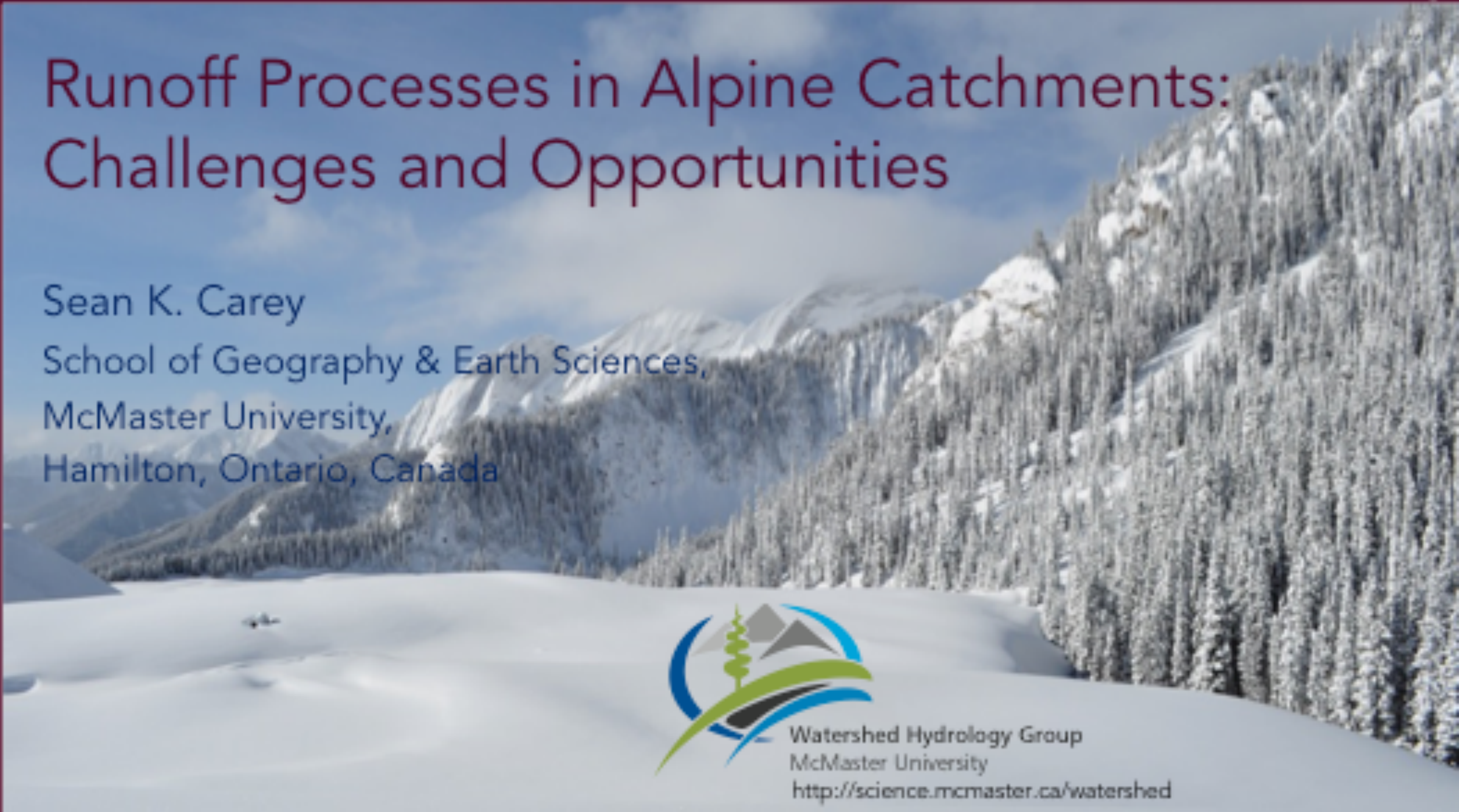


Runoff Processes in Alpine Catchments: Challenges and Opportunities

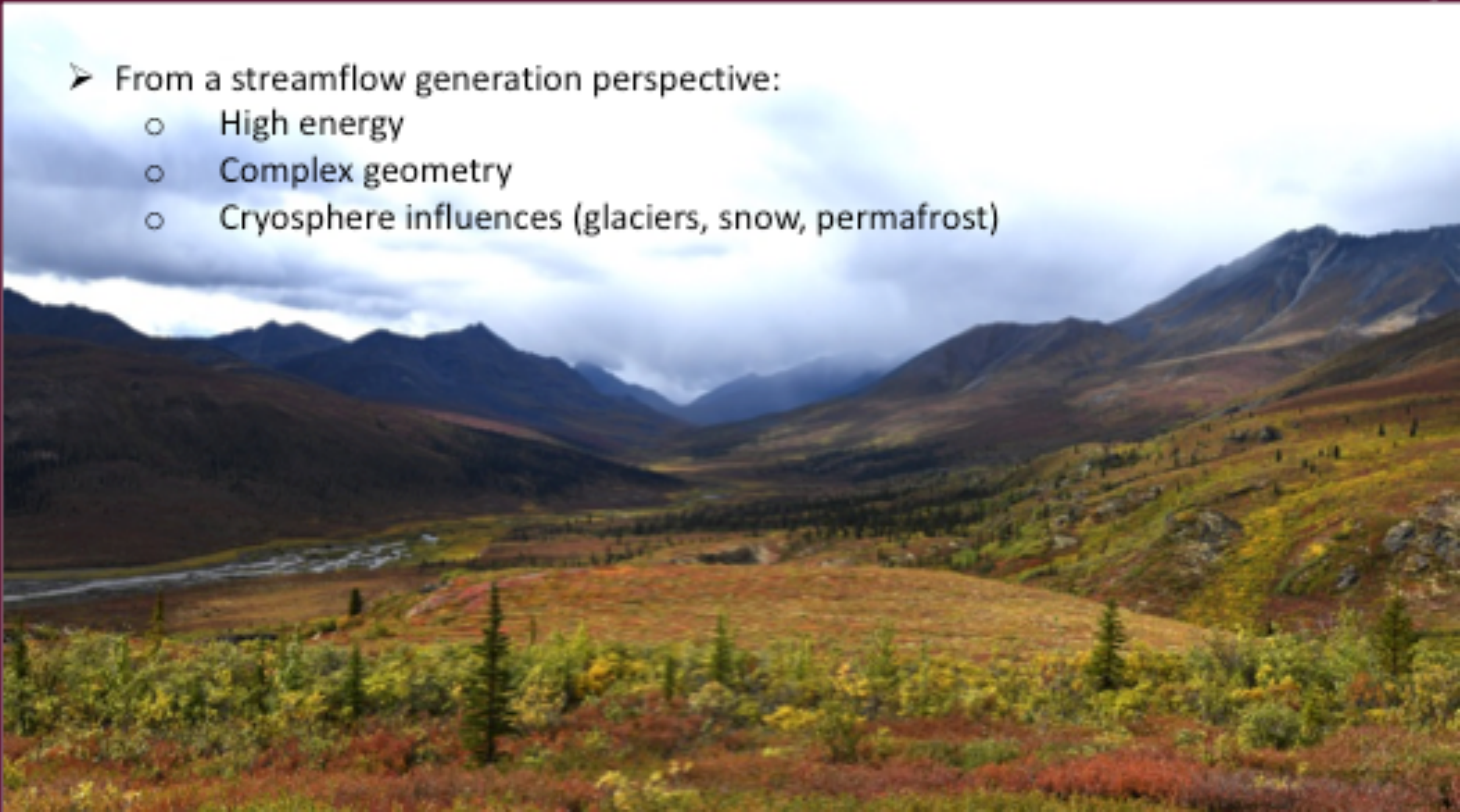
Sean K. Carey
School of Geography & Earth Sciences,
McMaster University,
Hamilton, Ontario, Canada

Watershed Hydrology Group
McMaster University
http://science.mcmaster.ca/watershed

A bit about me

- Hydrologist and dabbler at McMaster University in Canada.
- Have been working in Wolf Creek, Yukon Territory Canada since 1995.
- Have also worked in British Columbia
- Interested in all things 'watery'. Interested in how 'cold' affects water and the environment. Also concerned with human impacts in 'remote' areas.

- From a streamflow generation perspective:
  - High energy
  - Complex geometry
  - Cryosphere influences (glaciers, snow, permafrost)

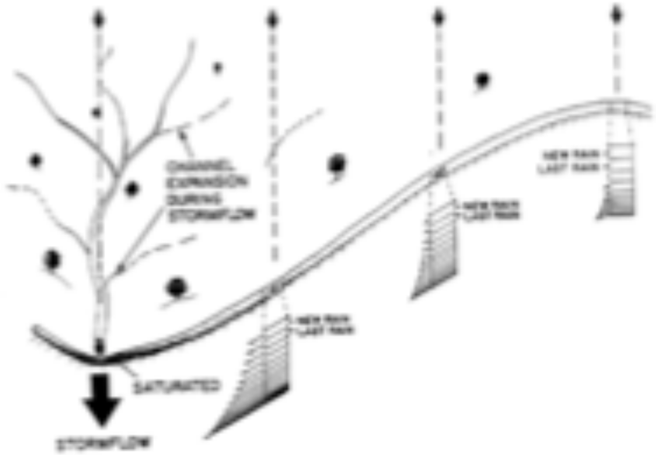


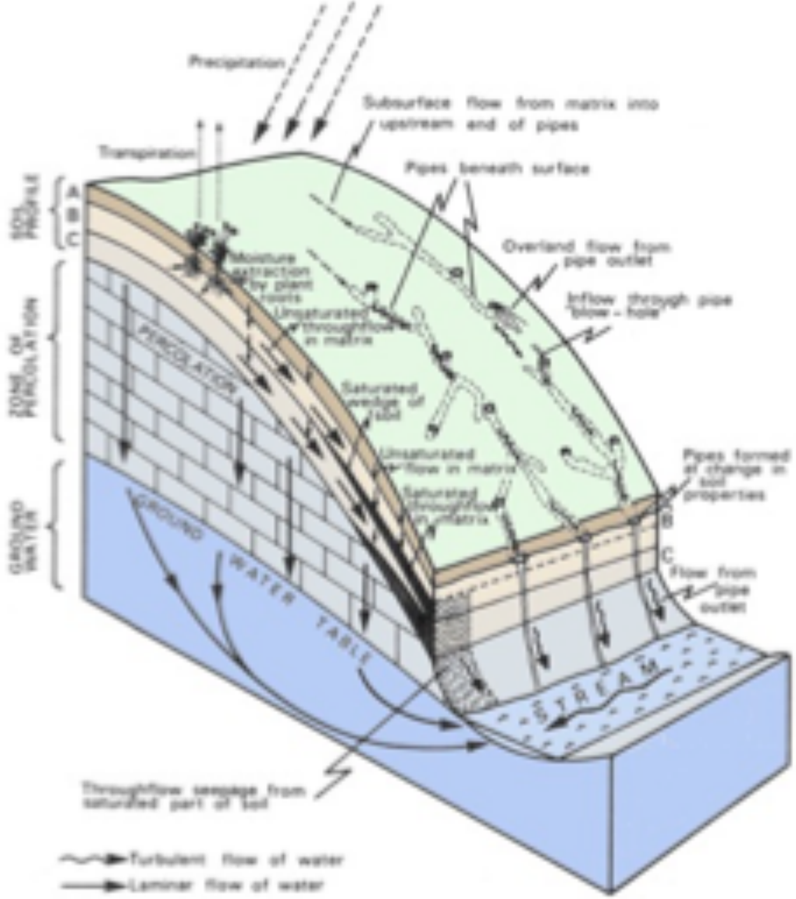
Runoff Processes in Alpine Catchments: Challenges and Opportunities

Runoff (hillslope) processes

- Largely concerned with how water moved from hillslopes to streams

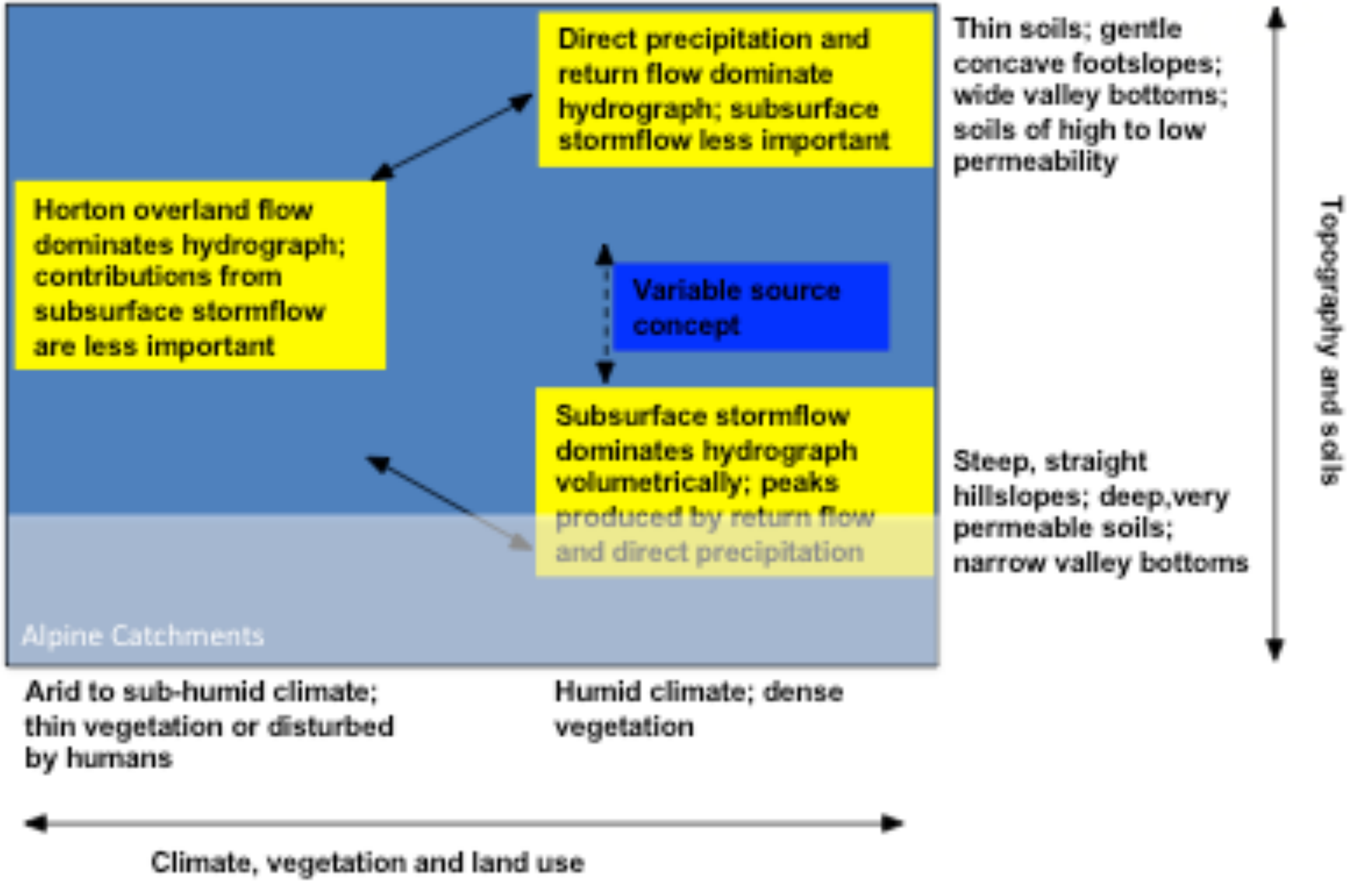
- Large literature beginning with Hortonian overland flow and moving to throughflow, saturated wedge, transmissivity feedback, etc.





From Kirkby (1978)

Synthesis of Runoff Processes



Runoff processes in relation to their major controls.

