Runoff Processes in Alpine Catchments: Challenges and Opportunities

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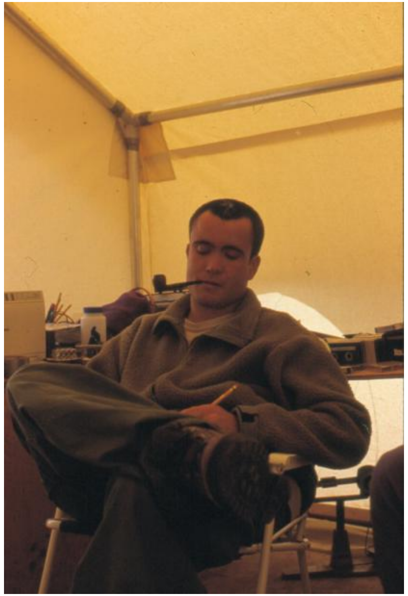
A bit about me

- 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.

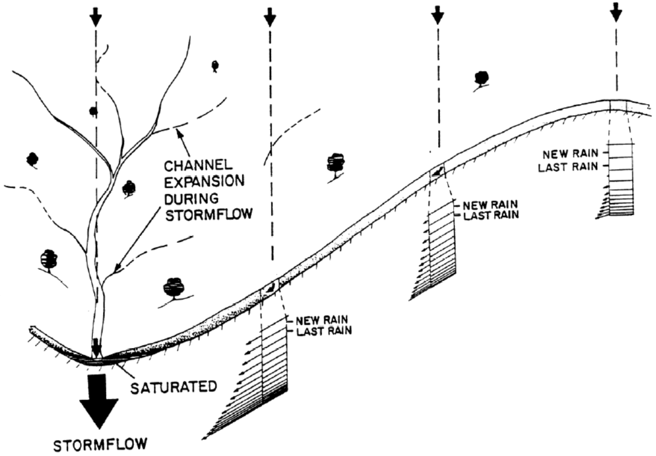


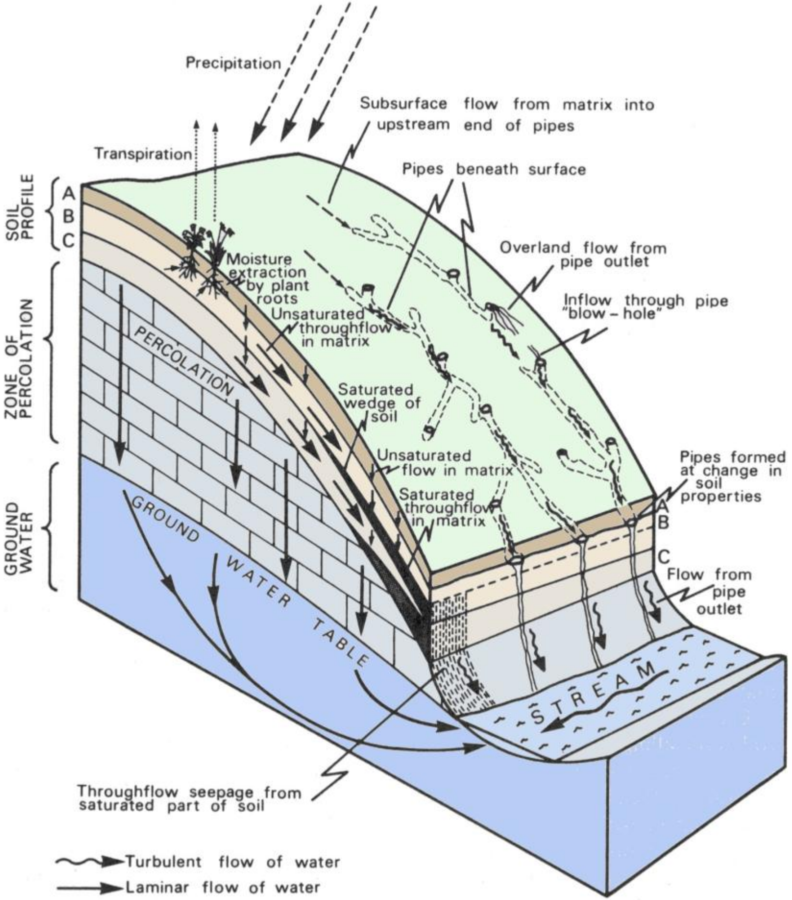
Alpine Catchments

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

Runoff (hillslope) processes

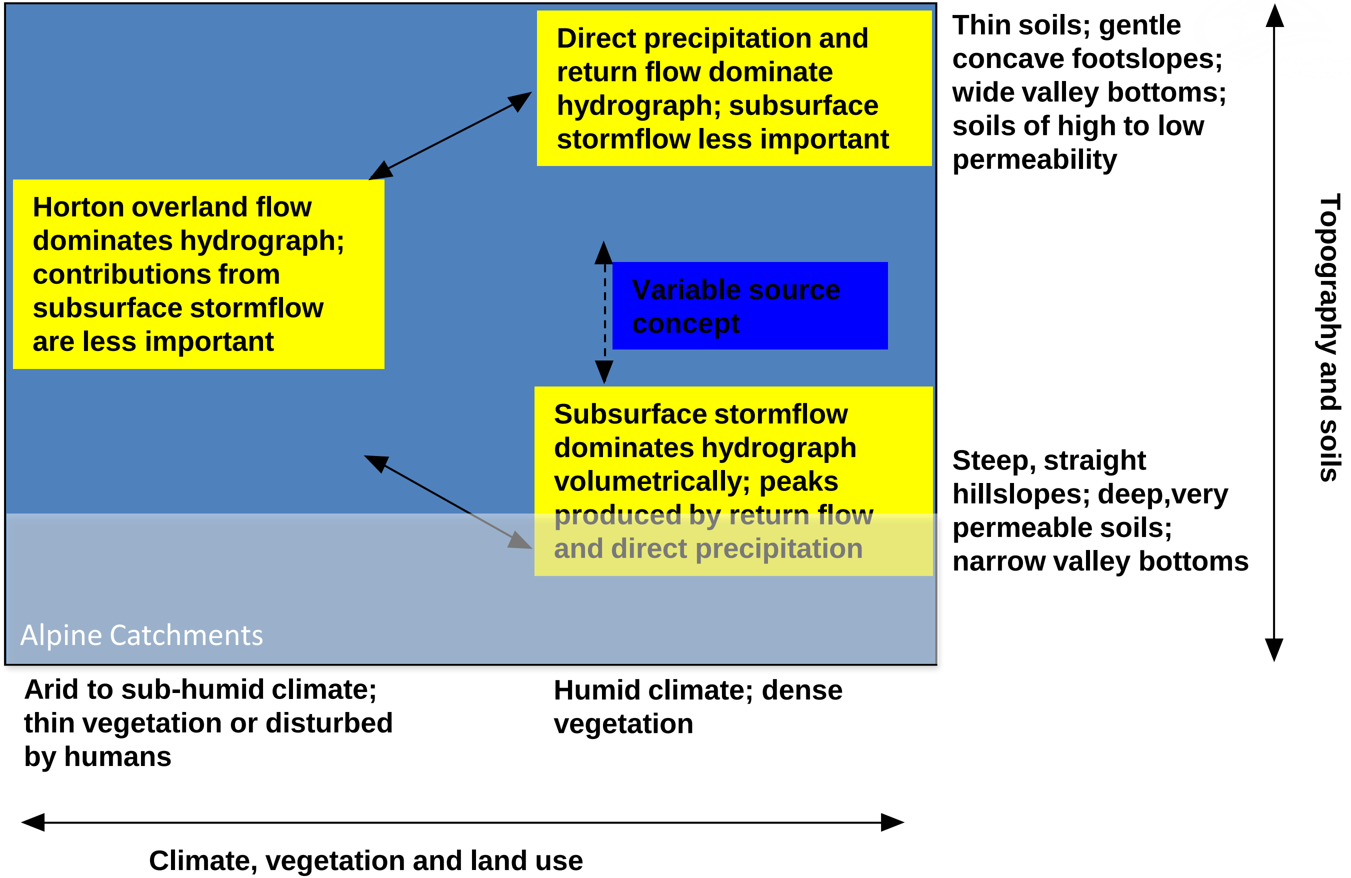
- Largely concerned with how water moved from hillslopes to streams
- Large literature beginning with Hortonian overland flow and moving to throughflow, saturated wedge, transmissivity feedback, etc.





