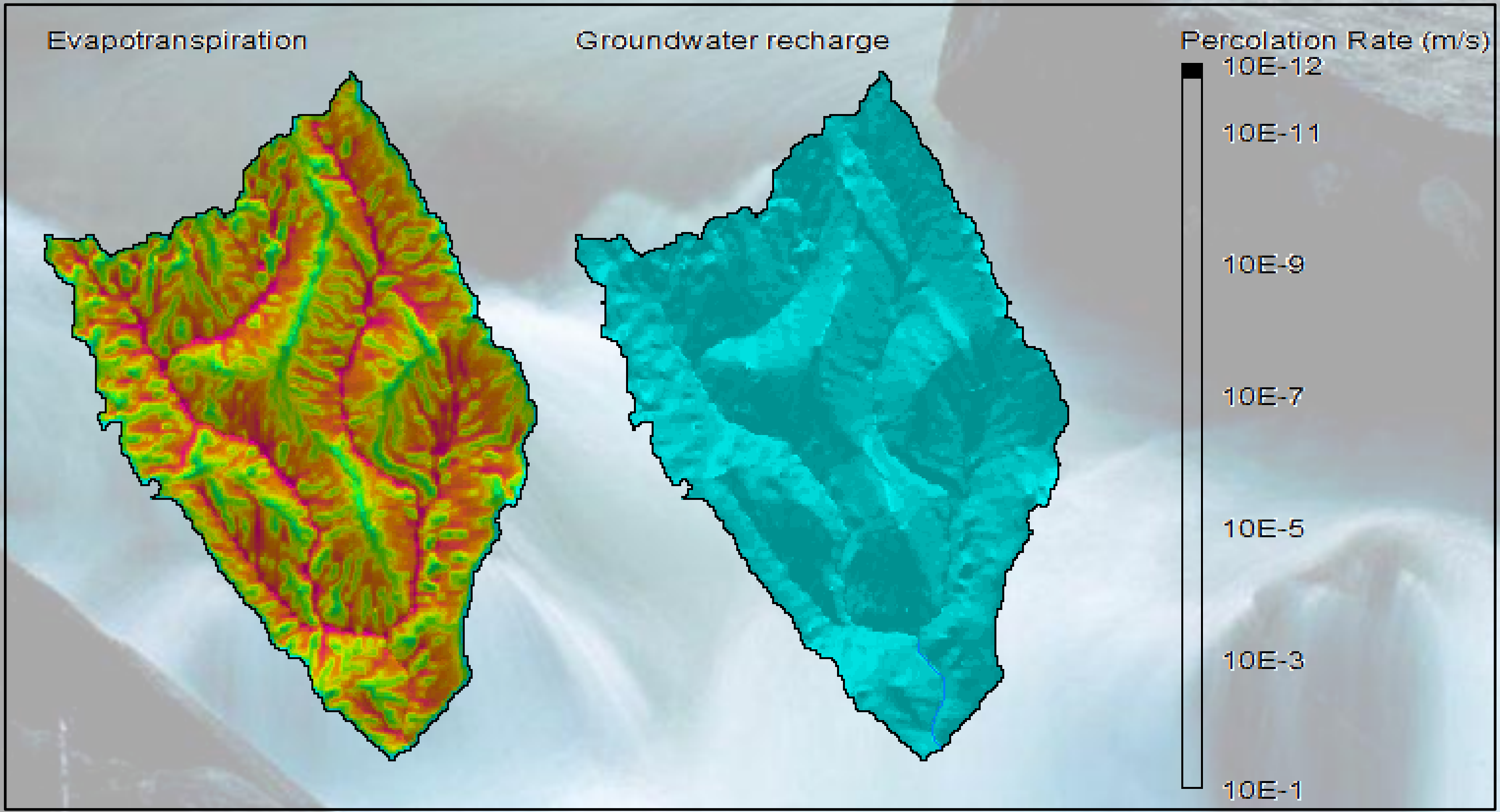


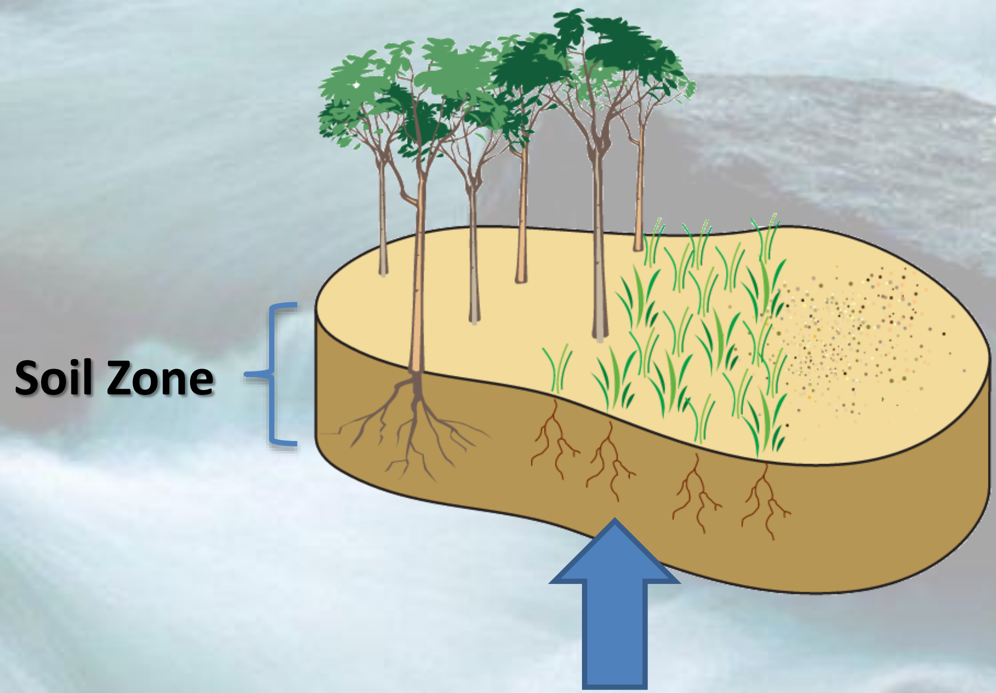
Konza Prairie Natural Area, near Manhattan Kansas, USA.
Image taken on August 15, 1987.

(Franks and Beven, 1997)