(From Dunne and Leopold, 1978)

Runoff Processes in Alpine Catchments: Challenges and Opportunities

Syntheses of Runoff Process

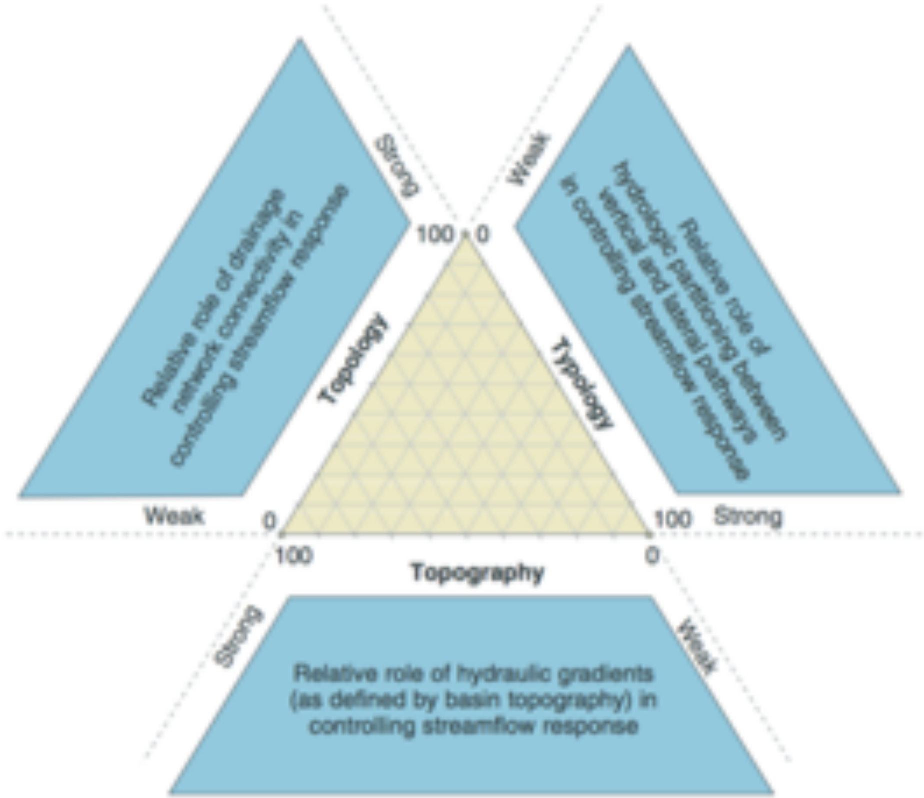
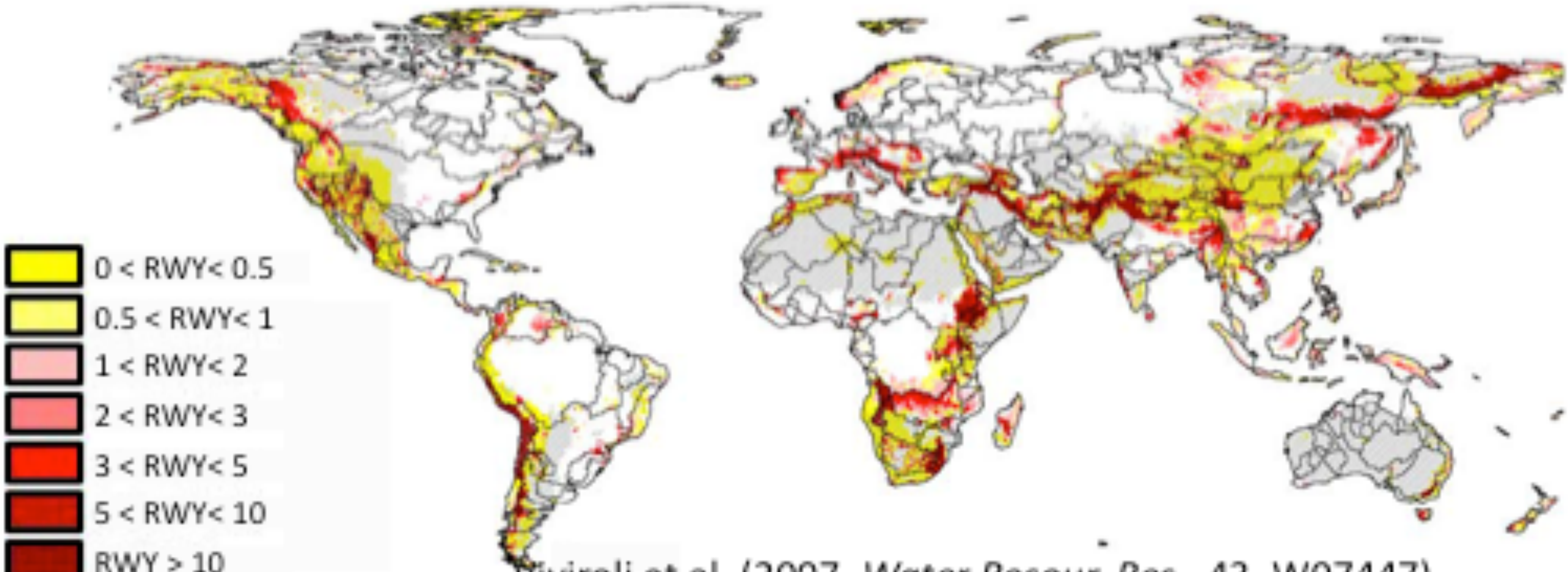


Figure 1. The T^3 (typology—topography—topology) template and the relative role of each factor in the regulation of streamflow response

From Jim Buttle (2006), Hydrological Processes

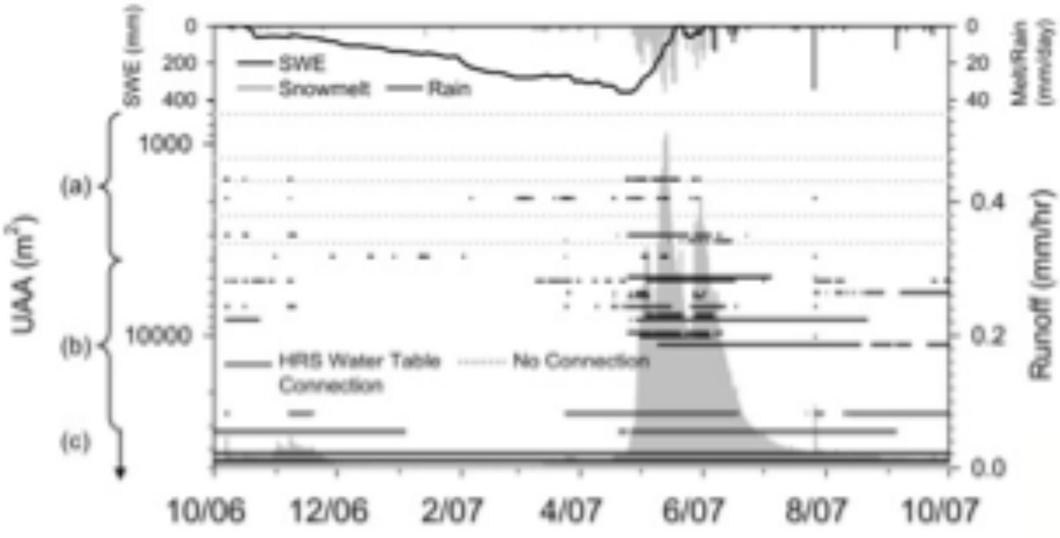
Mountains are the world's water towers

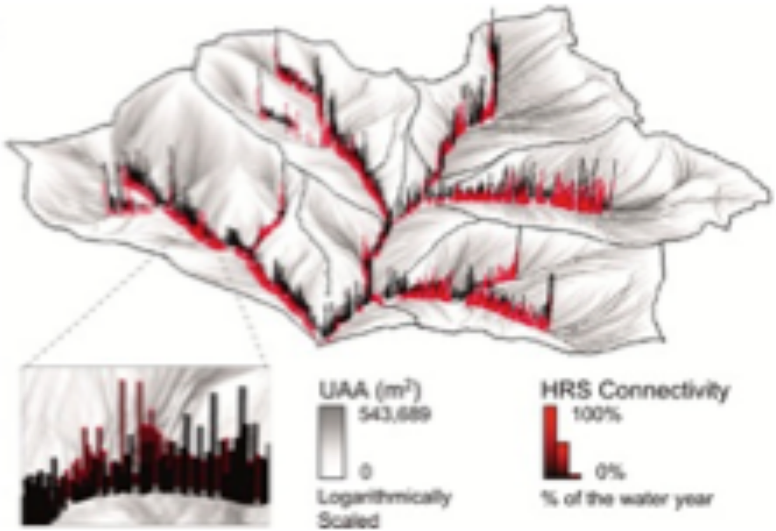
$$\text{Relative water yield (RWY)} = \frac{\text{Mountain runoff (mm/y)}}{\text{Lowland runoff (mm/y)}}$$



Viviroli et al. (2007, *Water Resour. Res.*, 43, W07447)

Steep Catchments – ephemeral linkages





Jencso and McGlynn 2009 WRR

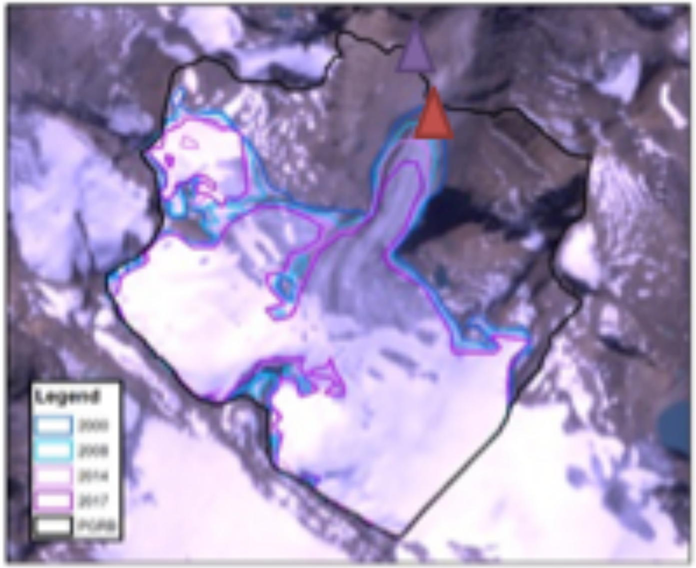
Key Factors for Alpine Watersheds

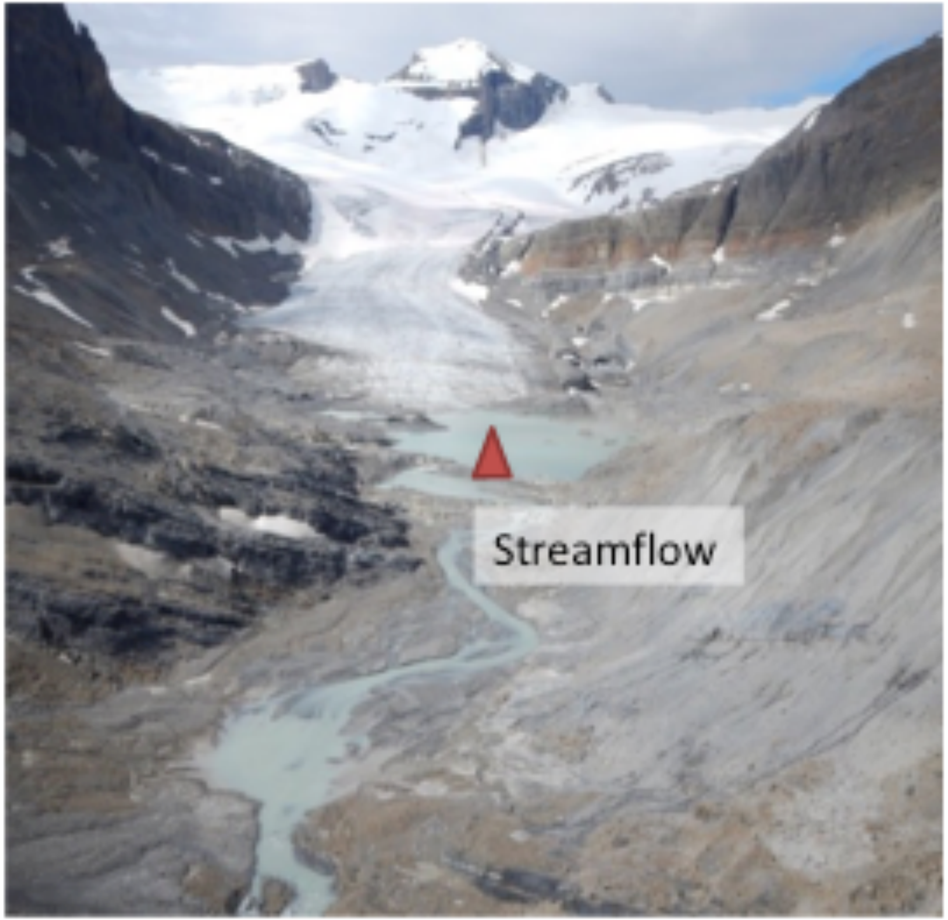
- Large thermal gradients
  - Elevation, aspect
- Poorly developed ‘soils’
  - Large porosity, uncertain geological setting
- Frozen ground status
- Glaciers and perennial snowpacks

Current Paradigms – snow and glaciers

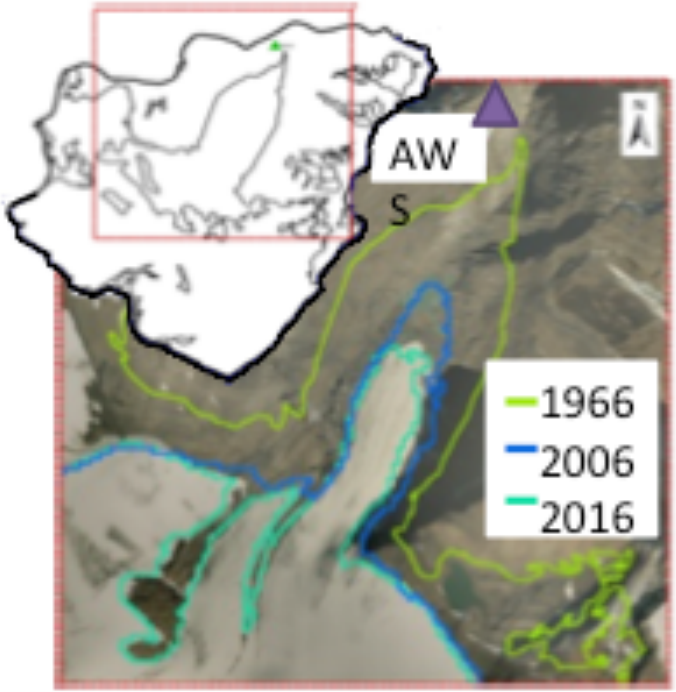
- Glacier and snow are key contributions to alpine streams
- Fairly well characterized, lots of healthy research
    - Focus is on global change