From Kirkby (1978)

Synthesis of Runoff Processes



Runoff processes in relation to their major controls.

(From Dunne and Leopold, 1978)

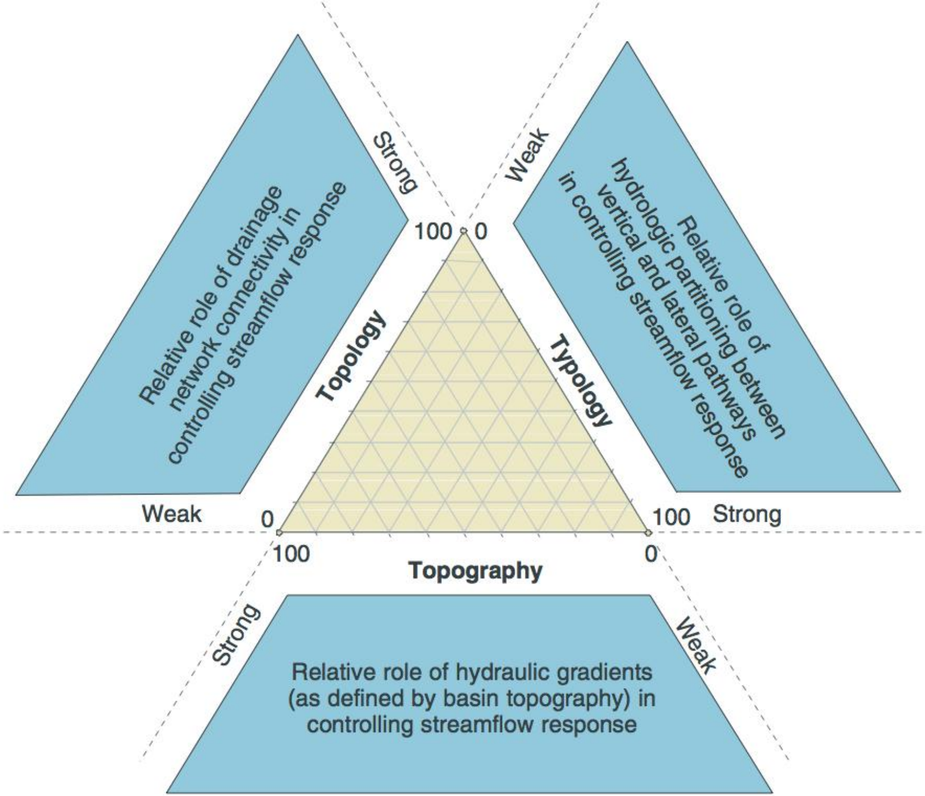
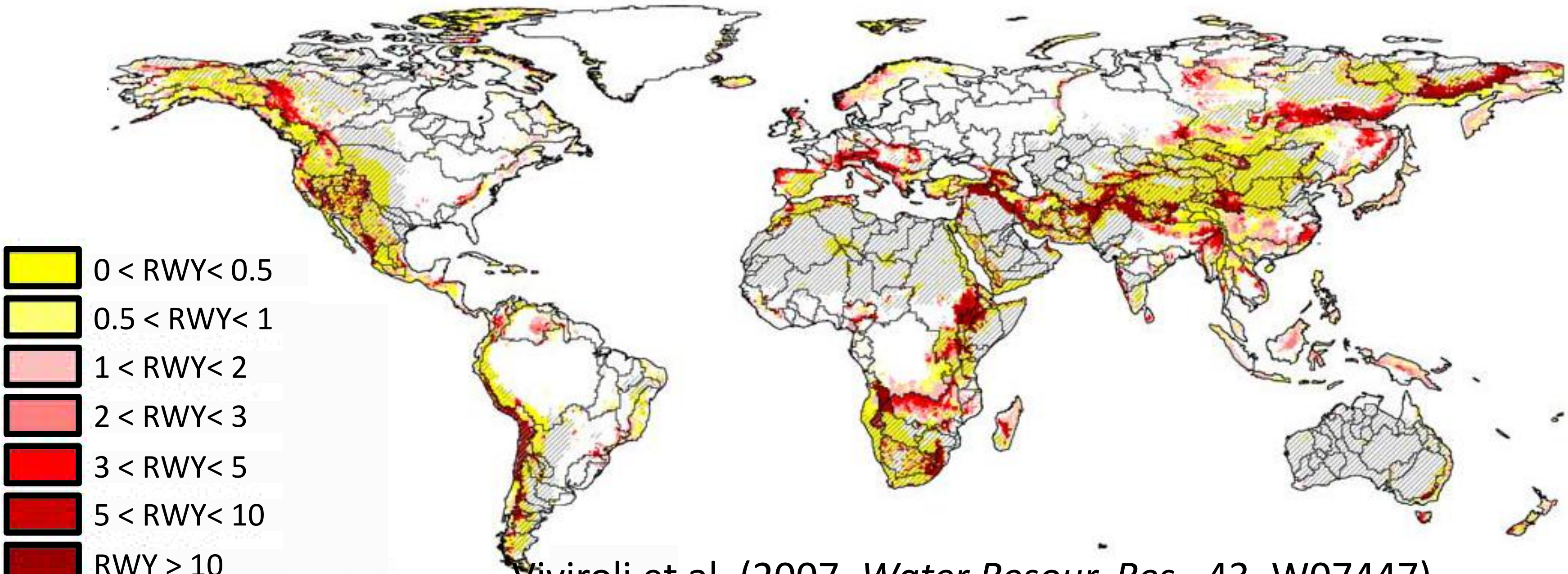


Figure 1. The T³ (typology—topography—topology) template and the relative role of each factor in the regulation of streamflow response