Increased Evapotranspiration potential in valleys

Inversion of the Topographic Influence

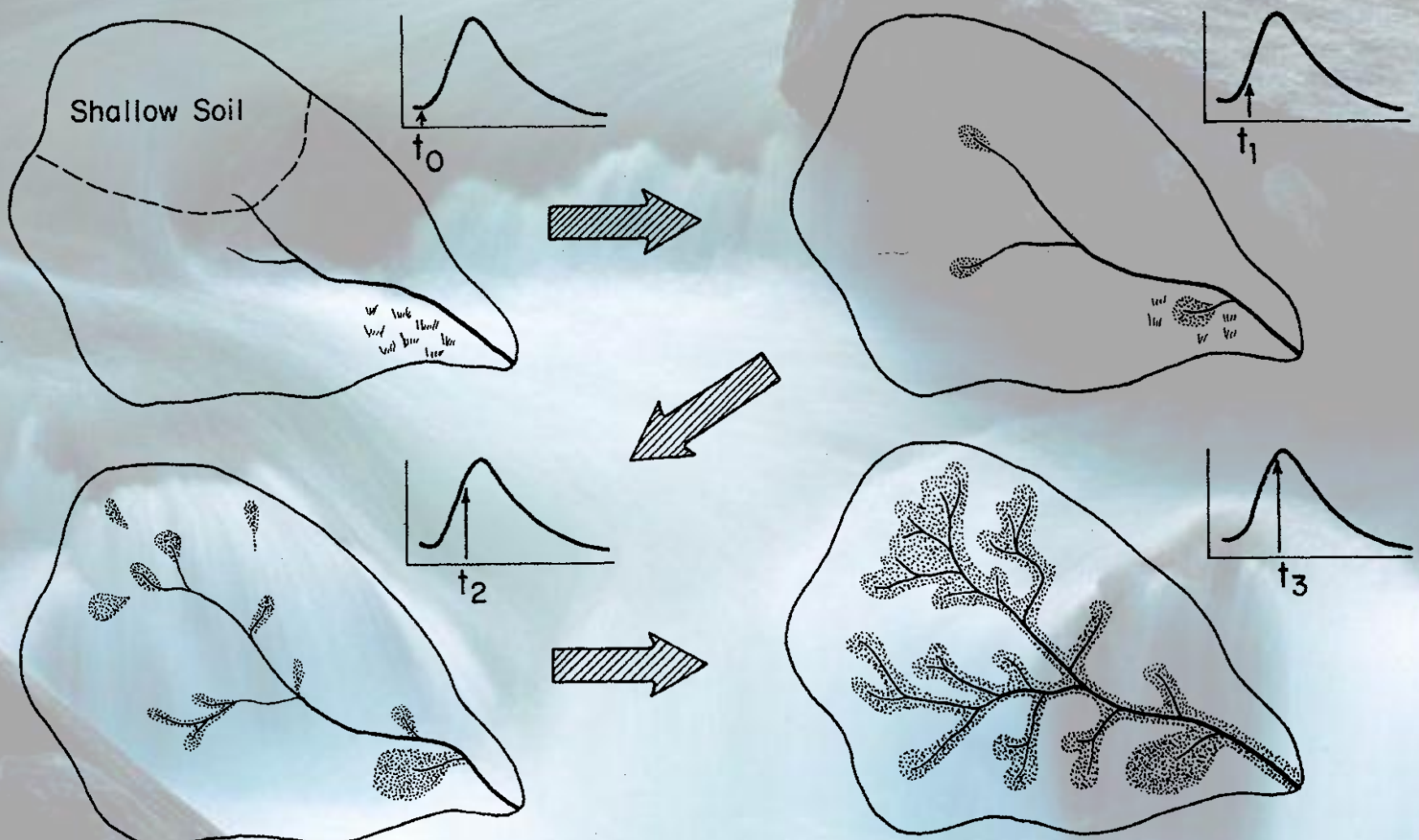




Groundwater Discharge:

The rate at which water is added to the soil zone <u>from</u> the groundwater system as the water table approaches the surface.