Example: Peyto Glacier in Canada

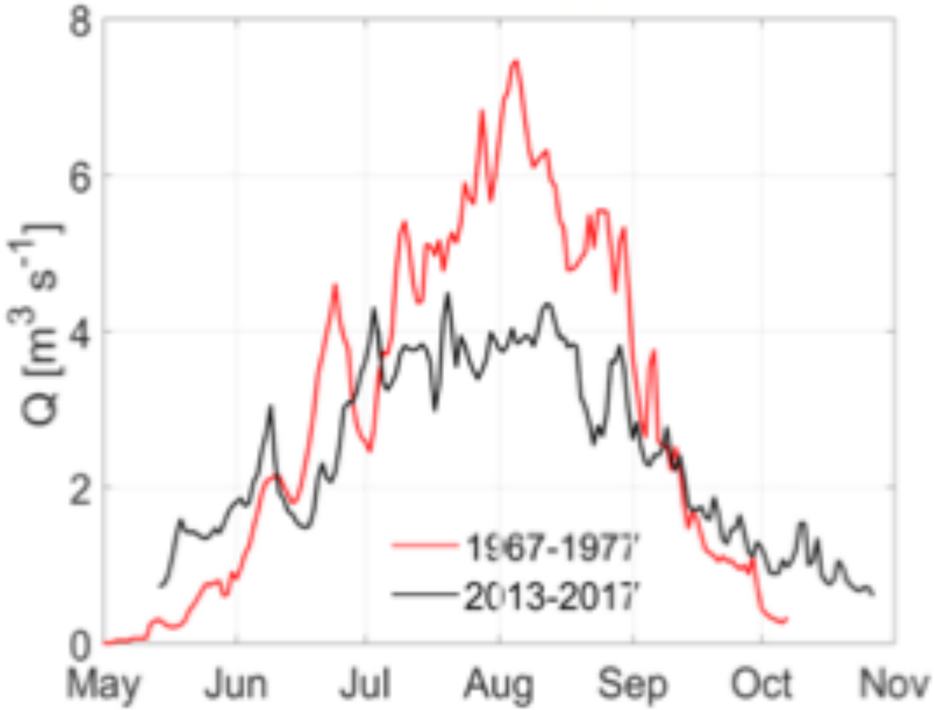


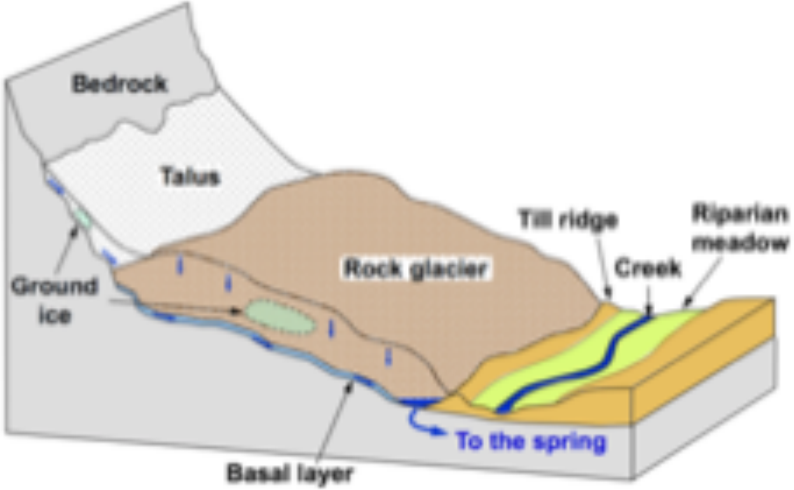


Example: Peyto Glacier in Canada



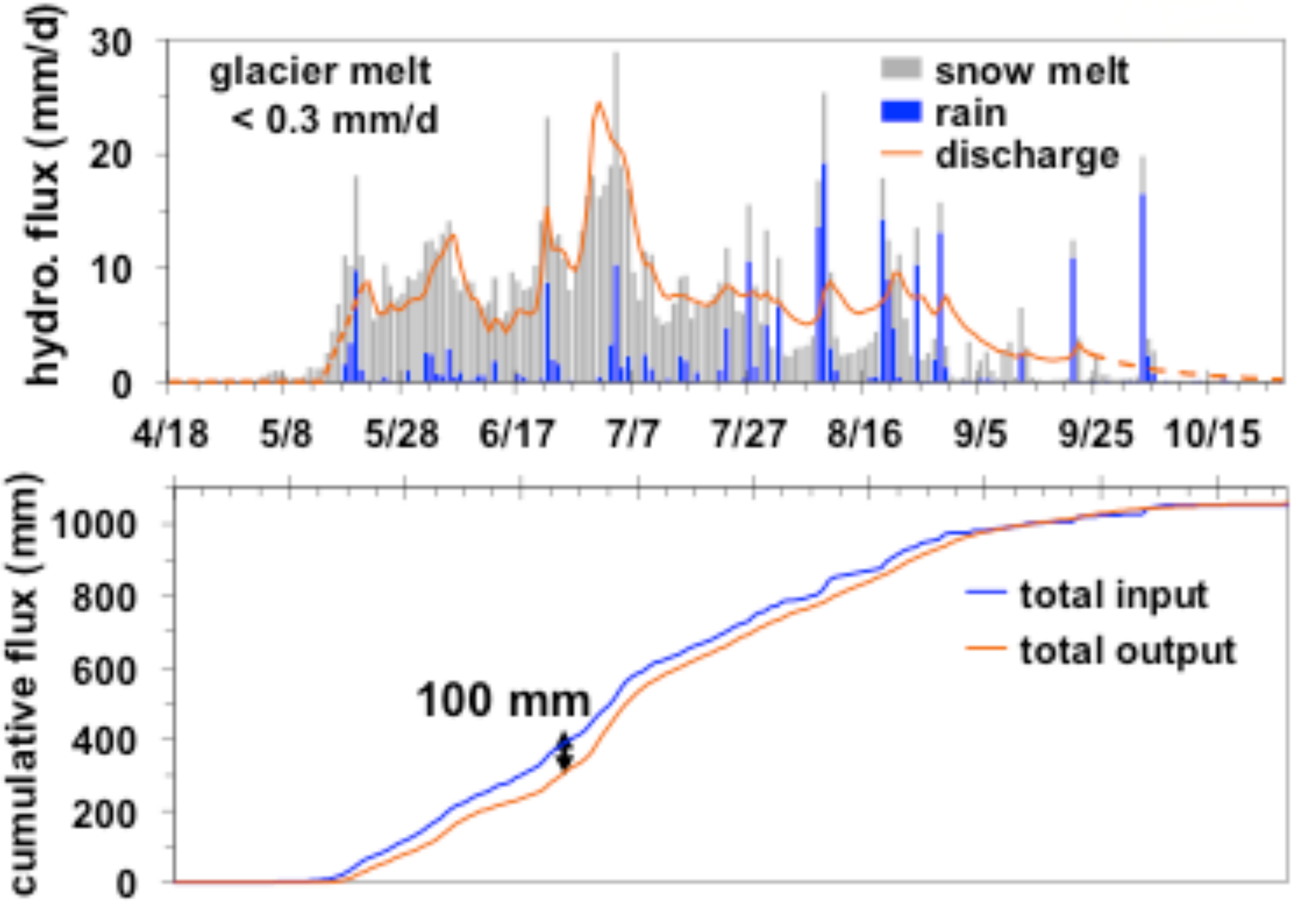
1966: 14.4 km^2
2016: 9.9 km^2





Material from M. Hayashi

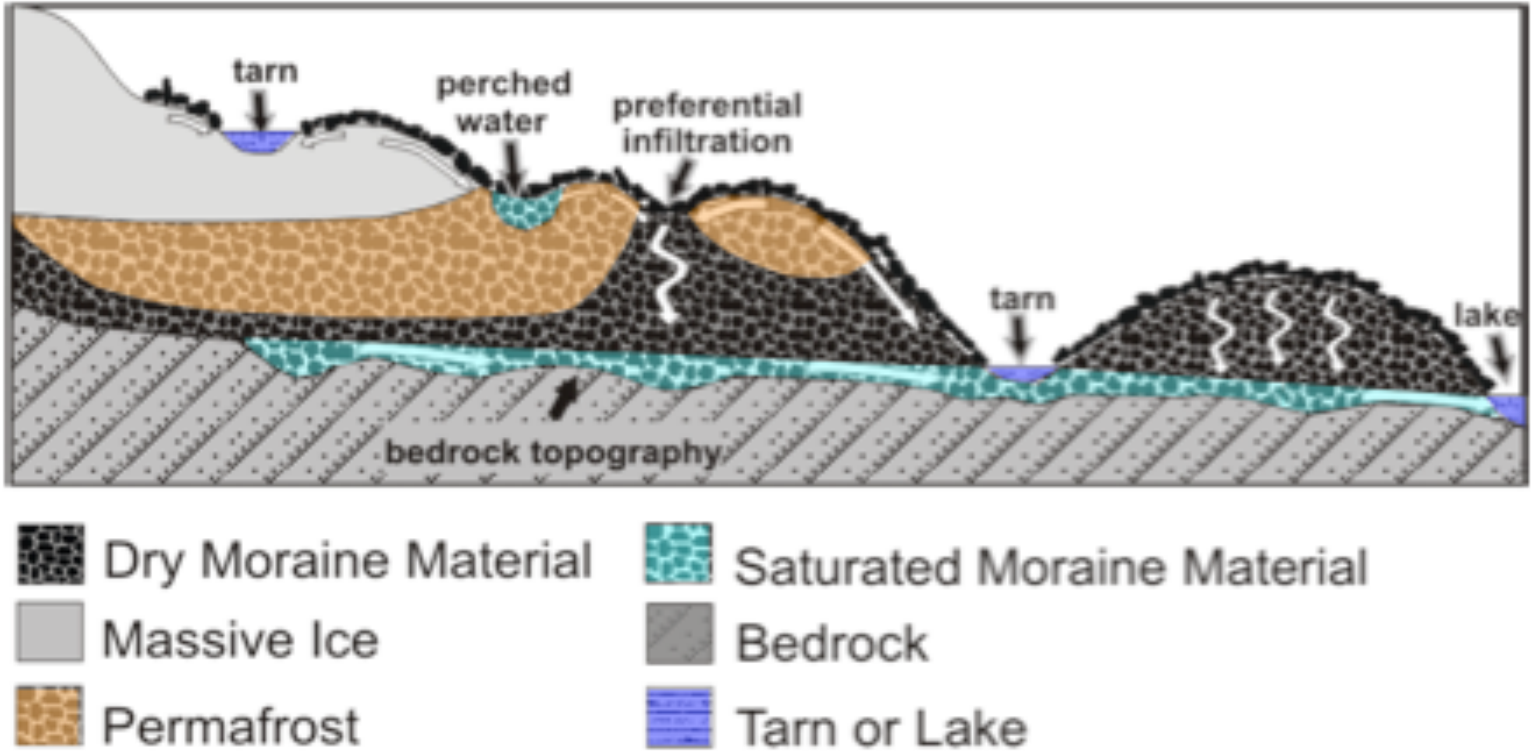
Conceptual model of groundwater processes



Hood & Hayashi (2015, *J. Hydrol.* 521:482-497)

Material from M. Hayashi

Conceptual model of groundwater processes



Langston et al. (2011, *Hydrol. Process*. 25: 2967)

Conceptual model of groundwater processes

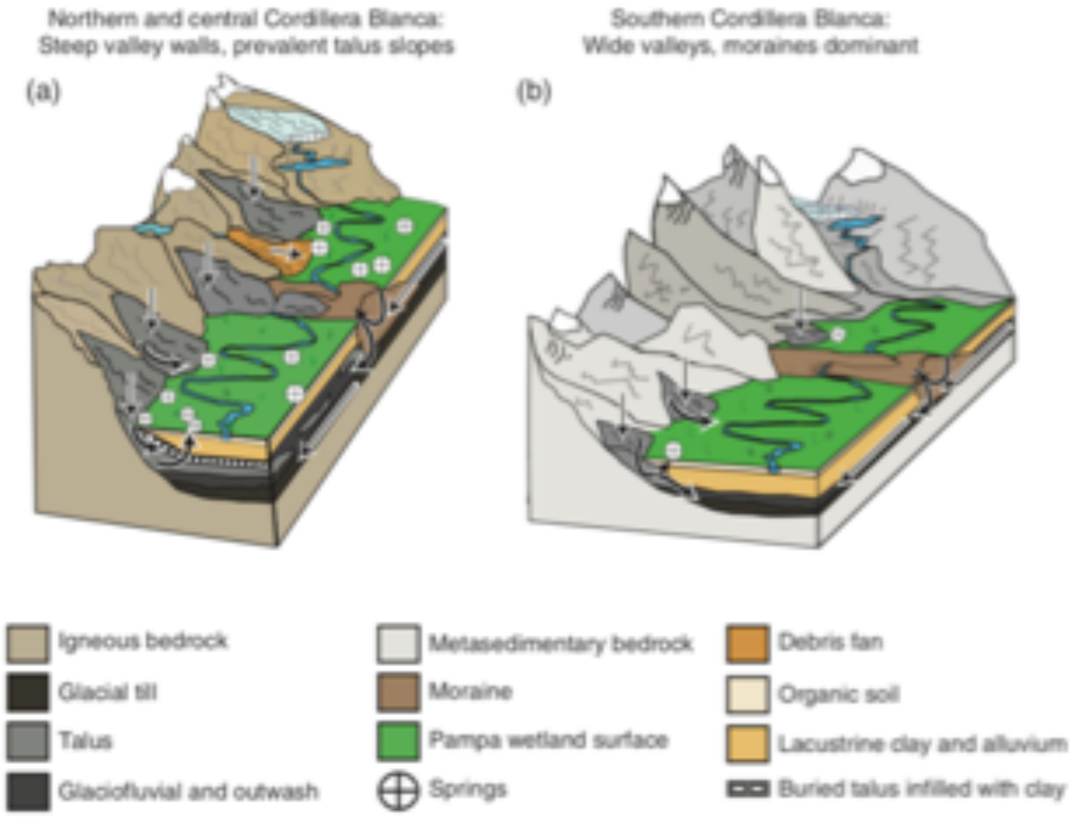


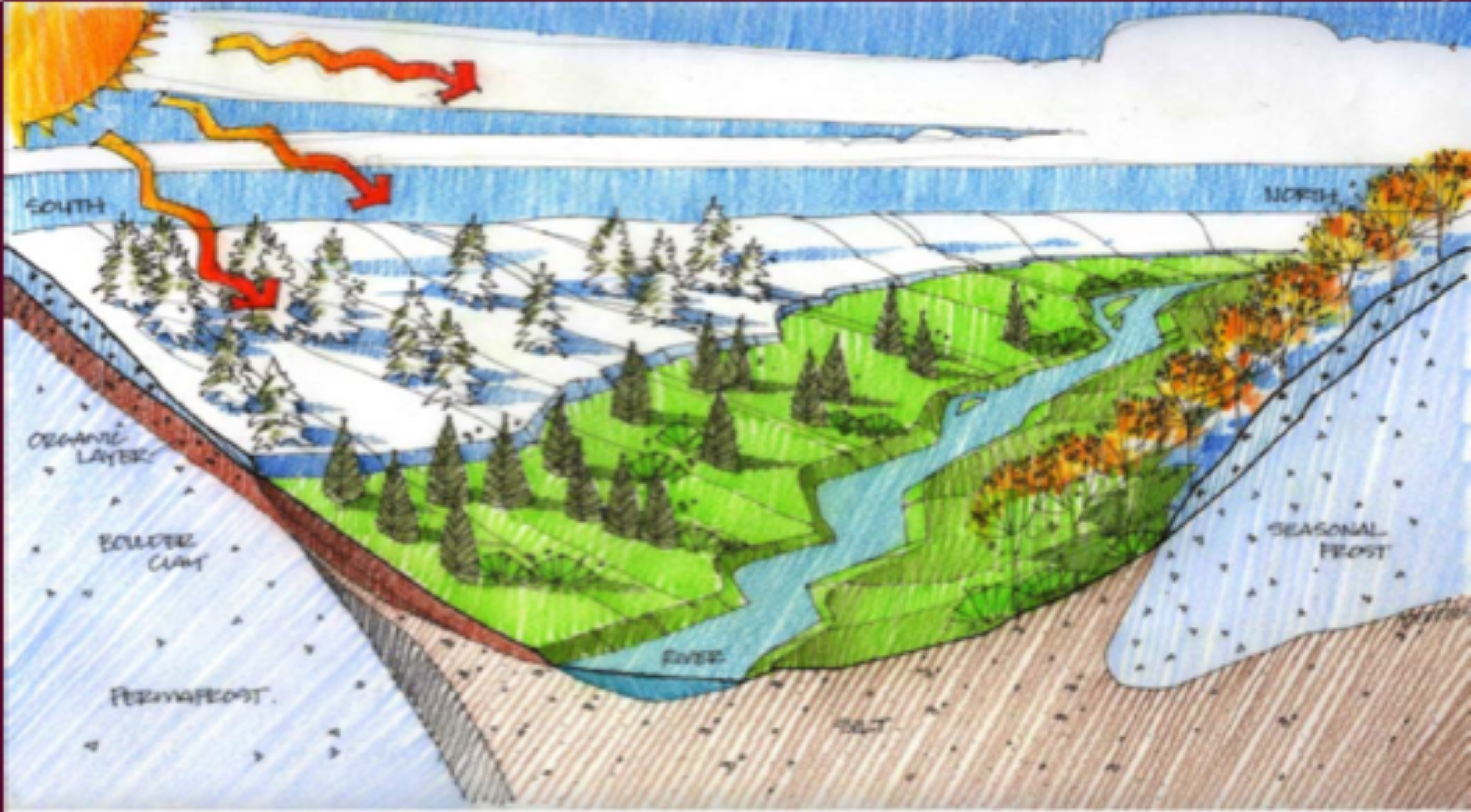
FIGURE 4 (a) Conceptual diagrams of groundwater flow for northern and central valleys (north of Huaraz) and (b) southern valleys (south of Huaraz) of the Cordillera Blanca. White arrows indicate direction of groundwater recharge, flow, and exchange