From Jim Buttle (2006), Hydrological Processes

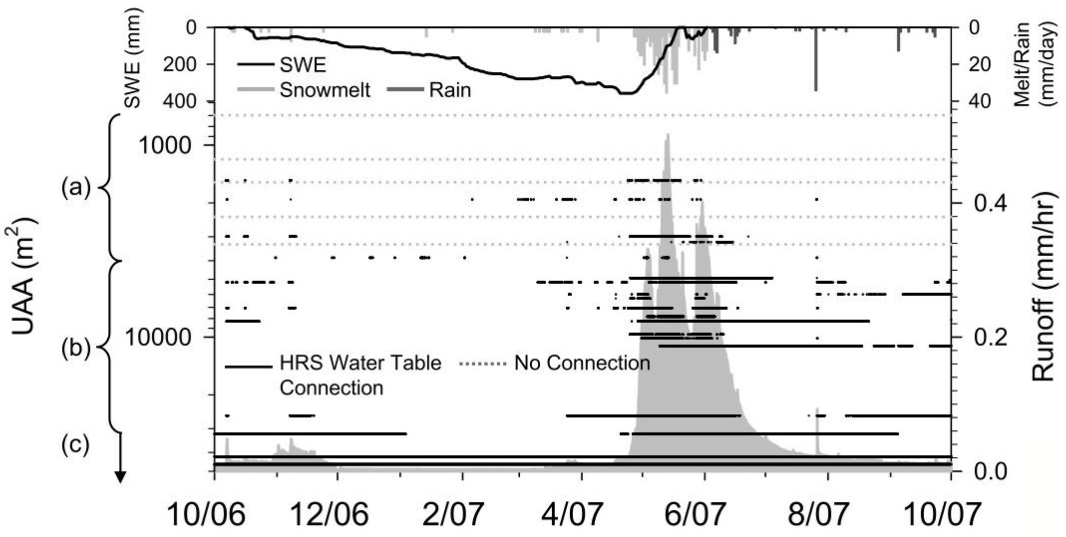
Mountains are the world's water towers

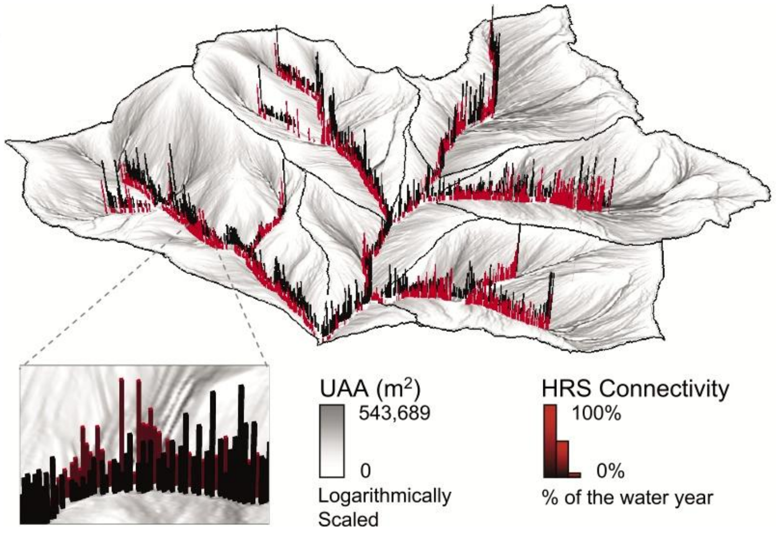
$$\text{Relative water yield (RWY)} = \frac{\text{Mountain runoff (mm/y)}}{\text{Lowland runoff (mm/y)}}$$