Variable Source Area Concept *(Hewlett & Hibbert, 1963)*



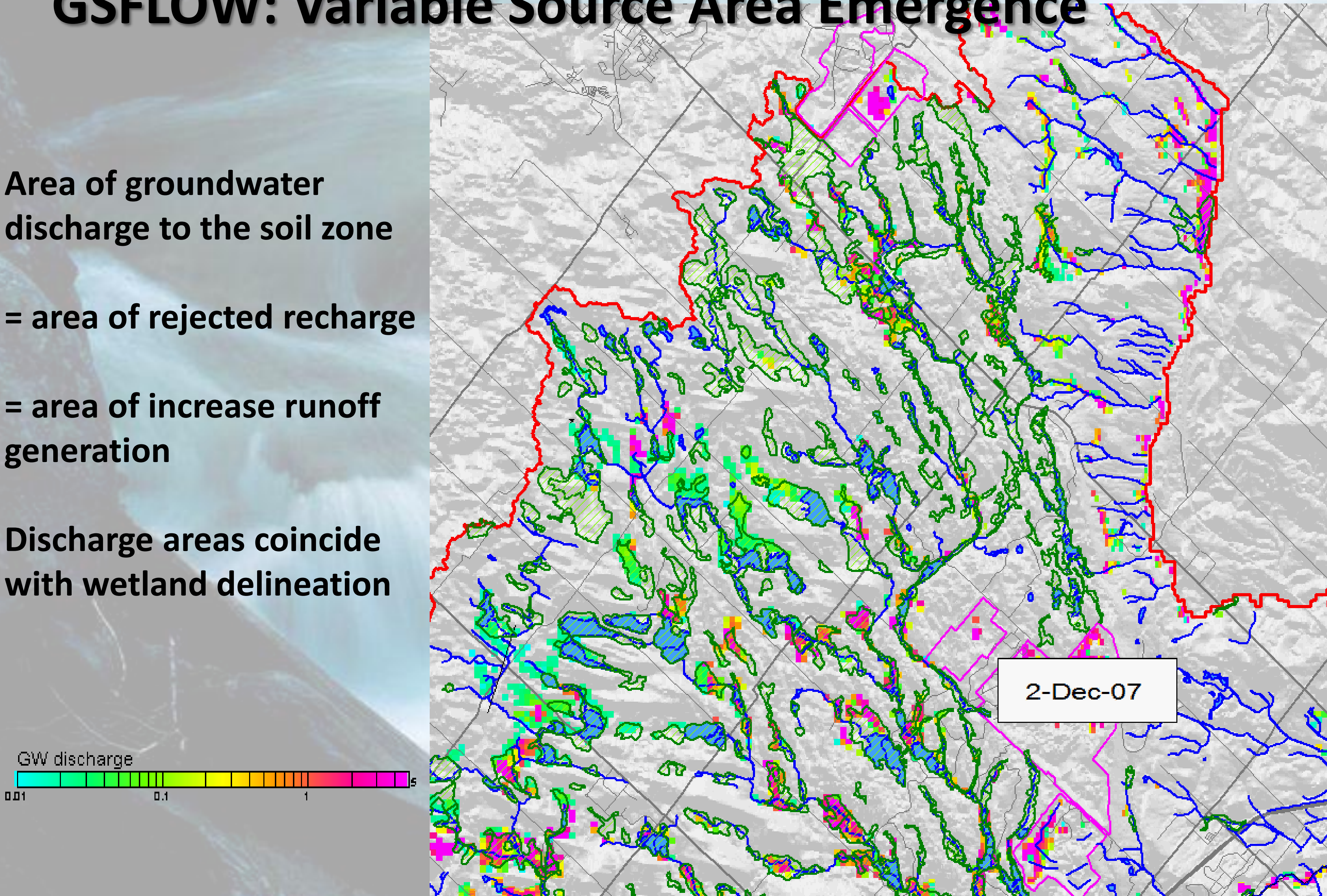
GSFLOW: Variable Source Area Emergence

Area of groundwater discharge to the soil zone

= area of rejected recharge

= area of increase runoff generation

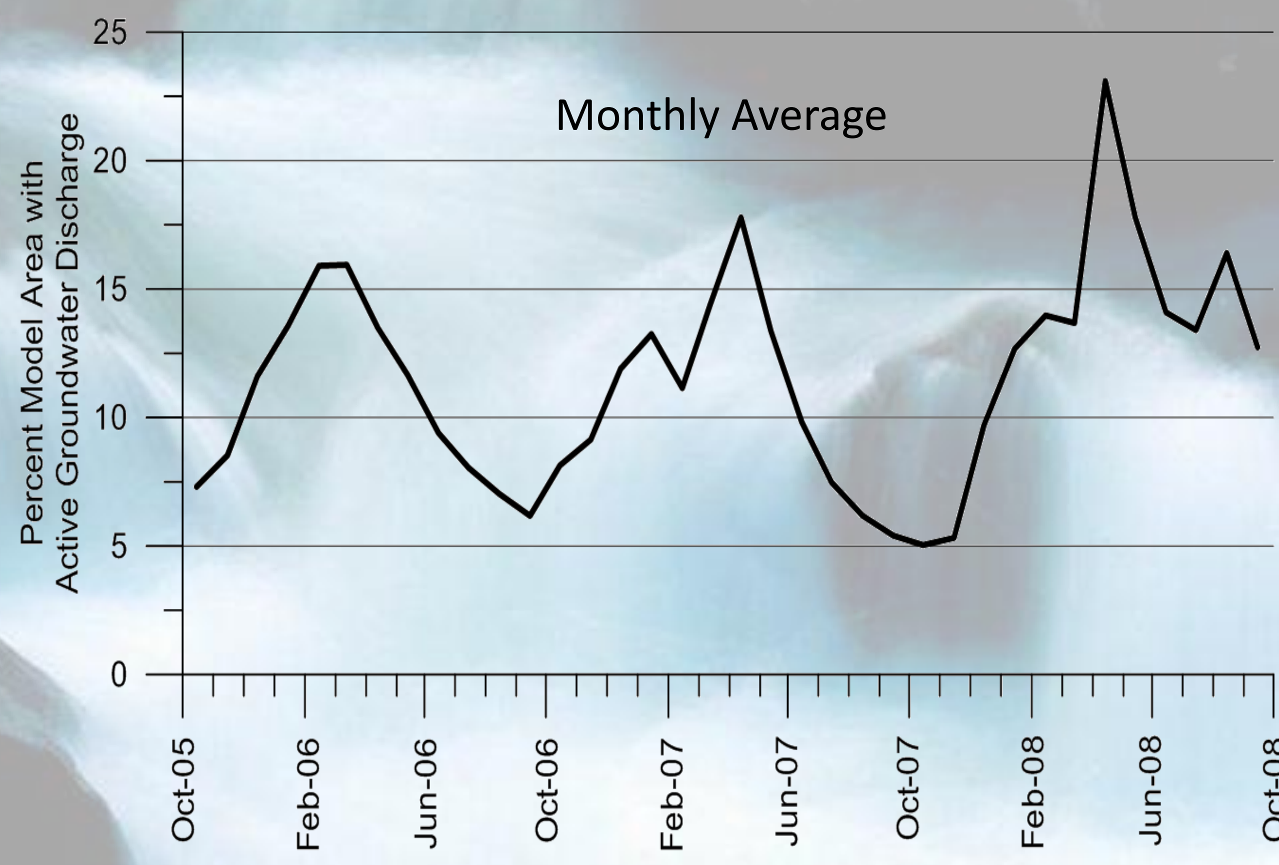
Discharge areas coincide with wetland delineation



GSFLOW: Variable Source Area

Daily Statistics: percent watershed area of rejected recharge

Min	4.6%
Max	28.4 %
Difference	~64 km²



Implications

- Coldwater streams, fisheries, in-stream flow needs are all a function of groundwater discharge.
- Wetland hydroperiod and the connectivity between recharge areas and wetland features are a function of both surface and groundwater processes.
- Lumped approach will under-prediction ET from wetlands and riparian habitats.
- Possible influence of advection under a heterogeneous ET regime.
- Localized surface saturation may result in reduced ET and greater long-term groundwater recharge.
- Minor fluctuations of a shallow groundwater table can have major impacts on runoff generation.

Conclusion

When surficial processes are of concern, one cannot model these systems unless a distributed integrated approach is taken (with rare exceptions).

Groundwater discharge and topography are first-order processes of the hydrologic cycle.

Limitations (??)

- Longer run times; BUT more calibration targets, qualitative targets such as wetlands, no more need for baseflow separation.

- Greater data requirements = increase uncertainty: An overstated issue.

    No difference in data requirements from a lumped approach, BUT extra information is gained (i.e., digital elevation models) by imposing topography on the runoff process.

Paradigm Shift??

1) Groundwater/Surface water modeling
or
Water modeling

2) Integrated modeling
vs.
De-coupled modeling

3) Top-down approach

References

Franks, S.W., K.J. Beven, 1997. Estimation of evapotranspiration at the landscape scale: A fuzzy disaggregation approach. Water Resources Research 33(12). pp. 2929-2938.

Hewlett, J.D., A.R. Hibbert, 1963. Moisture and energy conditions within a sloping soil mass during drainage. J. Geophys. Res. 68(4). Pp. 1081-1087.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008. GSFLOW—Coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240 p.

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