From Glas et al., 2018, Water Wires

Colder alpine systems

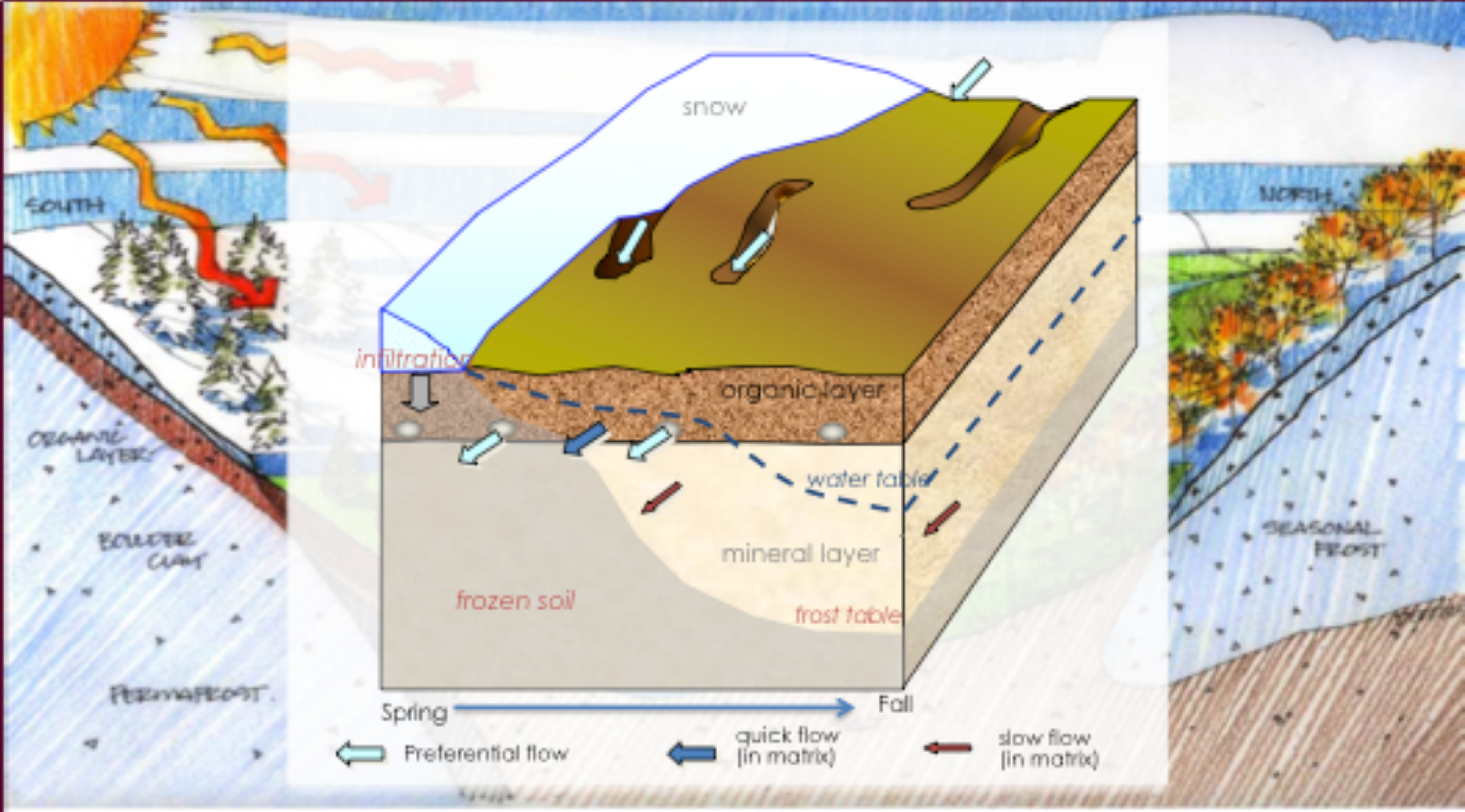
Runoff Processes in Alpine Catchments: Challenges and Opportunities

Colder alpine systems

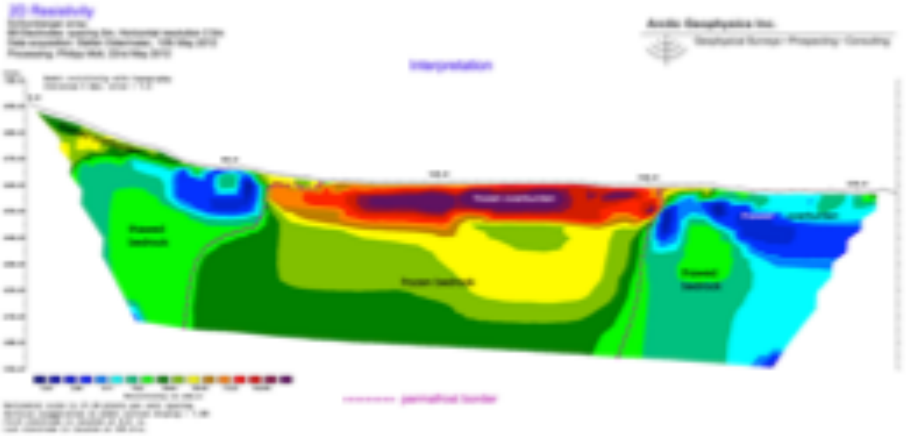


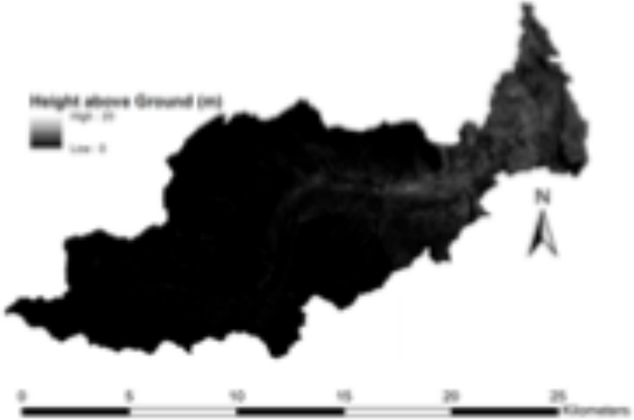
Runoff Processes in Alpine Catchments: Challenges and Opportunities

The importance of permafrost



Largely an issue of characterization and representation



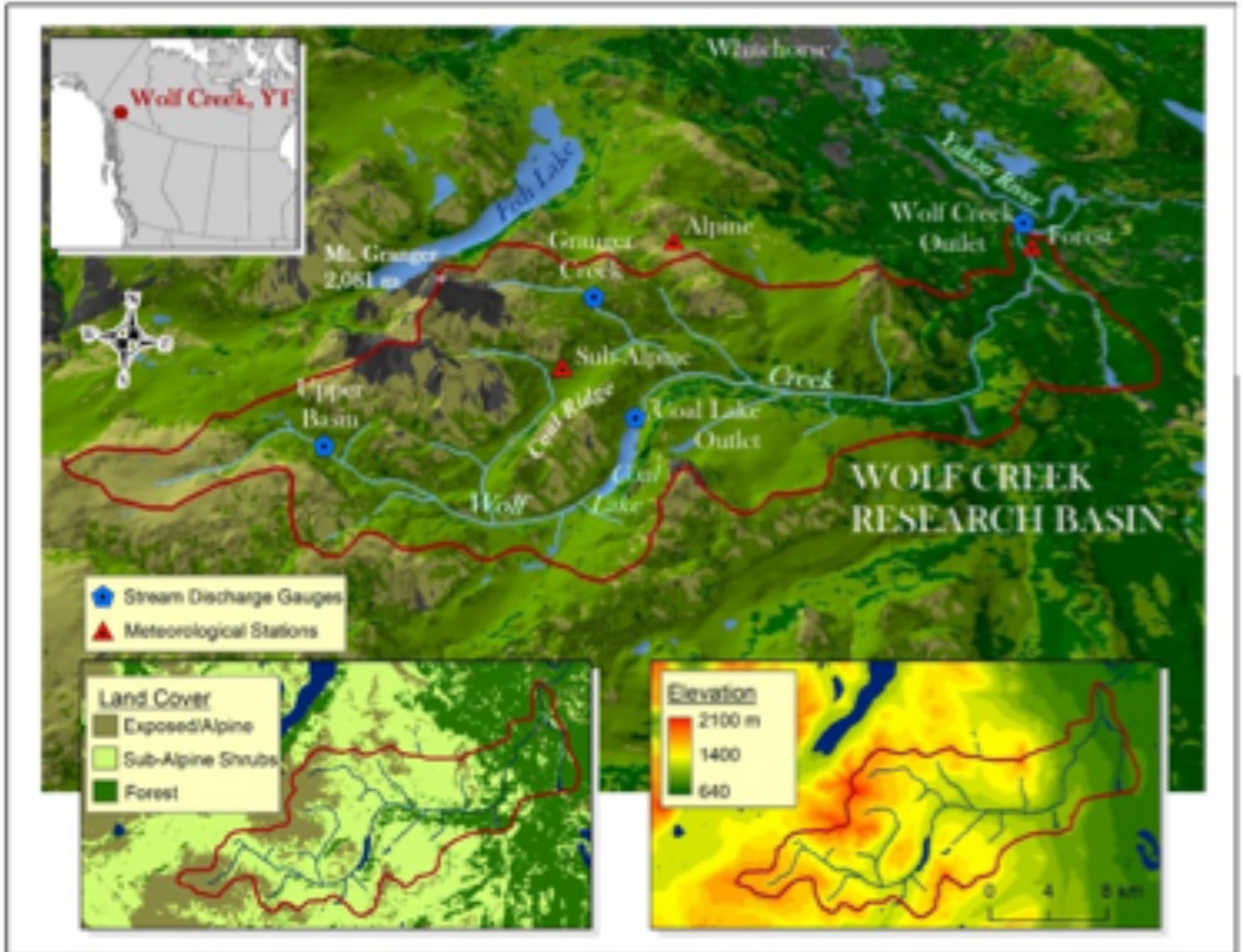


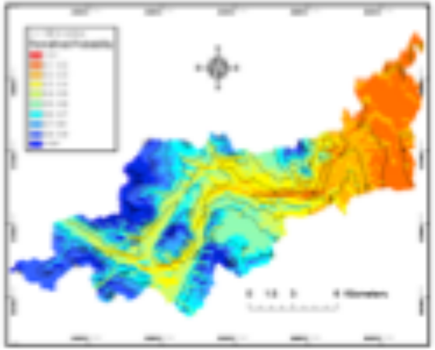
New Data Streams






Wolf Creek Research Basin



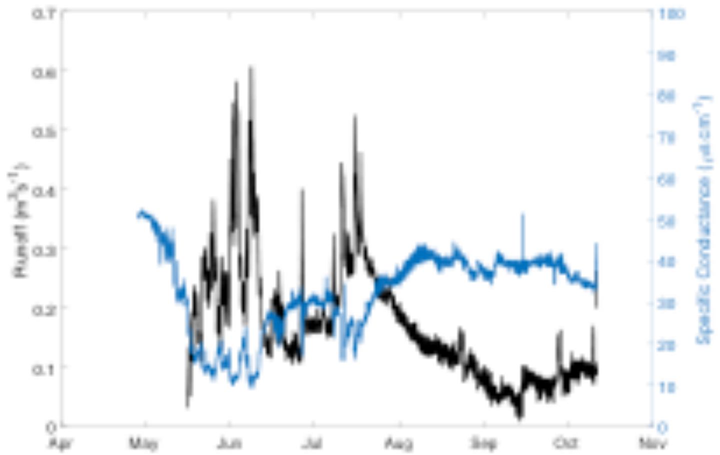


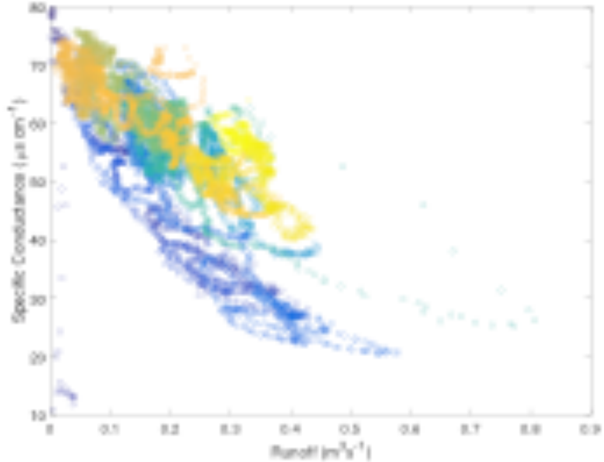
Permafrost probability map
Lewkowicz & Ednie 2004, PPP

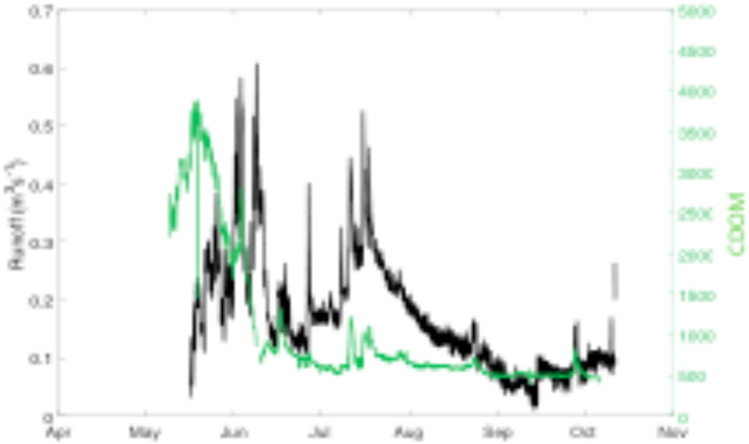
Wolf Creek Research Basin

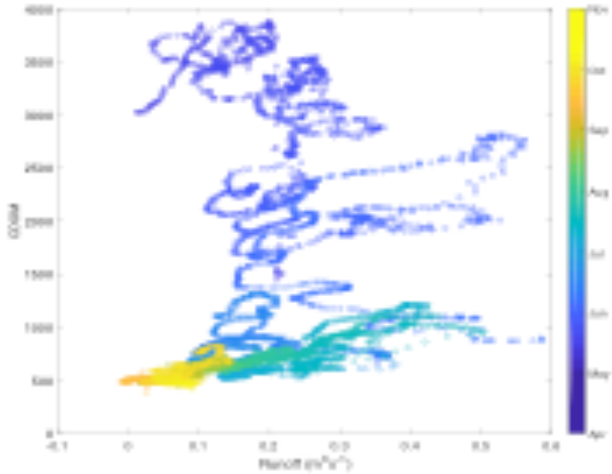
Runoff Processes in Alpine Catchments: Challenges and Opportunities

High frequency measurements

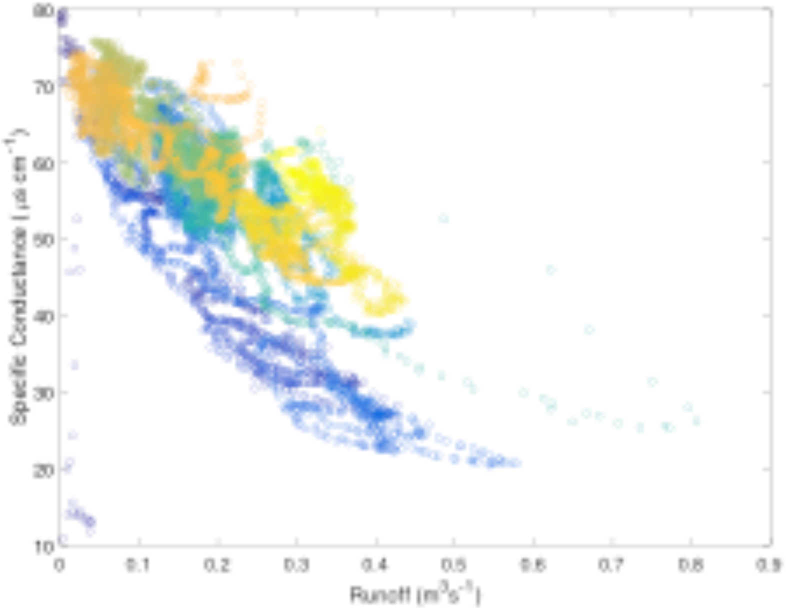


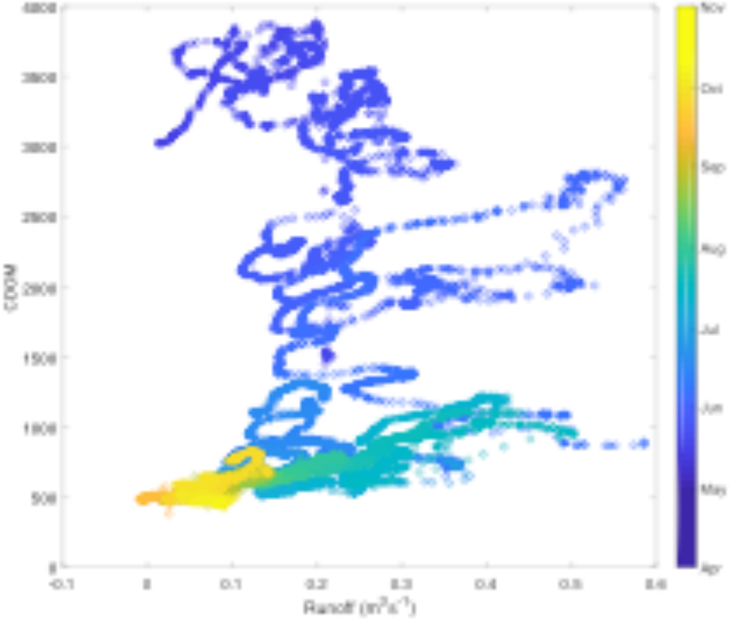






General High Frequency Confusion

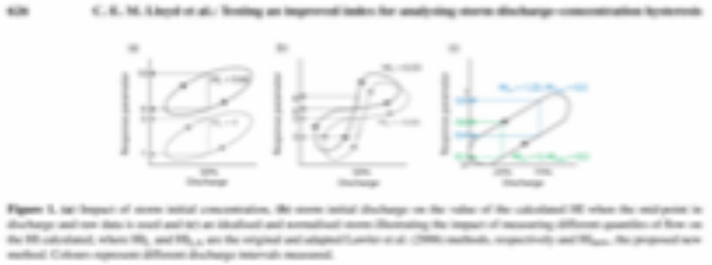




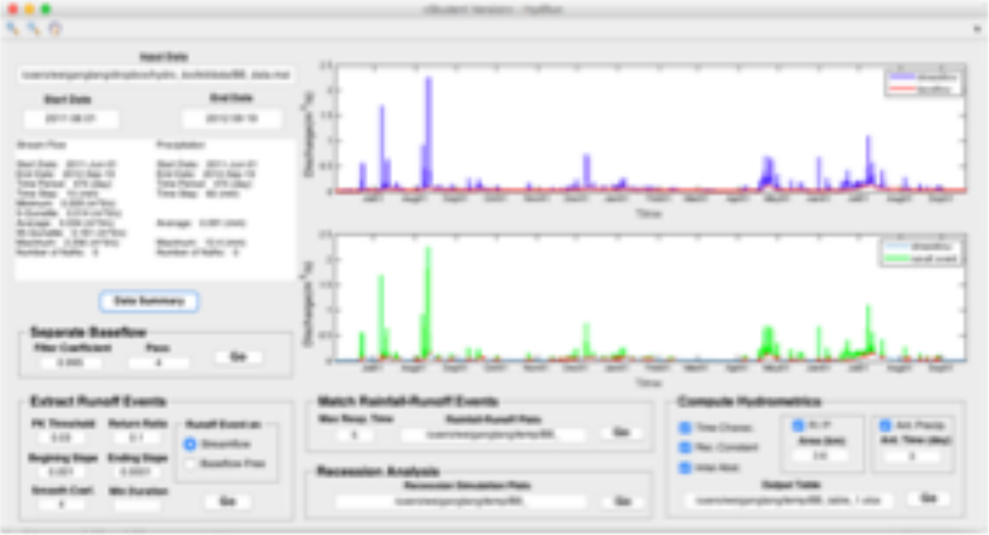
- Seasonal trend show gradual shifts in Q-SpC as flow paths decline atop frozen ground and as catchment dries
- General clockwise ‘flush’