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

Steep Catchments – ephemeral linkages





Jencso and McGlynn 2009 WRR

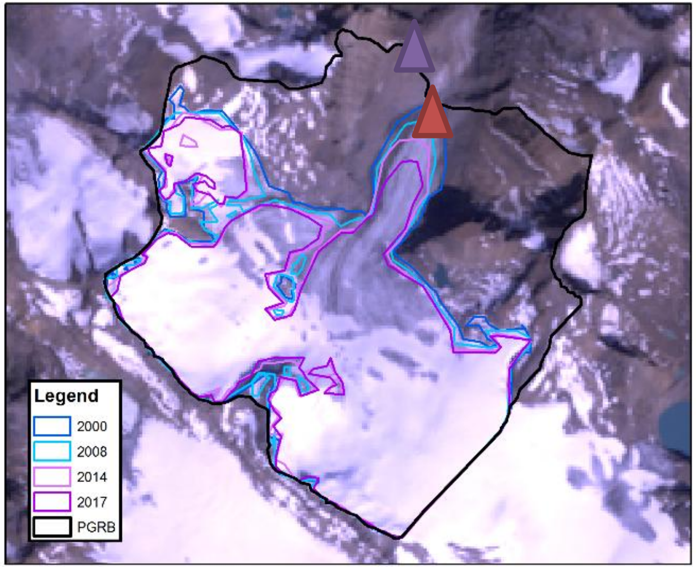
Key Factors for Alpine Watersheds

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

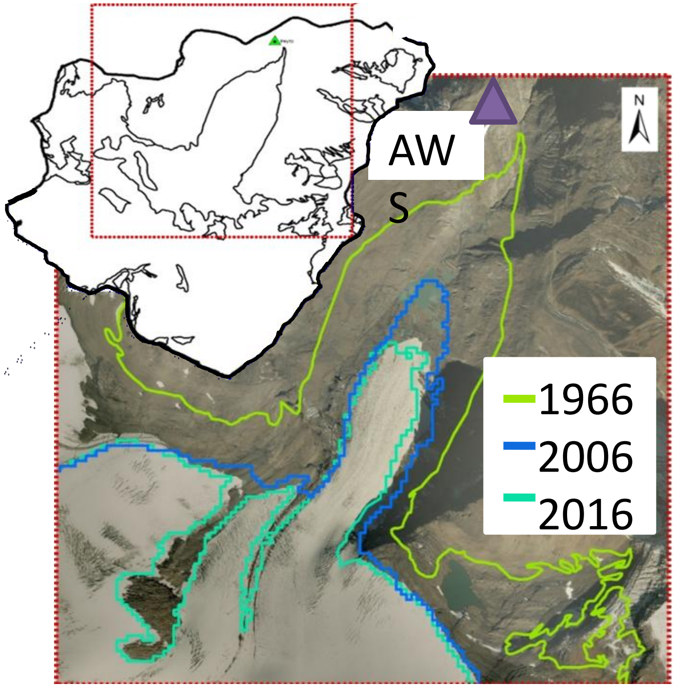
Current Paradigms – snow and glaciers

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

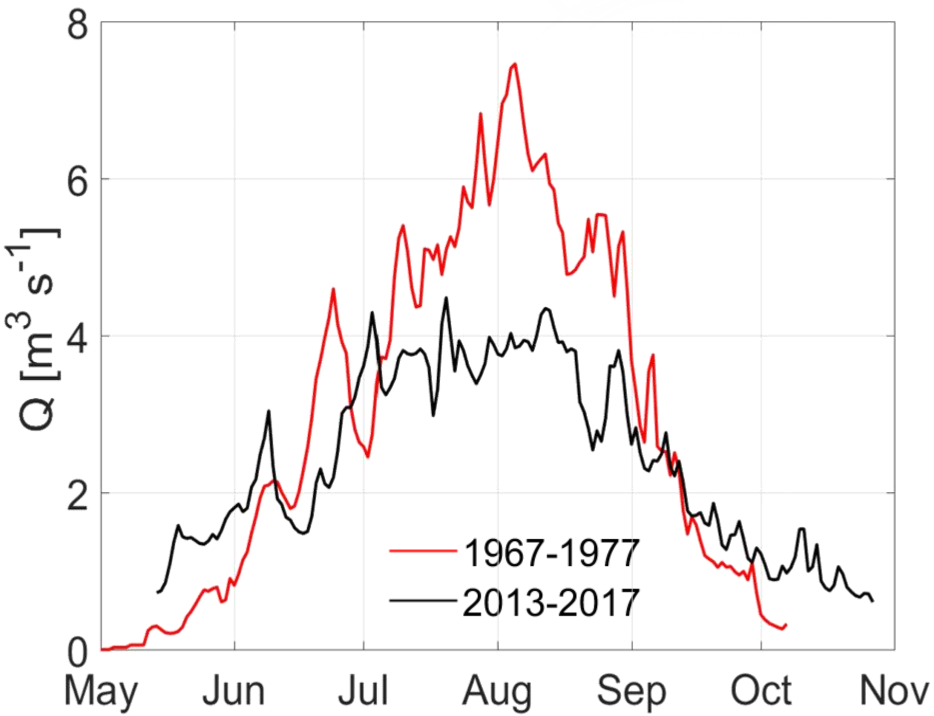
Example: Peyto Glacier in Canada

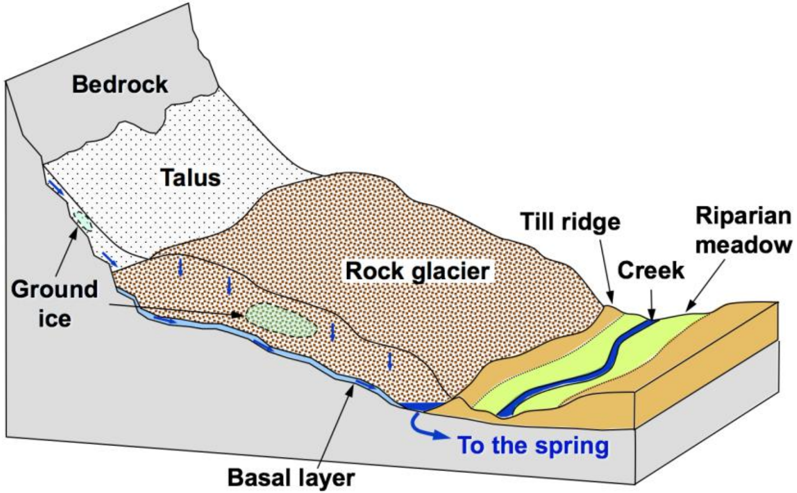


Example: Peyto Glacier in Canada

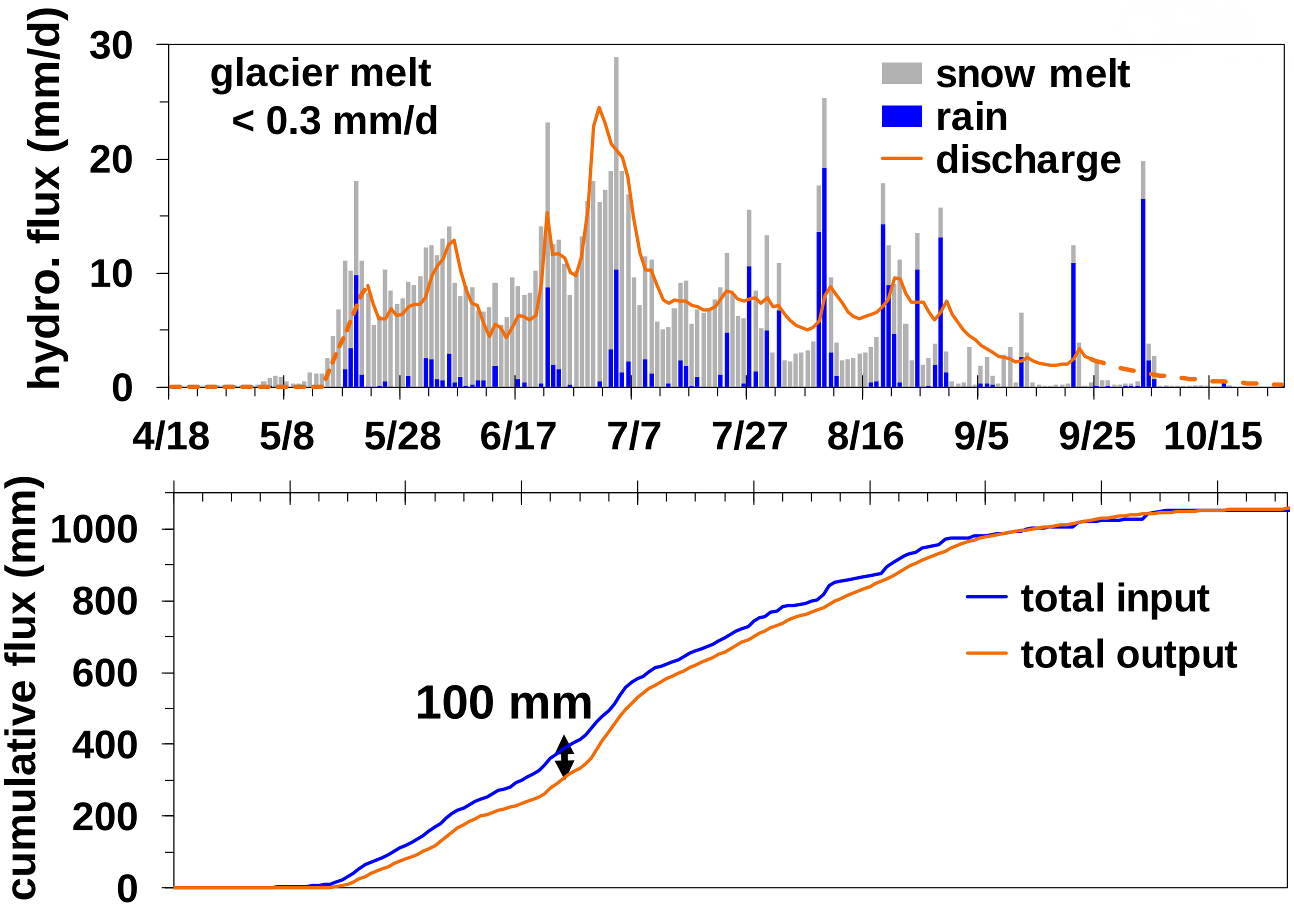


1966: 14.4 km^2
2016: 9.9 km^2