High frequency data streams

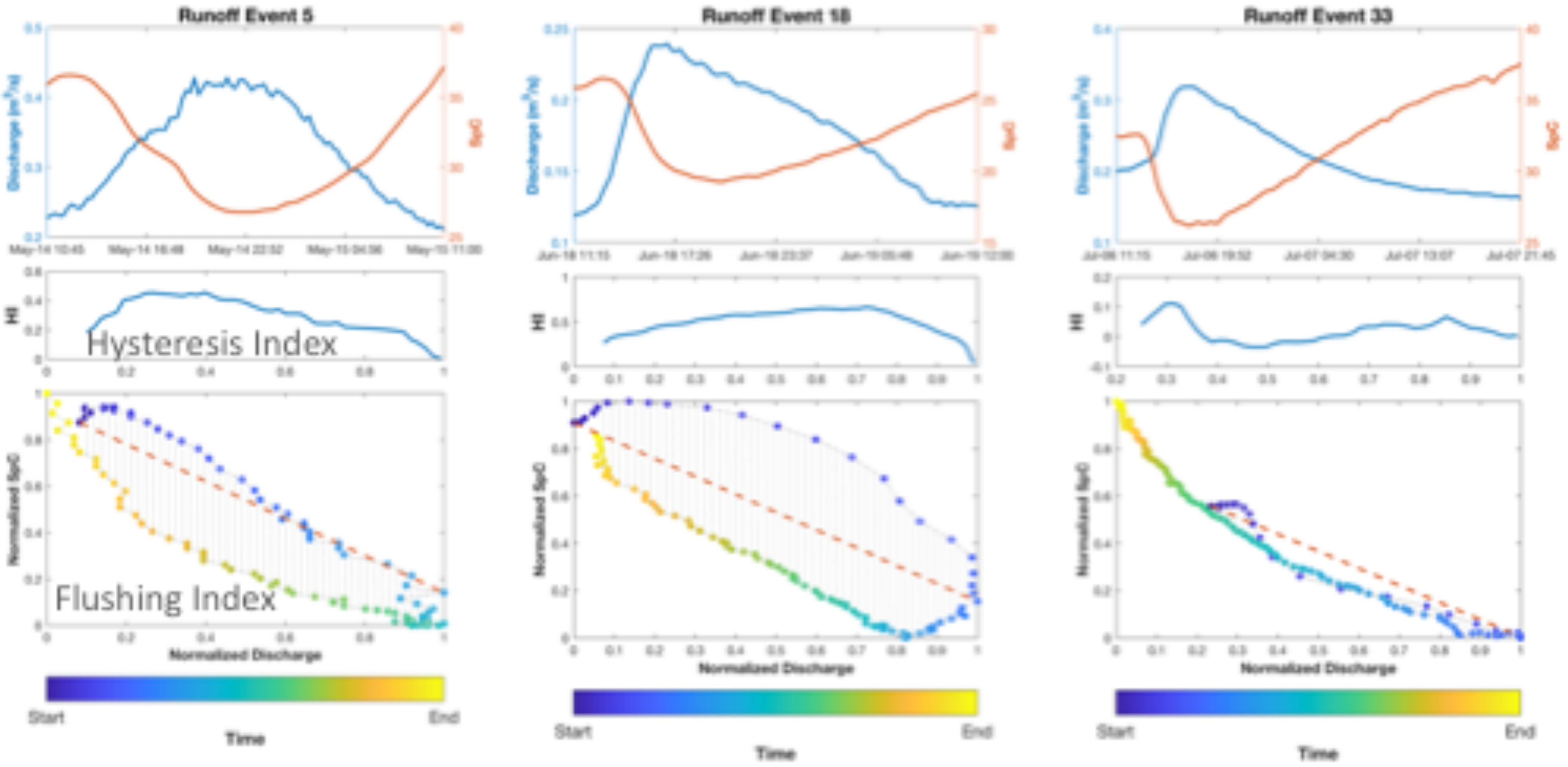
- Analyze in event responses for Q, SpC and DOC
- How do patterns change, what does hysteresis tell us about runoff processes and overall watershed connections



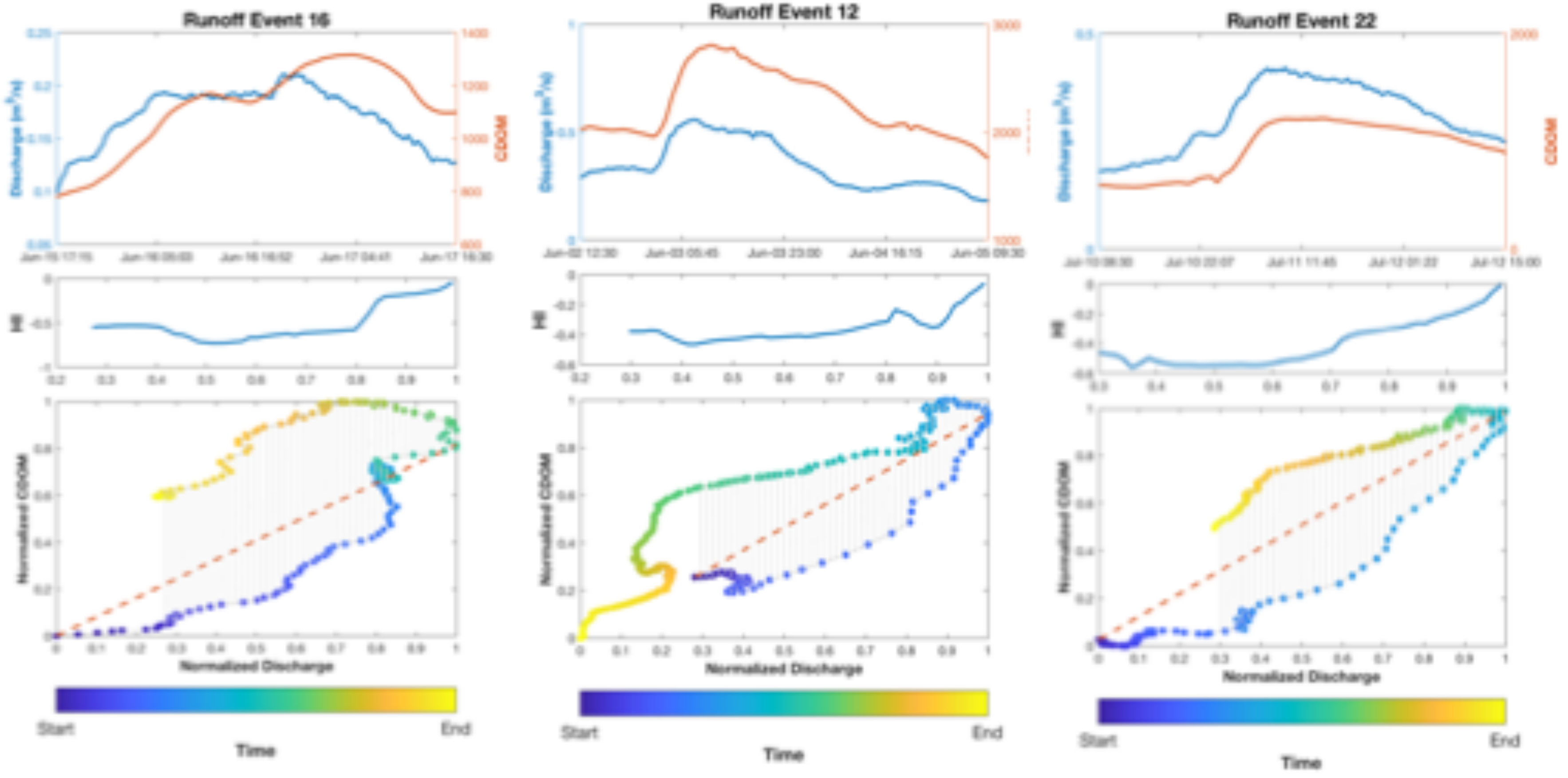
Lloyd, C et al. 2016. .Hydrology and Earth System Sciences, 20, 625–632.