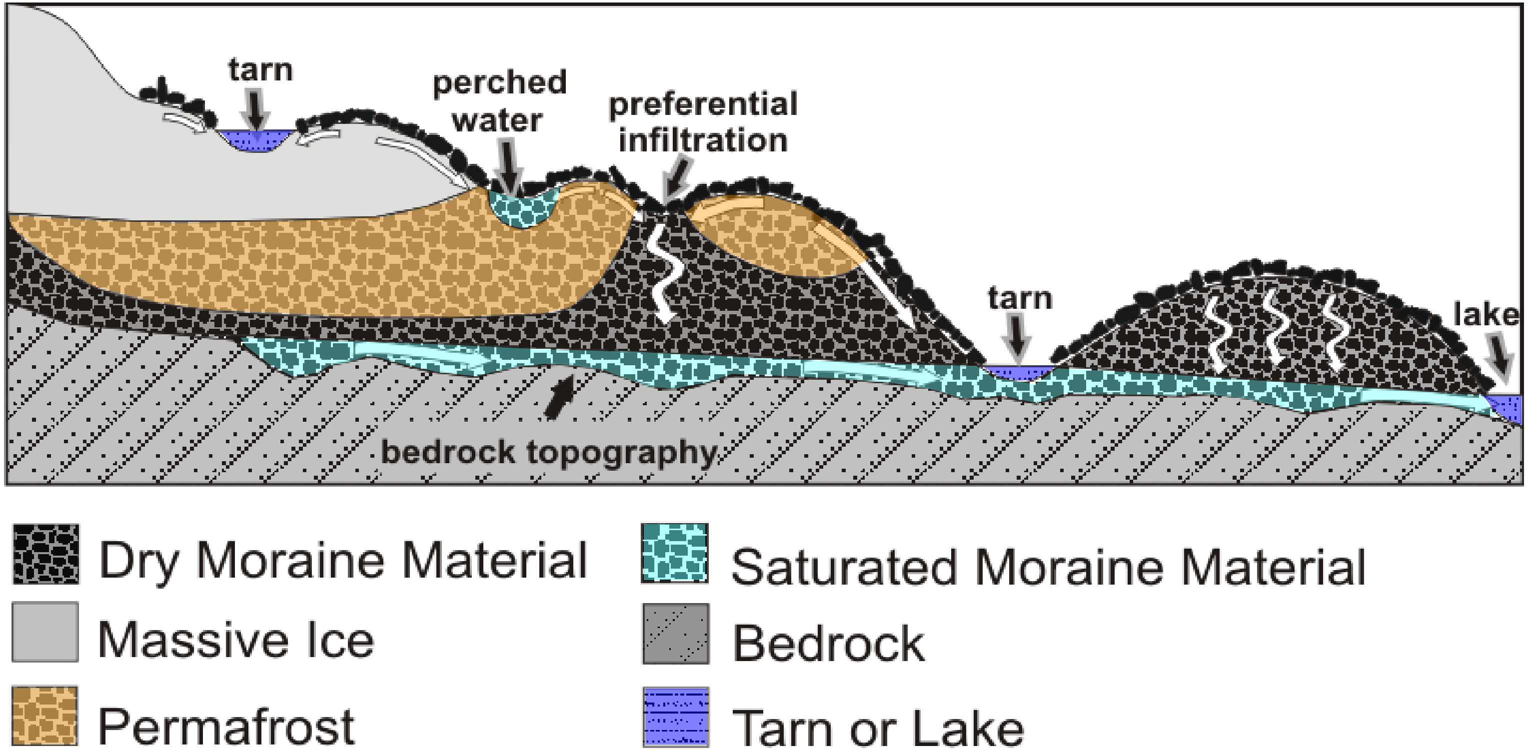
Material from M. Hayashi



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

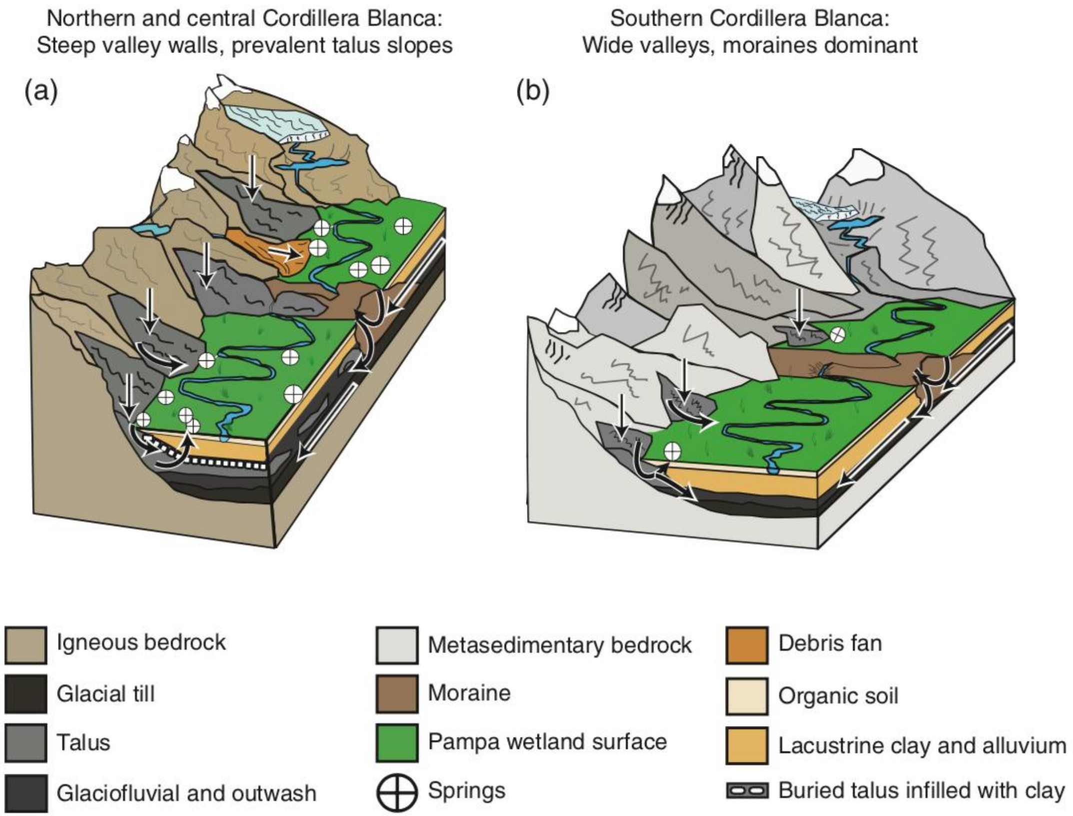


FIGURE 4 (a) Conceptual diagrams of groundwater flow for northern and central valleys (north of Huaraz) and (b) southern valleys (south of Huaraz) of the Cordillera Blanca. White arrows indicate direction of groundwater recharge, flow, and exchange

From Glas et al., 2018, Water Wires

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Colder alpine systems

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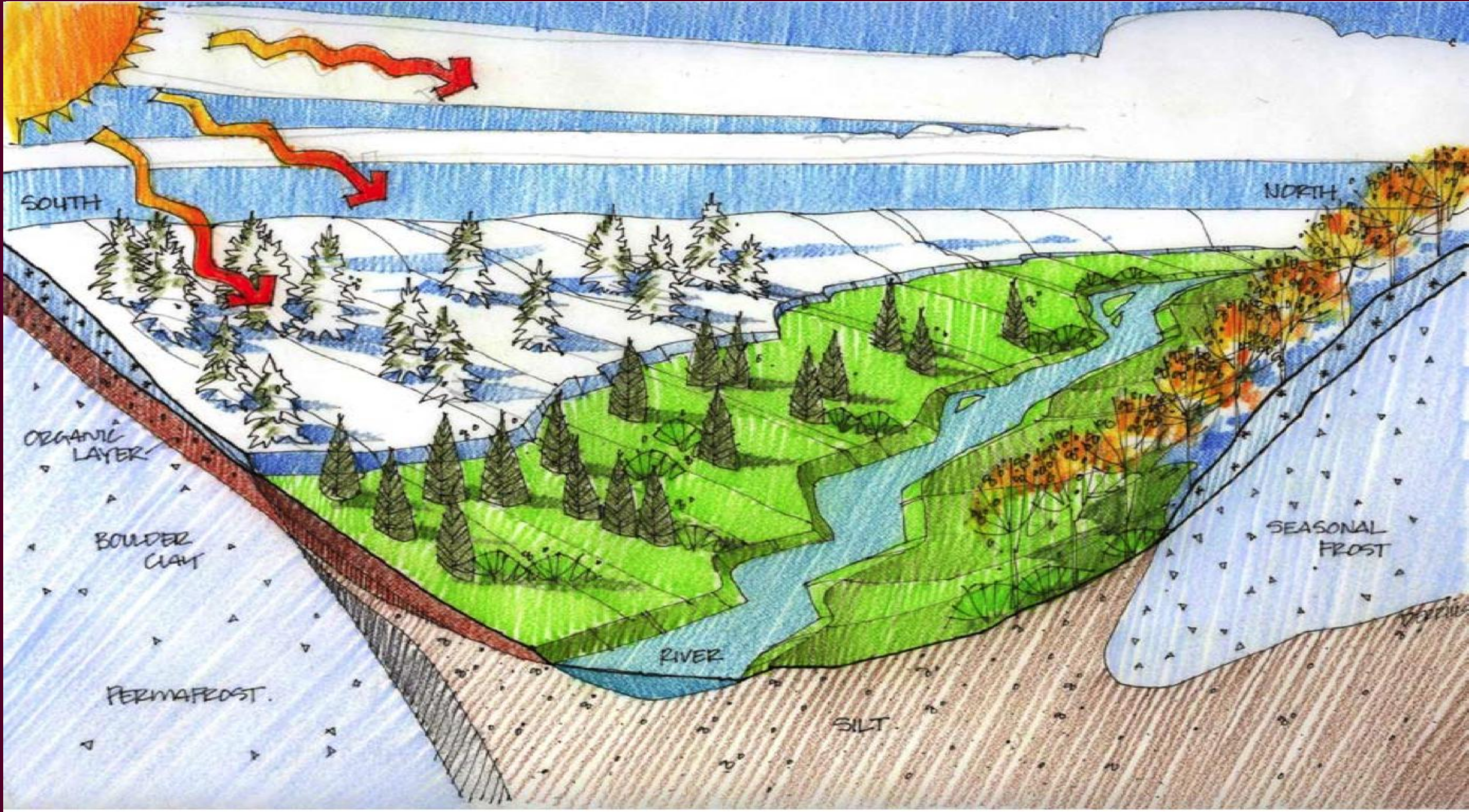
Colder alpine systems



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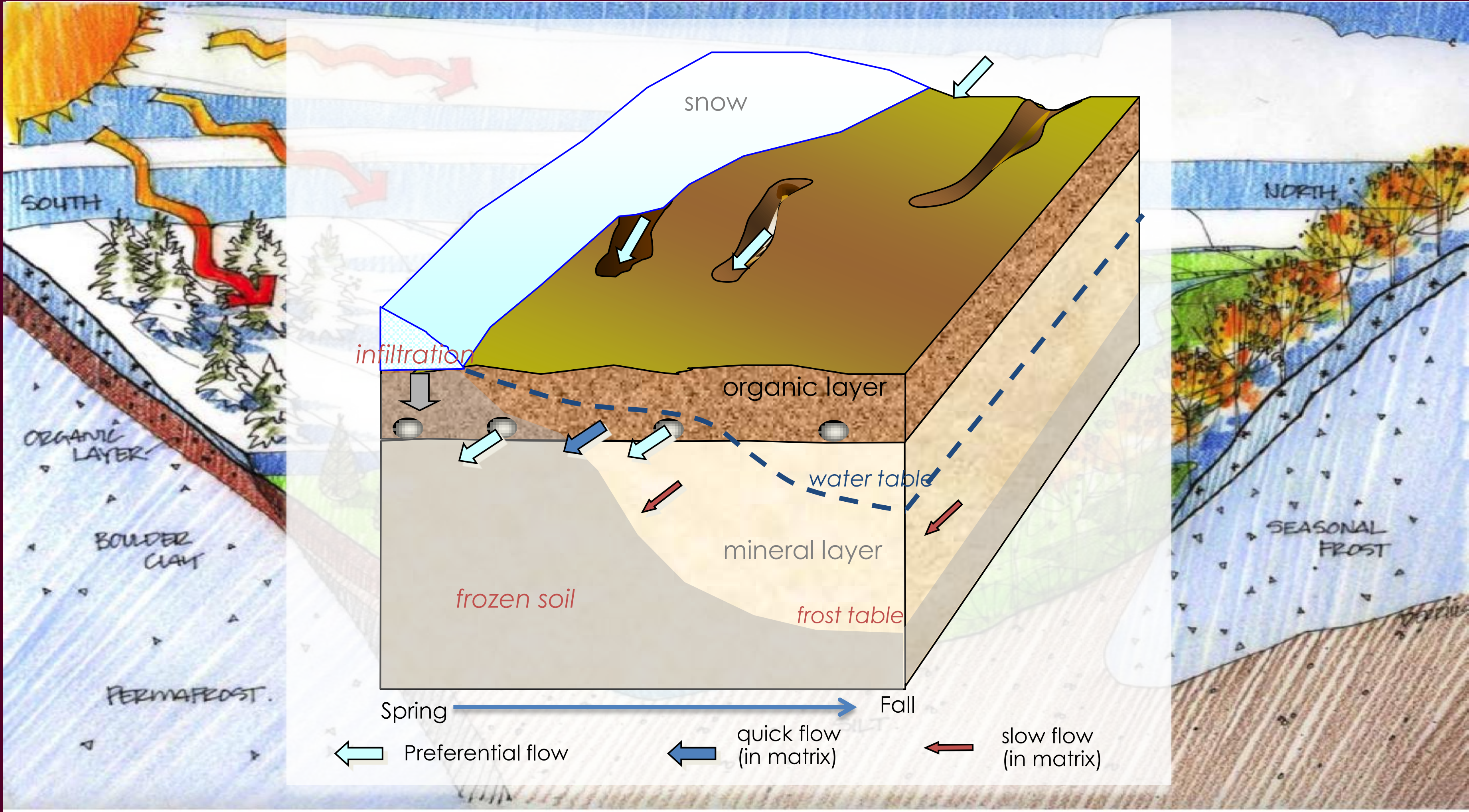
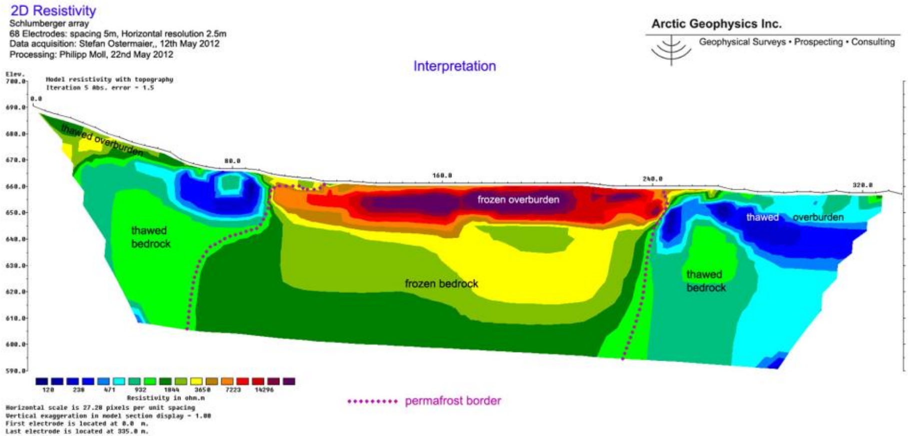
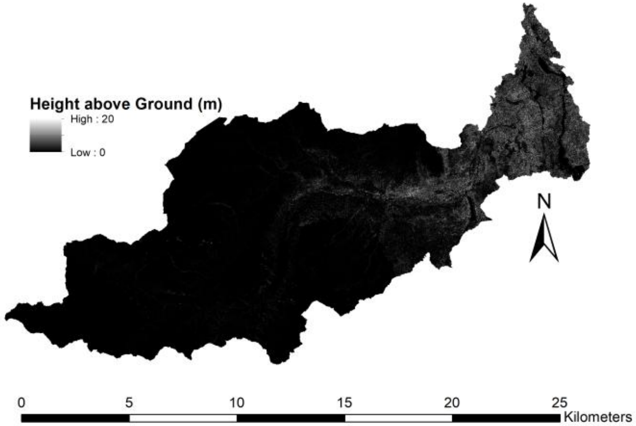
The importance of permafrost



Opportunities – Remote Sensing

Largely an issue of characterization and representation





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New Data Streams






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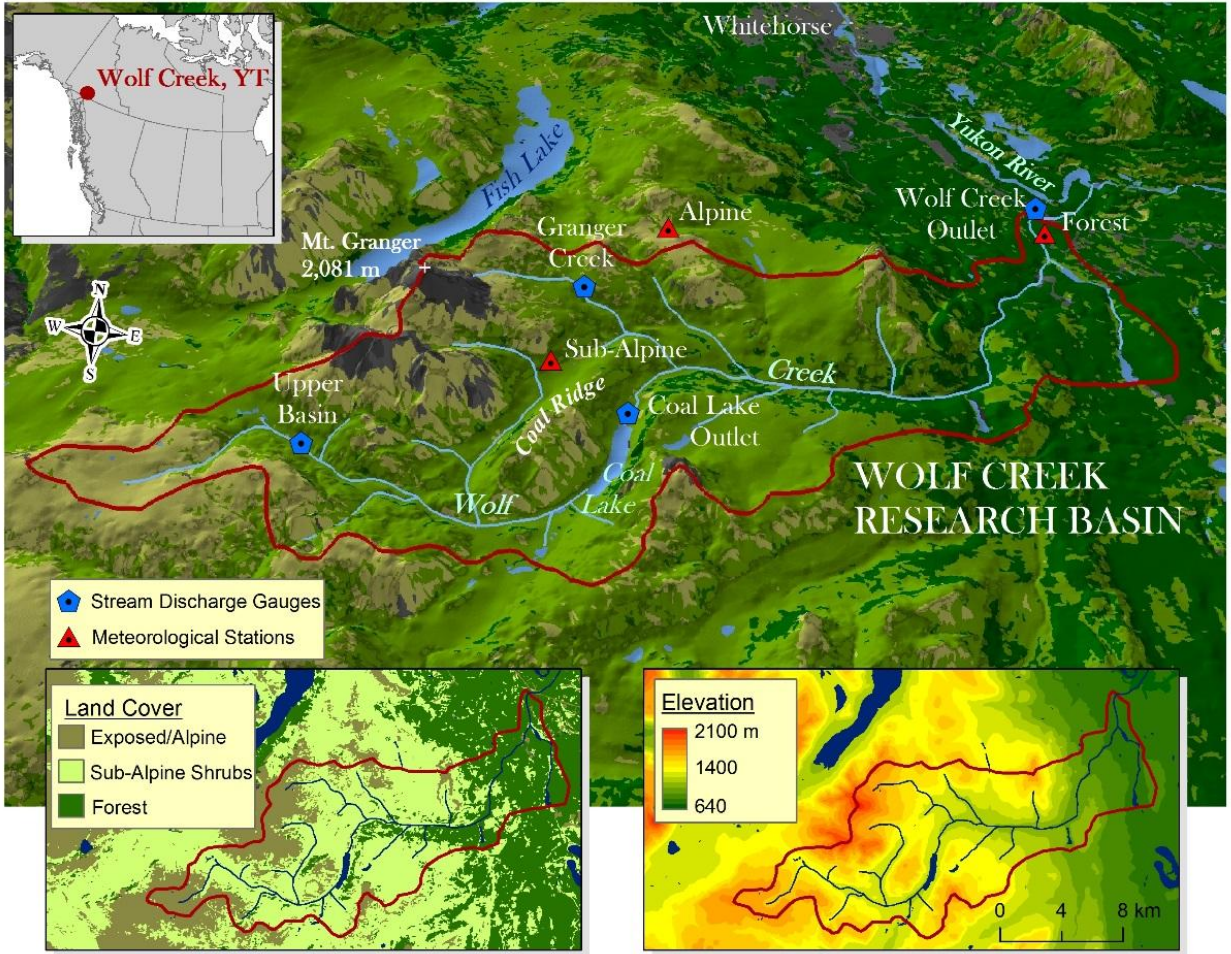
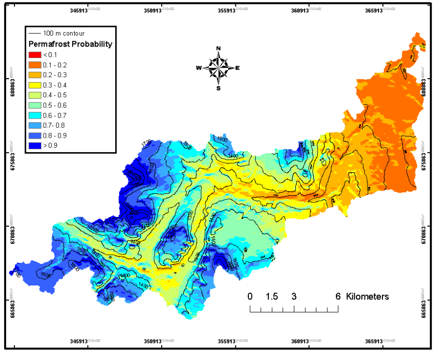
Wolf Creek Research Basin