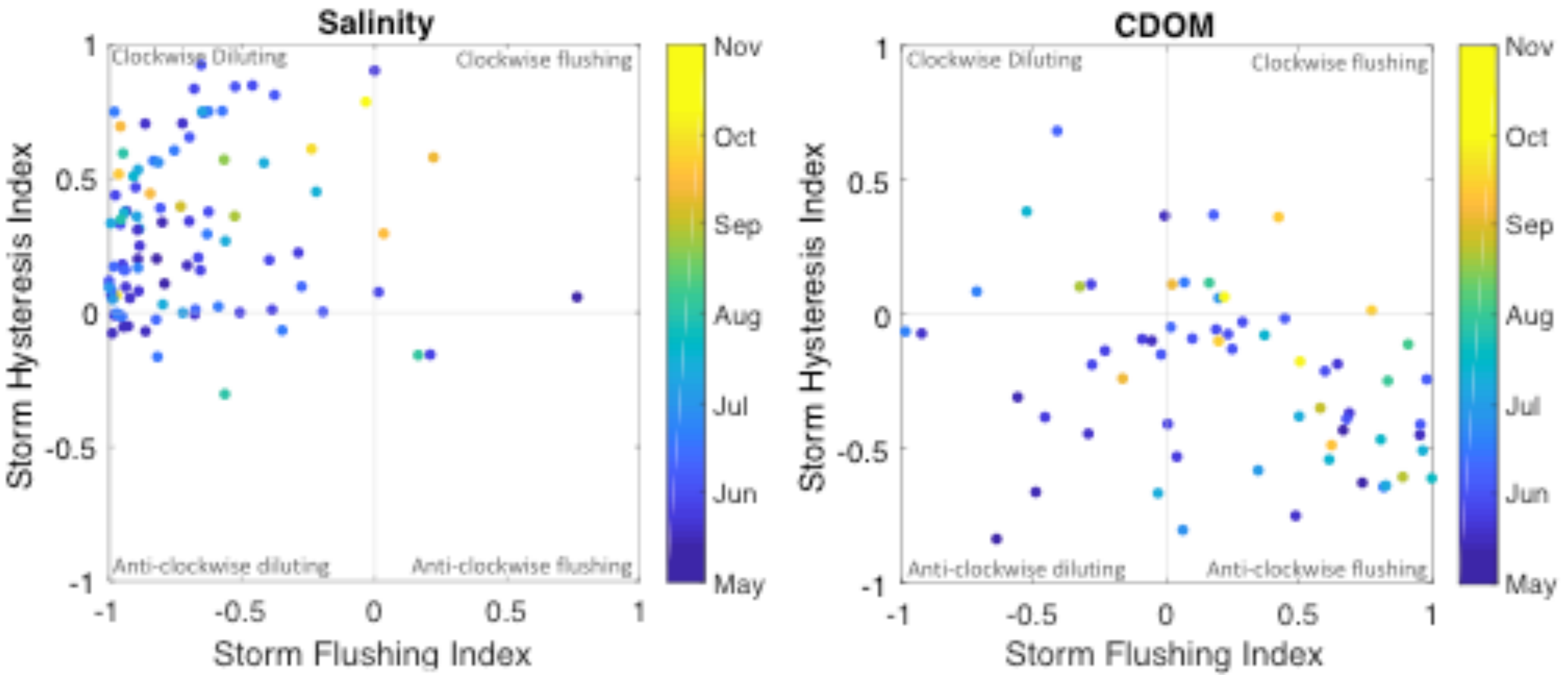
Event analysis - SpC



Event analysis - CDOM

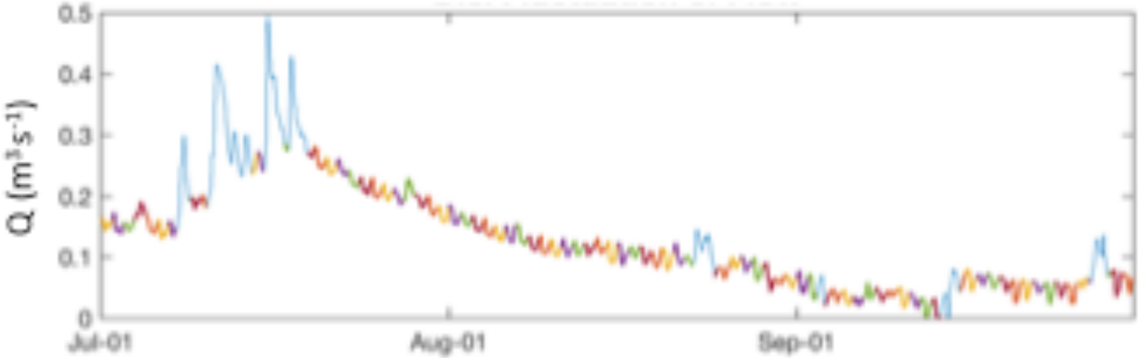


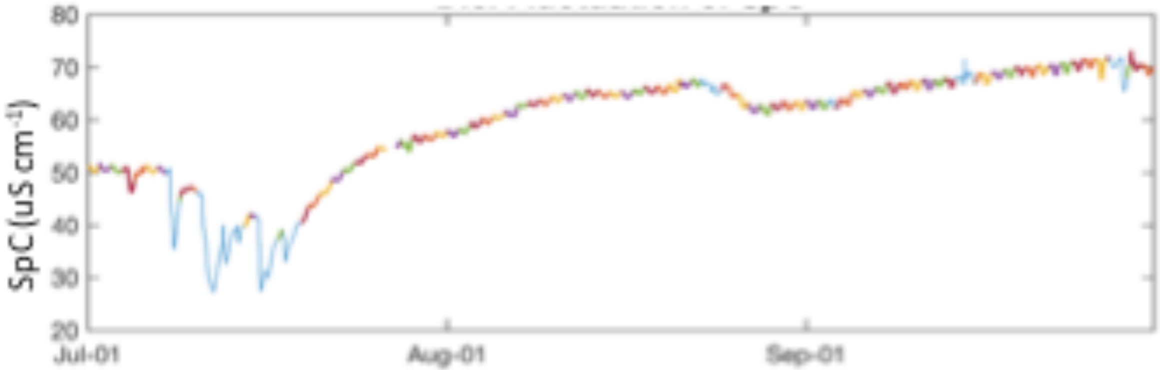
Summary Indices



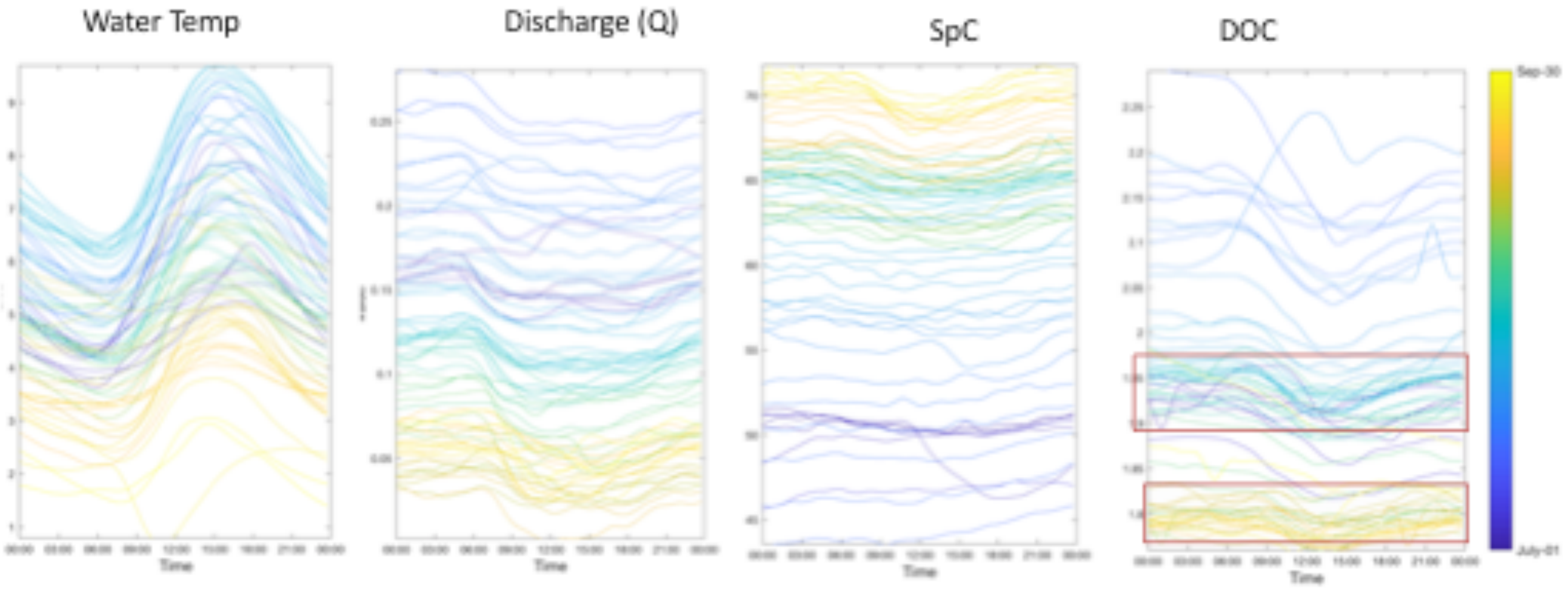
Diel signatures

- Q and SpC from July 1 to Sept 30

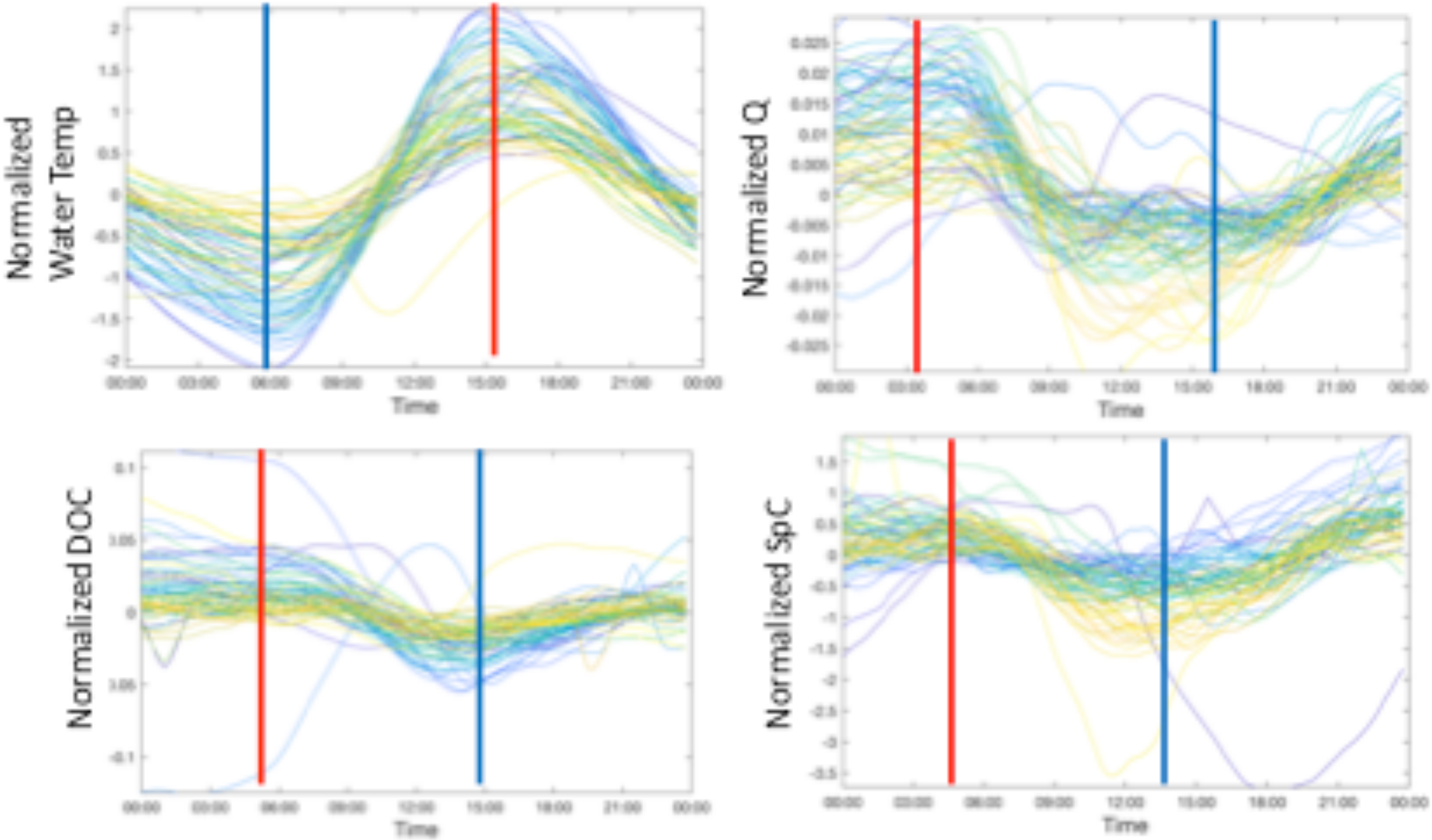




Diel signatures

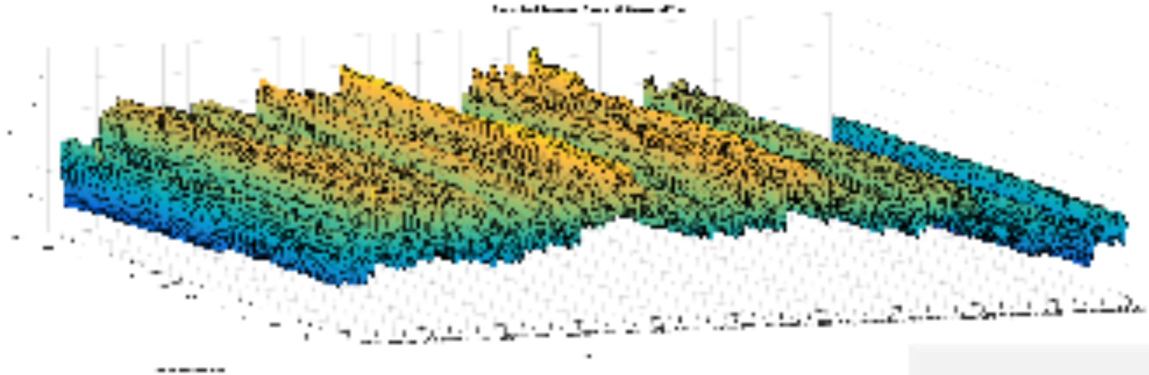


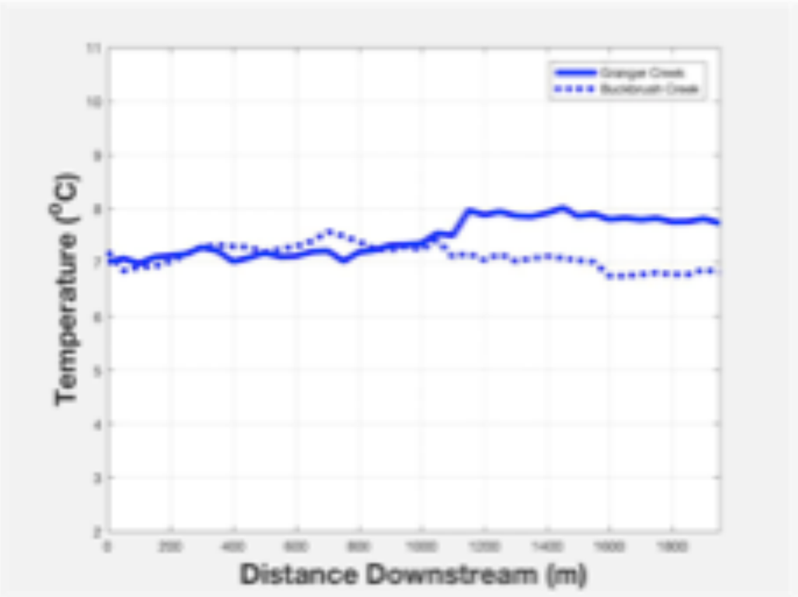
Diel signatures



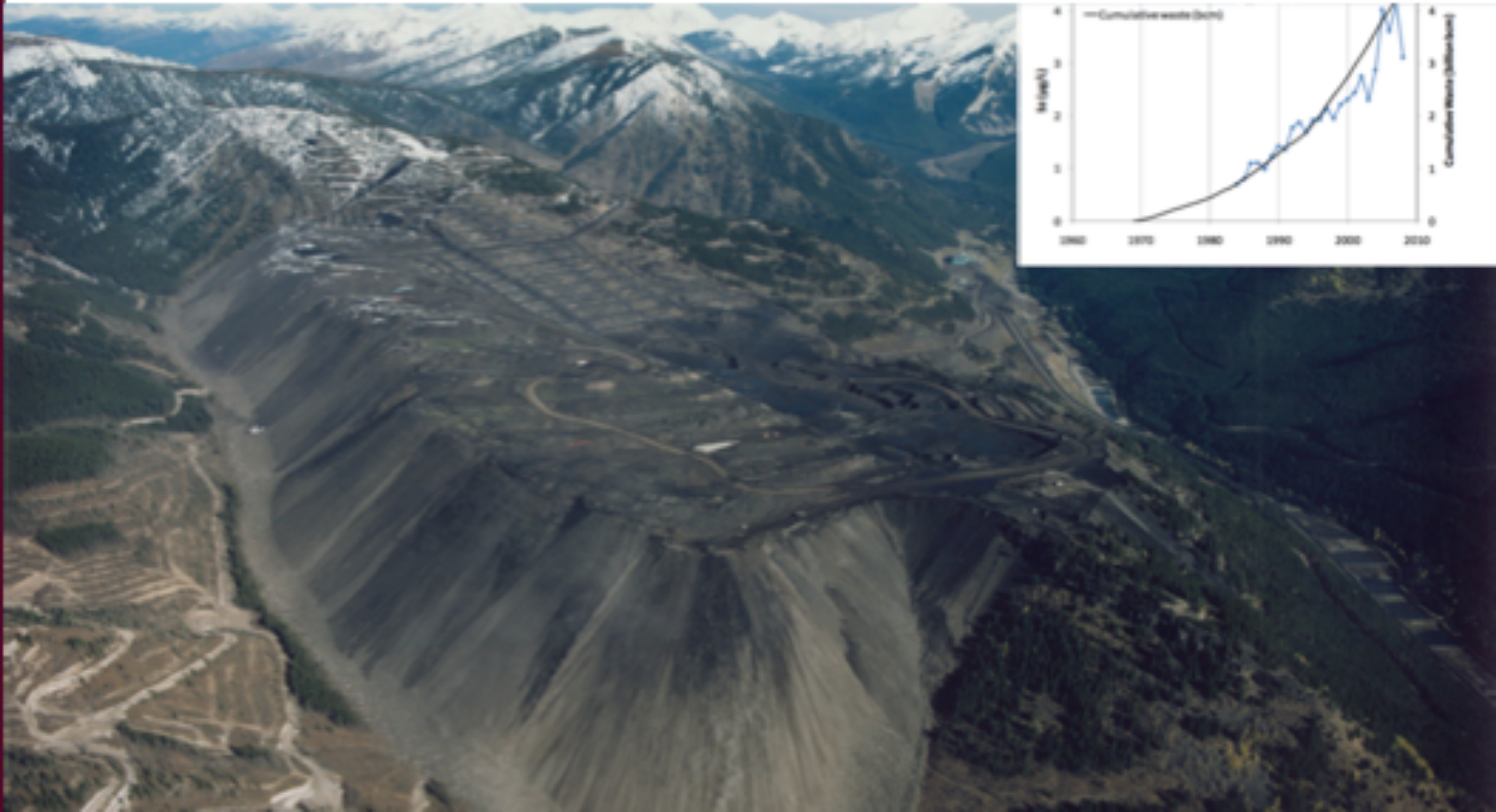
- Water temp out of phase means viscosity is not a driver

Stream temperature to understand groundwater

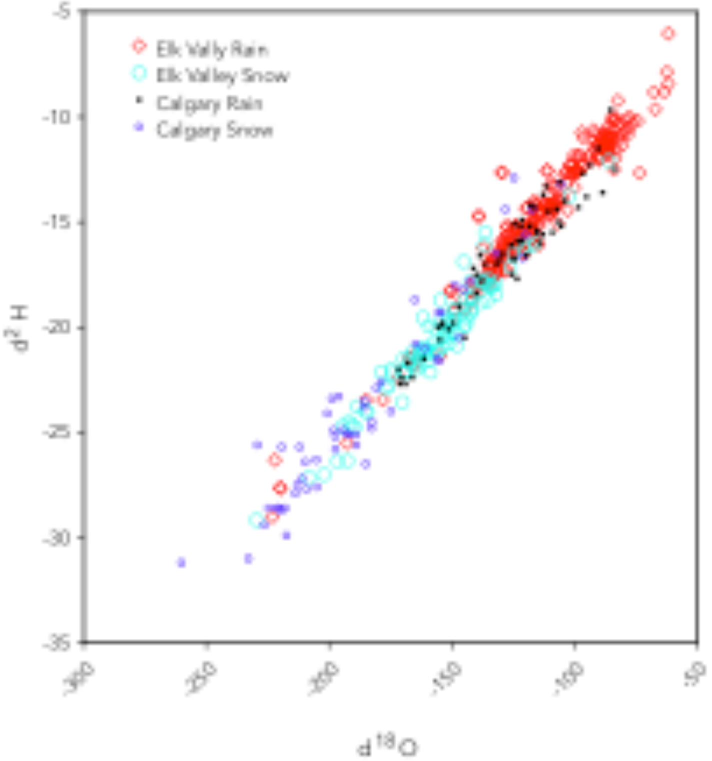


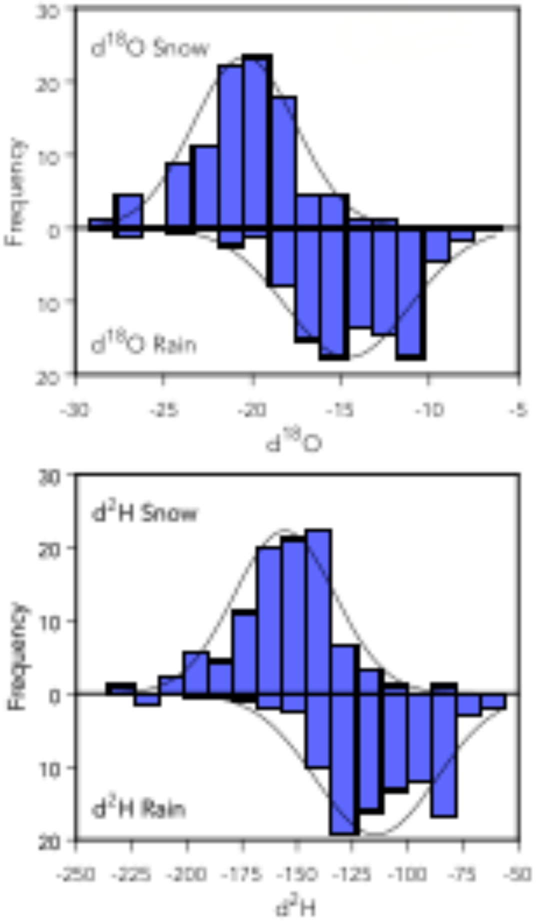


Isotopes and the dark arts



Stable Isotopes

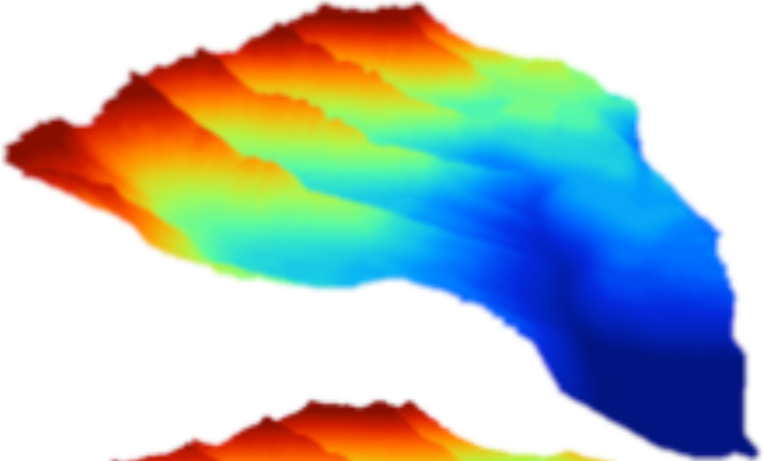


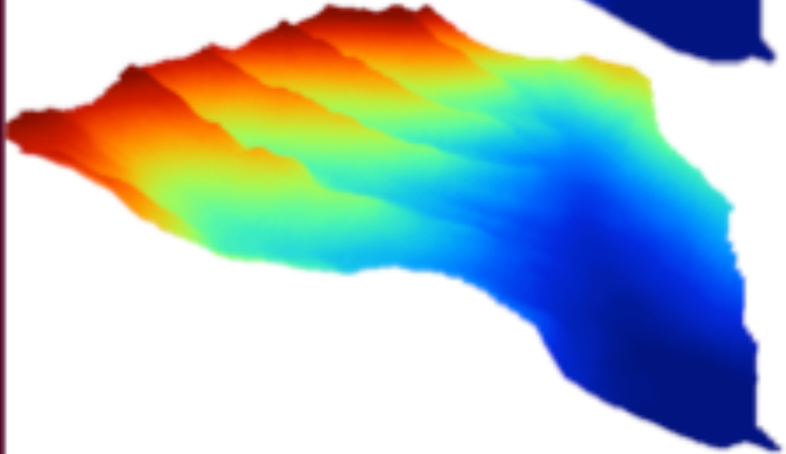


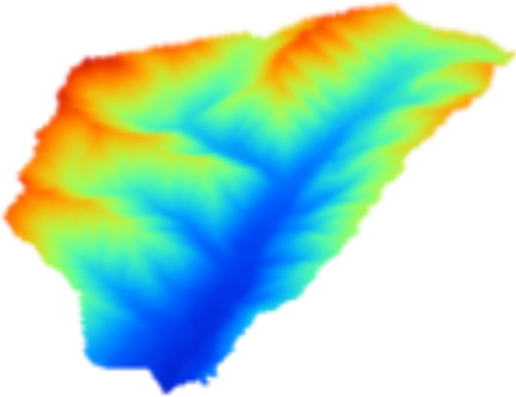
⇉ LMWL similar to Calgary

⇉ Distribution of snow and rain

West Line and Dry Creek

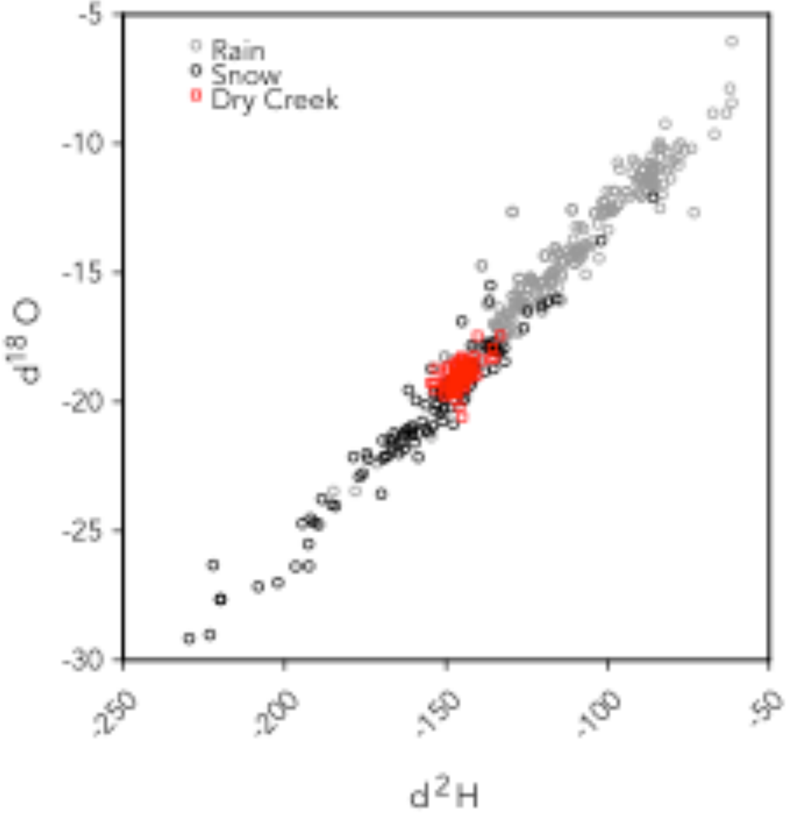






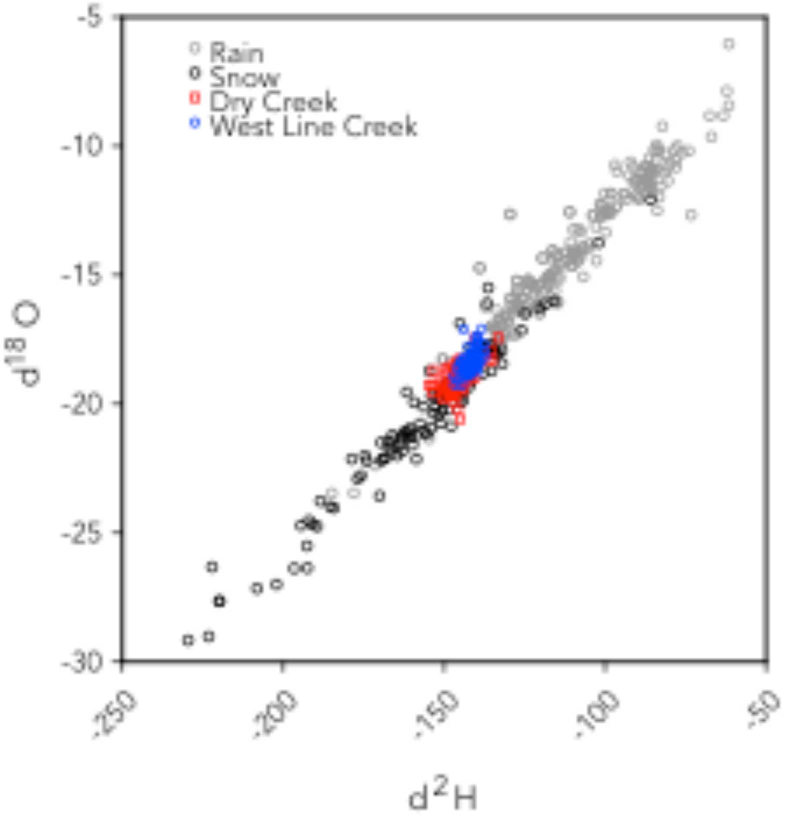
N50°02.016' W114°48.867'

Stable Isotopes



⇒ Dry Creek (reference) – little variation seasonally in streamflow signal

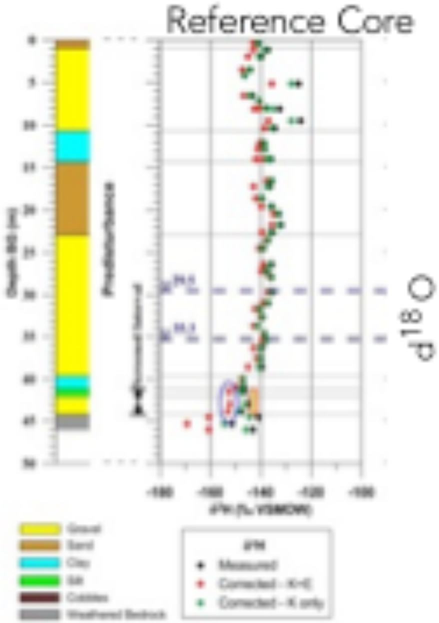
Stable Isotopes

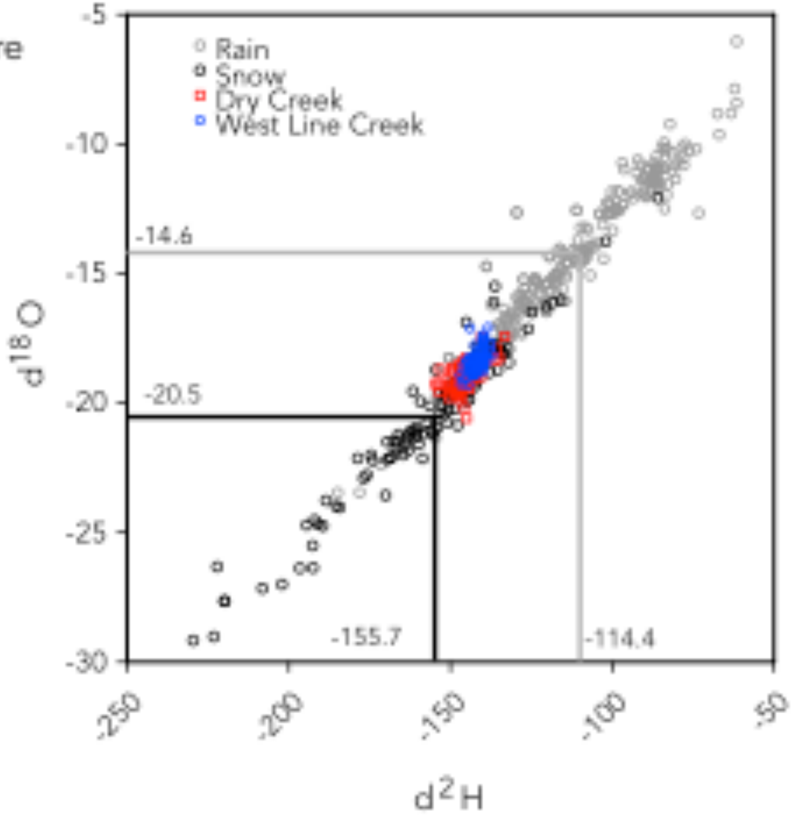


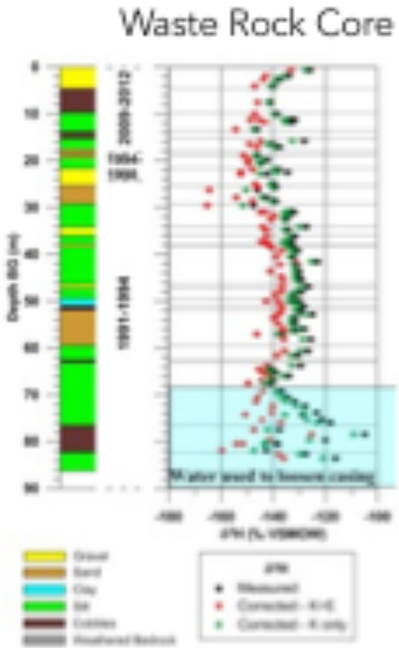
⇒ Dry Creek (reference) – little variation seasonally in streamflow signal
⇒ West Line Creek (mine) – signal even more dampened, heavier

Runoff Processes in Alpine Catchments: Challenges and Opportunities

Stable Isotopes



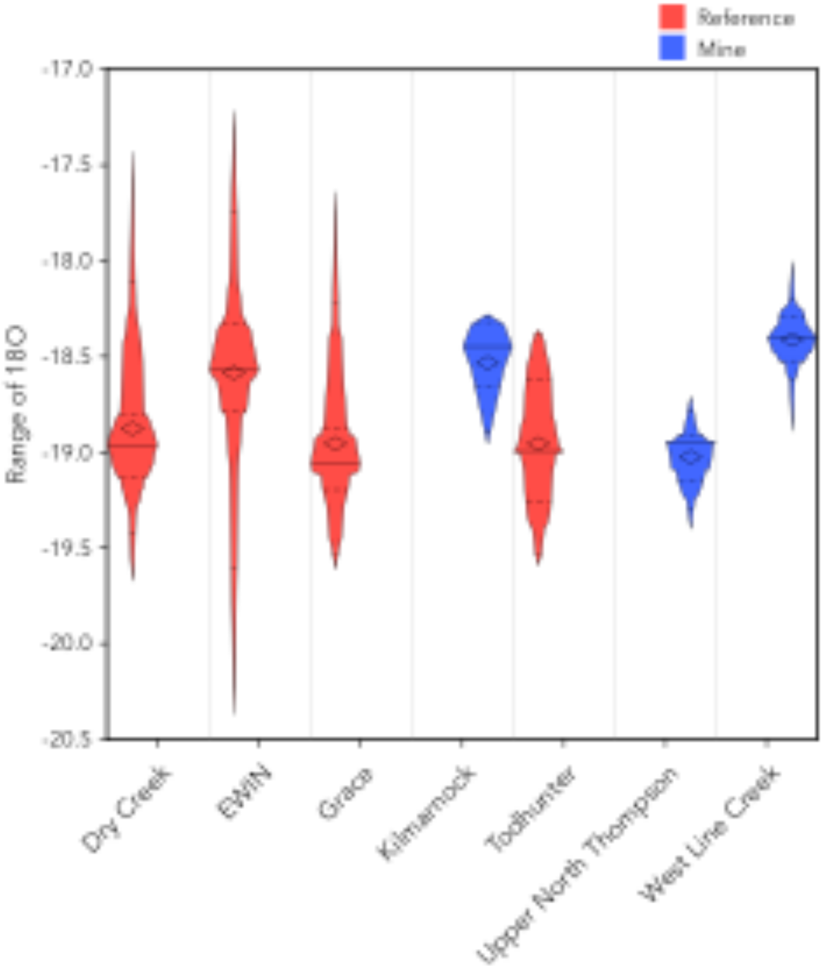




Core figures provided by Lee Barbour,
U of Saskatchewan

⇒ Dry Creek (reference) – little variation seasonally in streamflow signal
⇒ West Line Creek (mine) – signal even more dampened, heavier
⇒ Signal more representative of snow, particularly at Dry Creek

Stable Isotopes



⇒ Box percentiles of d[18]O from reference and mine-influenced watersheds

⇒ Greater distribution of isotopes commonly inferred as a proxy for decreased transit times and reduced storage

Results – Context with other watersheds

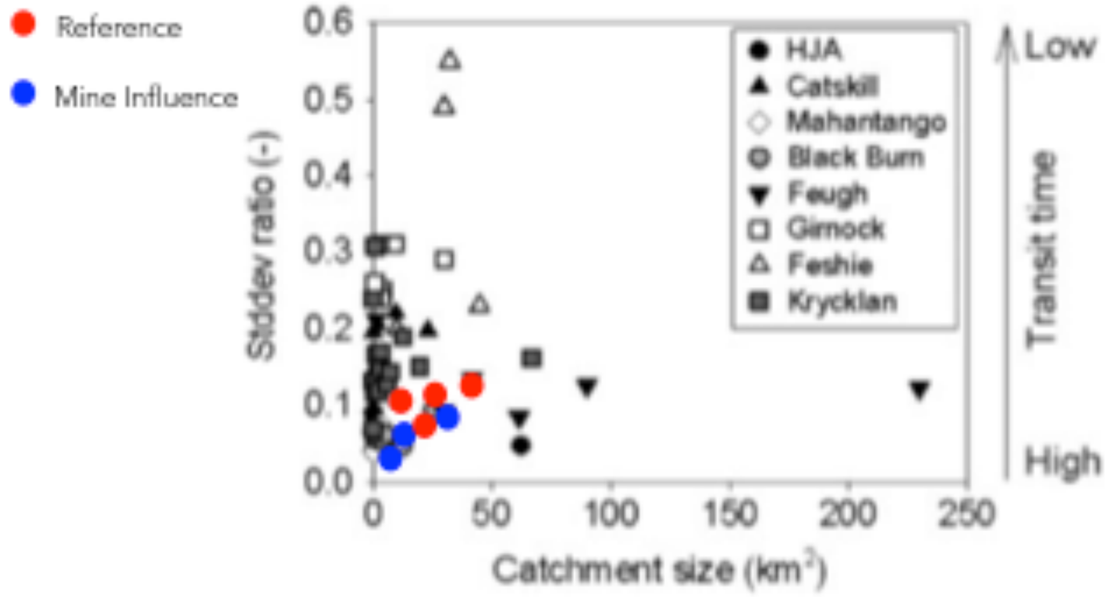


Figure 5. Relationship between catchment size and the inverse transit time proxy ITTP (ratio of standard deviations of $\delta^{18}O$ measurements of stream water to precipitation) for the eight catchments and their associated sub-catchments

Comparison of transit times with literature values from alpine watersheds
Tetzlaff et al., (2009). Hydrological Processes, 23, 945-953

Overview

Transit times—the link between hydrology and water quality at the catchment scale

Markus Hrachowitz,[1*] Paolo Benettin,[2] Boris M. van Breukelen,[1] Ophelie Fovet,[3] Nicholas J.K. Howden,[4] Laurent Ruiz,[3] Ype van der Velde[5] and Andrew J. Wade[6]