Permafrost probability map
Lewkowicz & Ednie 2004, PPP

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Wolf Creek Research Basin

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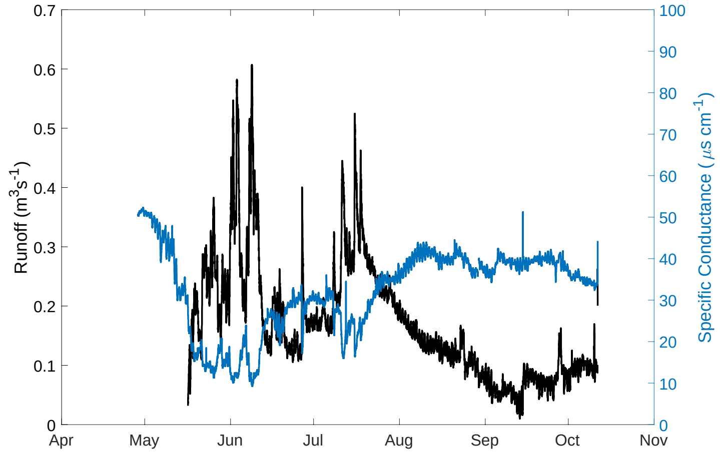
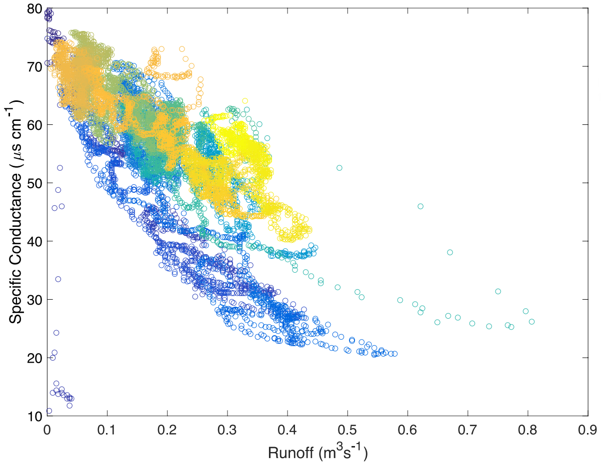
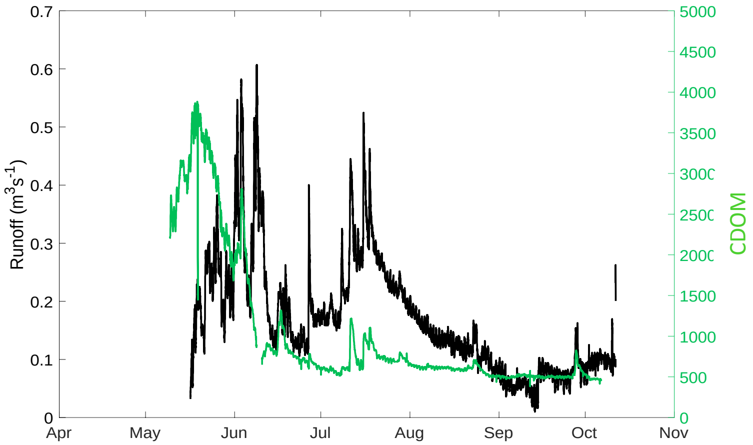
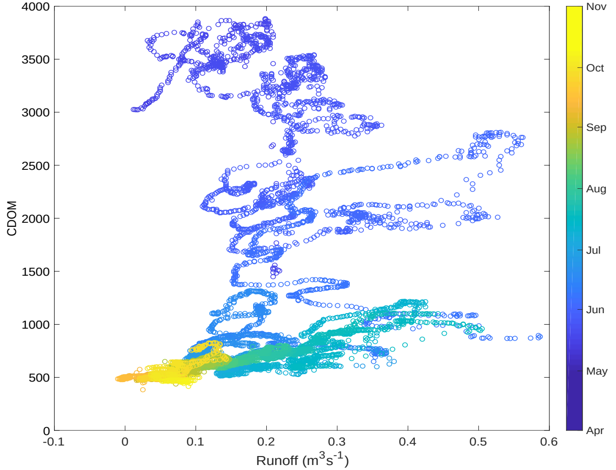
High frequency measurements