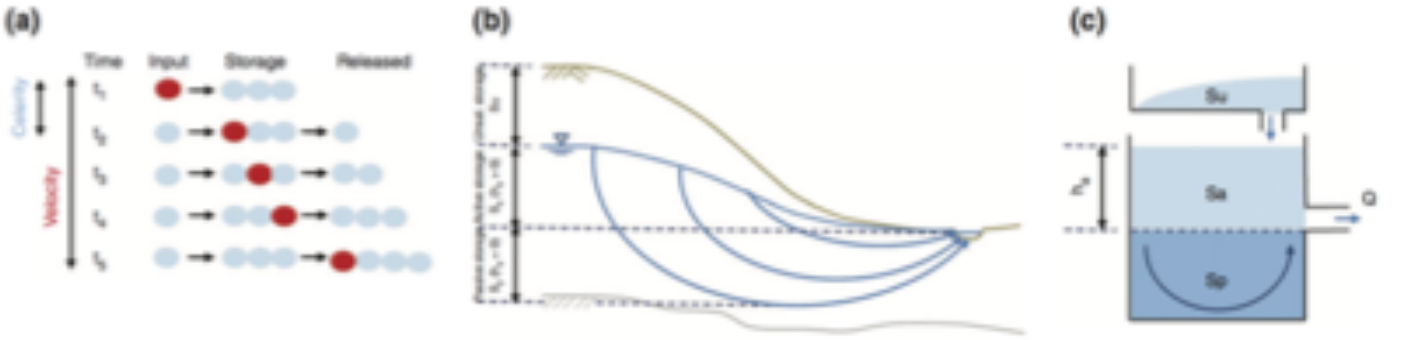
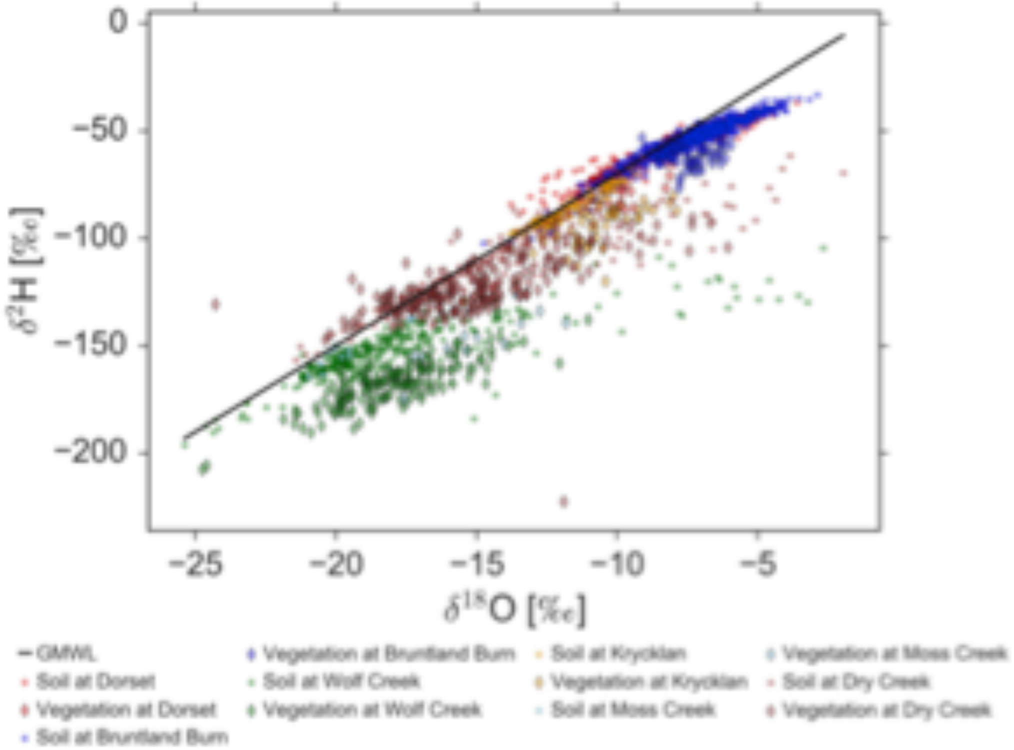
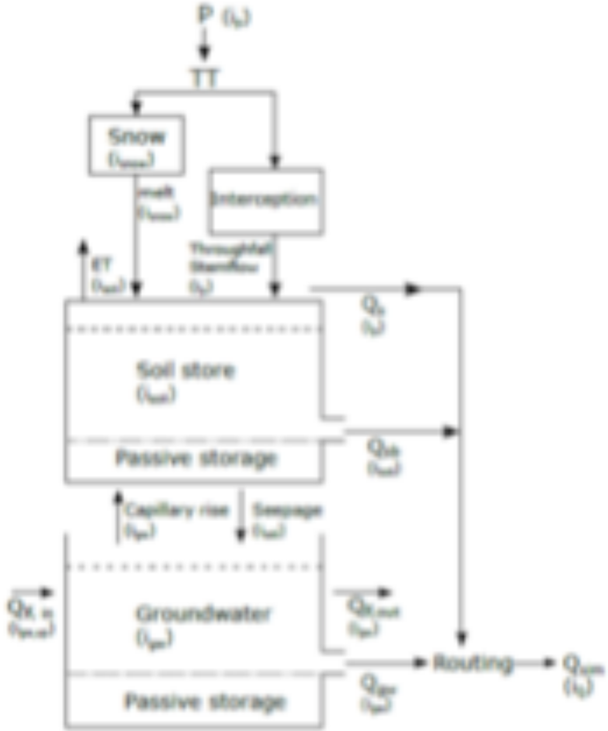


FIGURE 2 | (a) Conceptualization of the difference between celerity-driven hydrological response and velocity-driven transport processes using the analogy of a game of billiards. A new input at t_1 (red ball) causes a disturbance of the system that propagates with a celerity and that generates a response (blue ball) at t_2. The red ball itself, however, is released from the system only at t_5 as it travels at a velocity that is much smaller than the celerity. (b) For a groundwater-dominated system, the propagation of the pressure wave to the stream is controlled by the wave celerity and the active storage S_A (i.e., the pressure head h_A) while the movement of the actual particles is controlled by the flow velocity and the length of the flow trajectory through a hydrologically passive storage volume S_P (after Ref 47), which (c) can be conceptualized in a model with a mixing volume below a given storage threshold. S_U represents the unsaturated zone whose nonlinear behavior is indicated by the curved line.

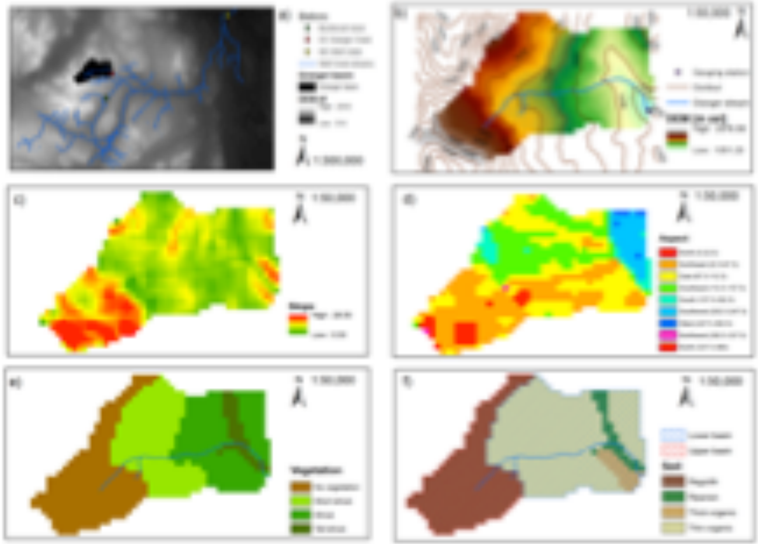
Stable isotopes of water

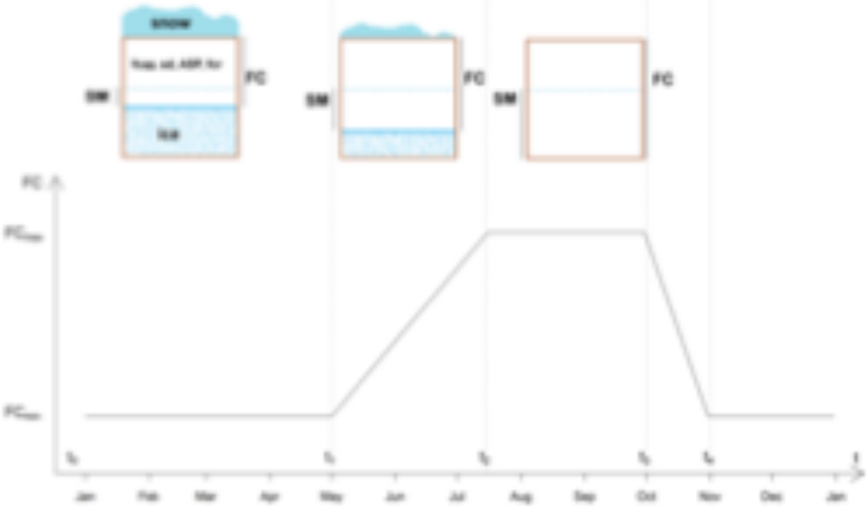




- ➢ VEWA – International inter-comparison project with common methodologies to trace water and isotopes through the soil-plant-stream continuum.

Isotope-aided models

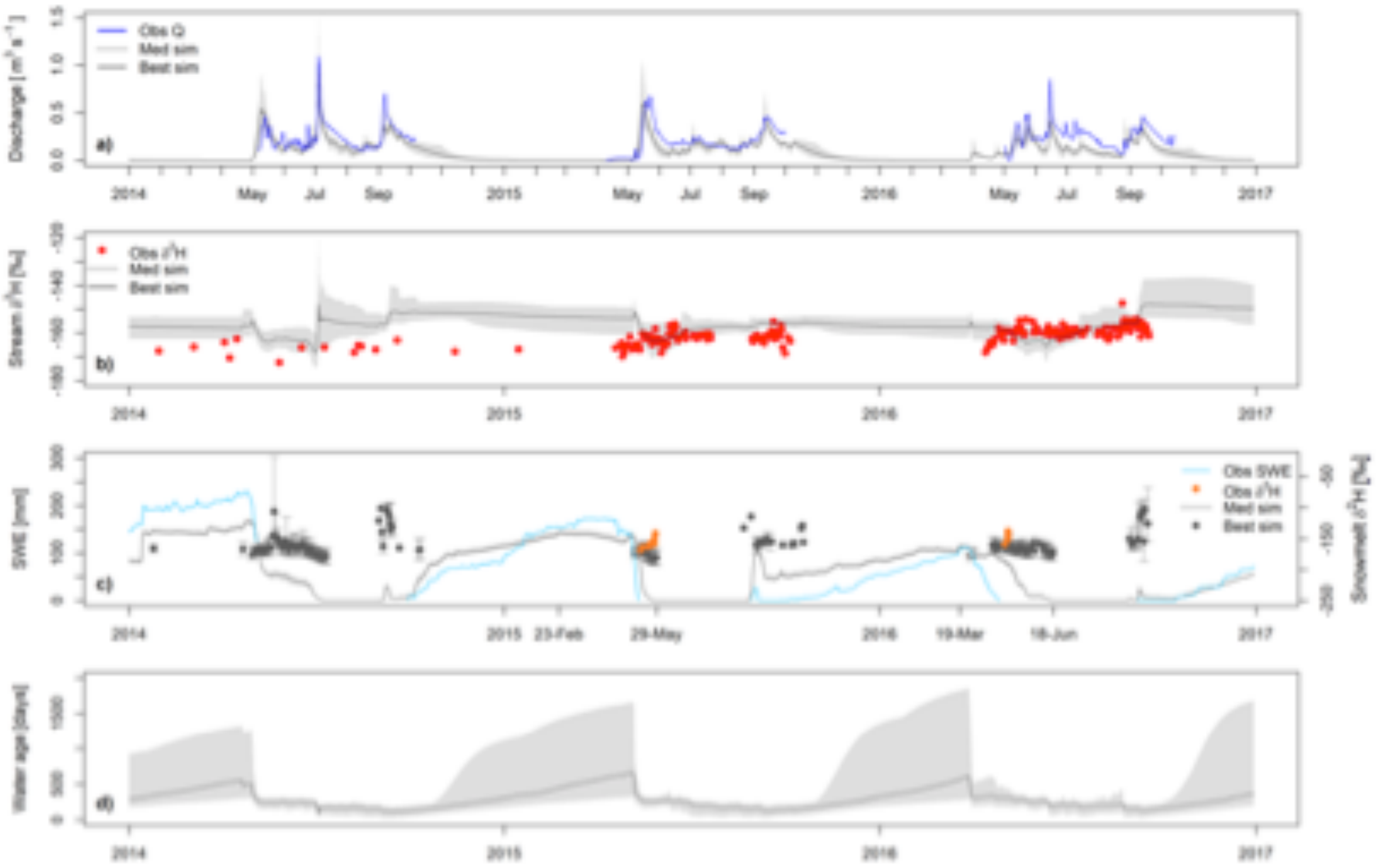




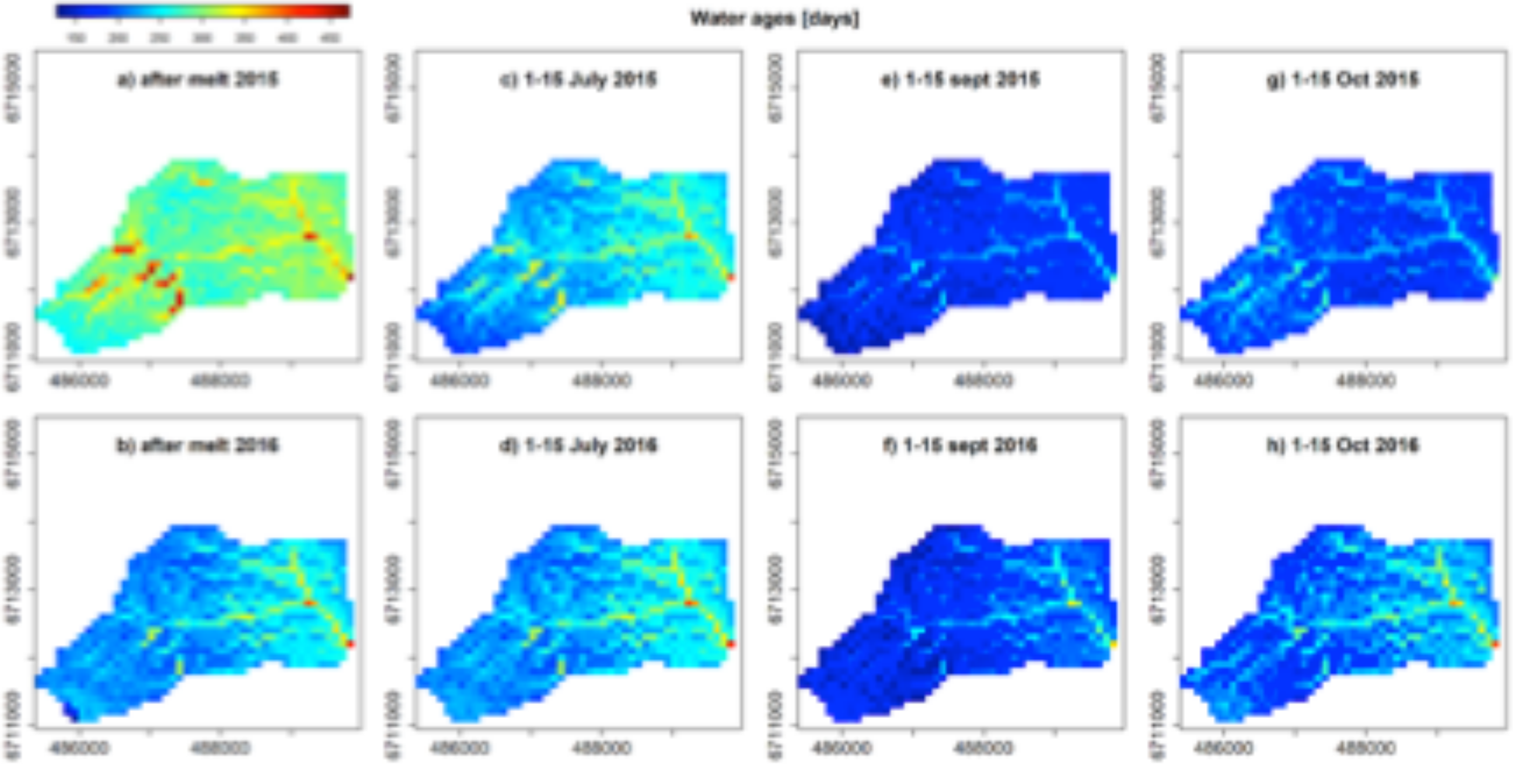
STARR - Ala-aho et a. (2017)

Runoff Processes in Alpine Catchments: Challenges and Opportunities

Isotope-aided models



Isotope-aided models



Thank you!