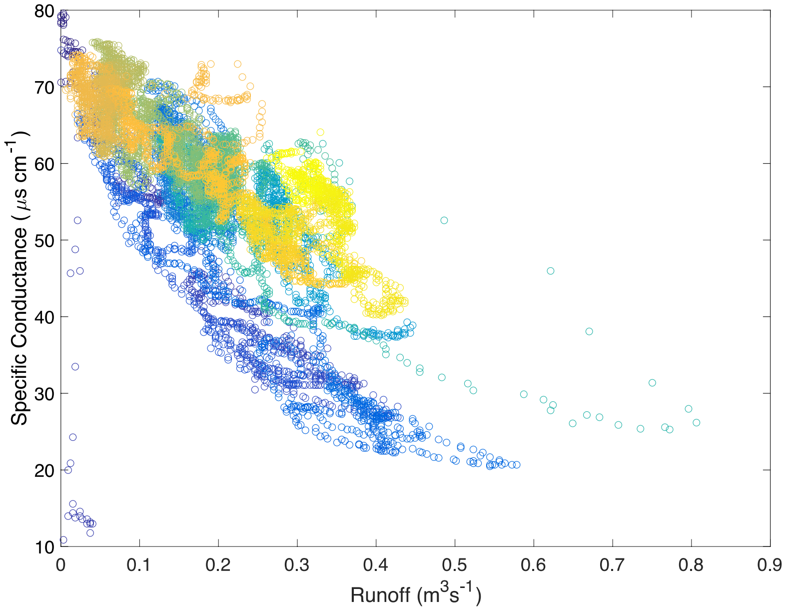


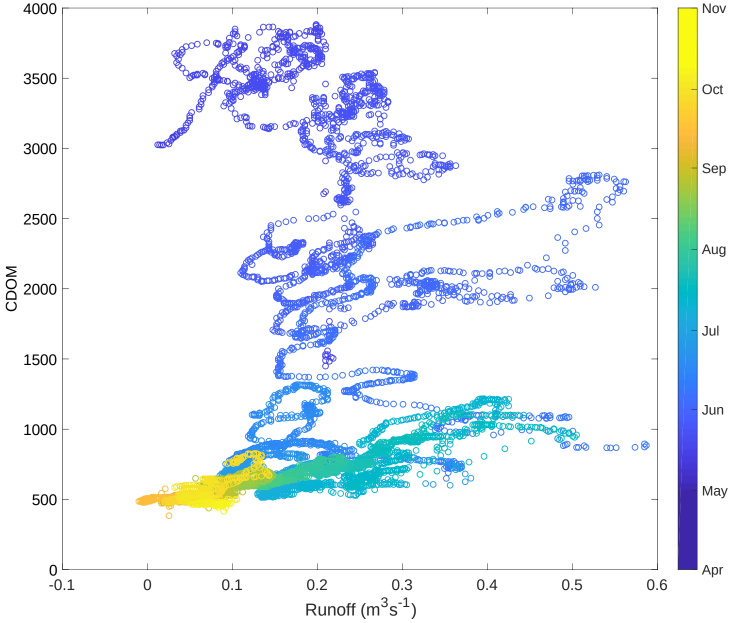






General High Frequency Confusion





- 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

Hydrological Processes

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SPECIAL ISSUE CANADIAN GEOPHYSICAL UNION 2017

HydRun: A MATLAB toolbox for rainfall-runoff analysis

Weigang Tang, Sean K. Carey

Accepted manuscript online: 27 March 2017 Full publication history

DOI: 10.1002/hyp.11185 View/save citation

626 C. E. M. Lloyd et al.: Testing an improved index for analysing storm discharge–concentration hysteresis

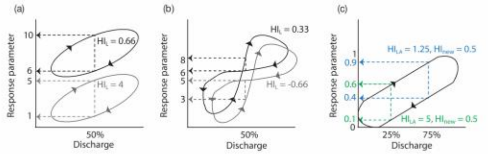
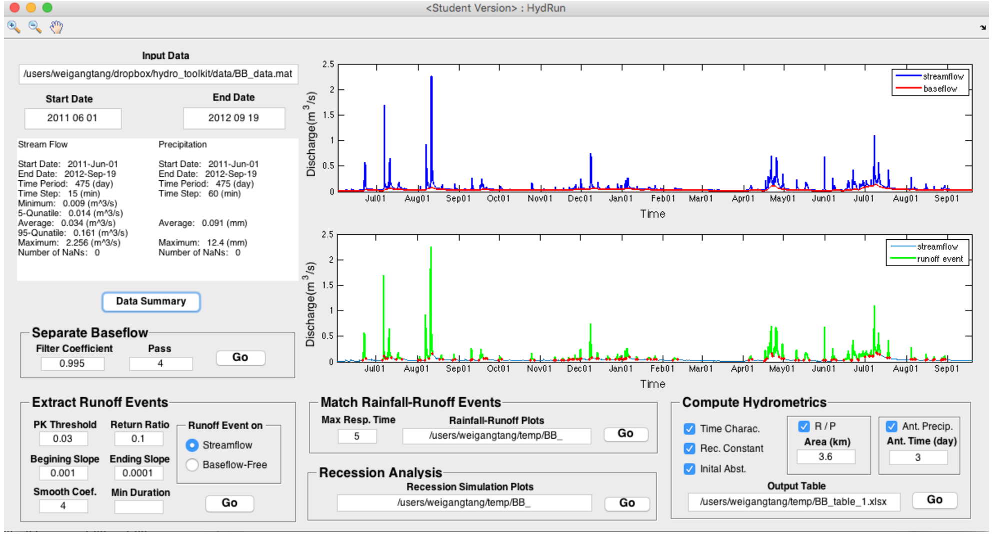


Figure 1. **(a)** Impact of storm initial concentration, **(b)** storm initial discharge on the value of the calculated HI when the mid-point in discharge and raw data is used and **(c)** an idealised and normalised storm illustrating the impact of measuring different quantiles of flow on the HI calculated, where HI_L and HI_{LA} are the original and adapted Lawler et al. (2006) methods, respectively and HI_{new}, the proposed new method. Colours represent different discharge intervals measured.

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



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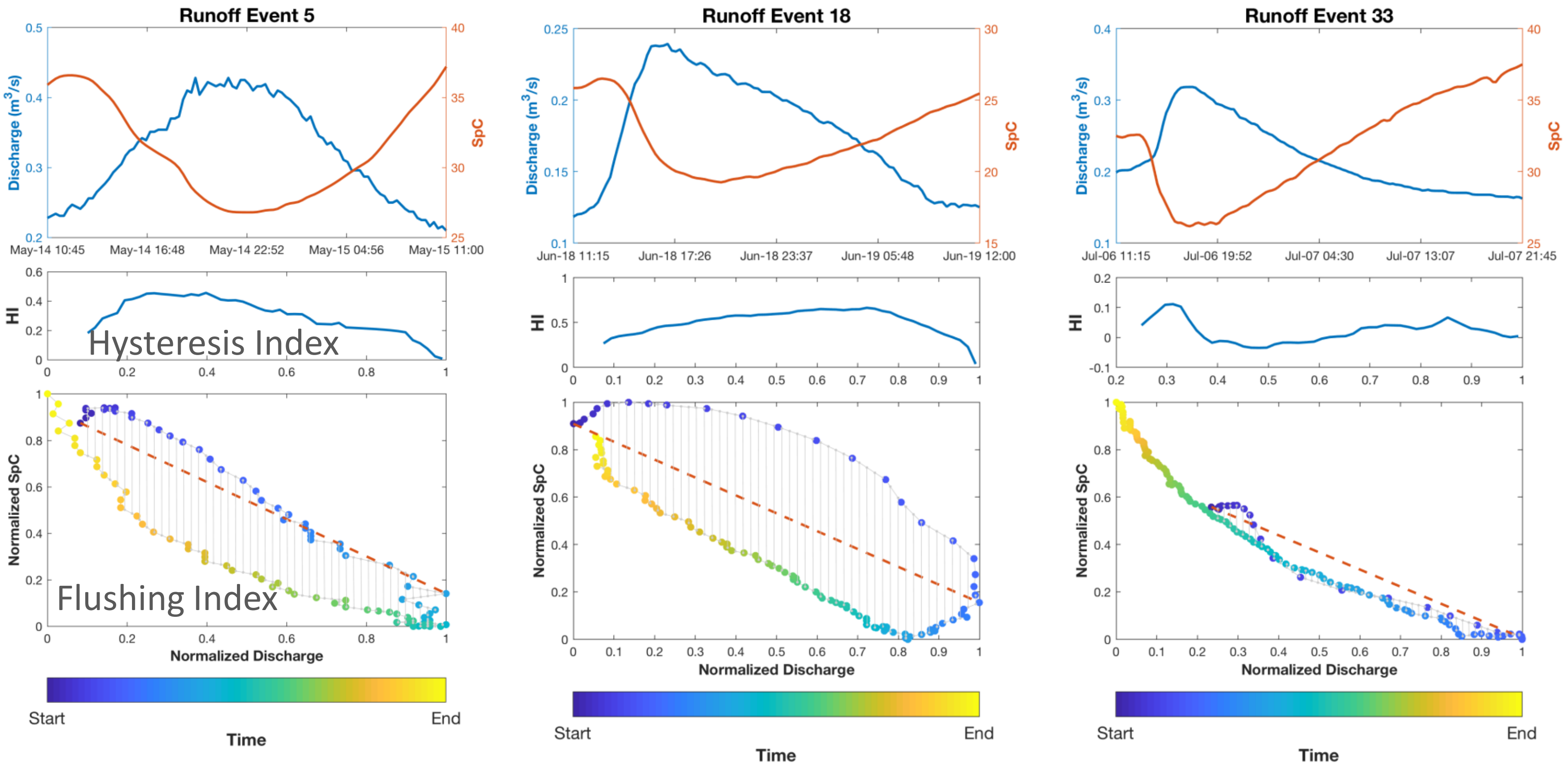
Event analysis - SpC



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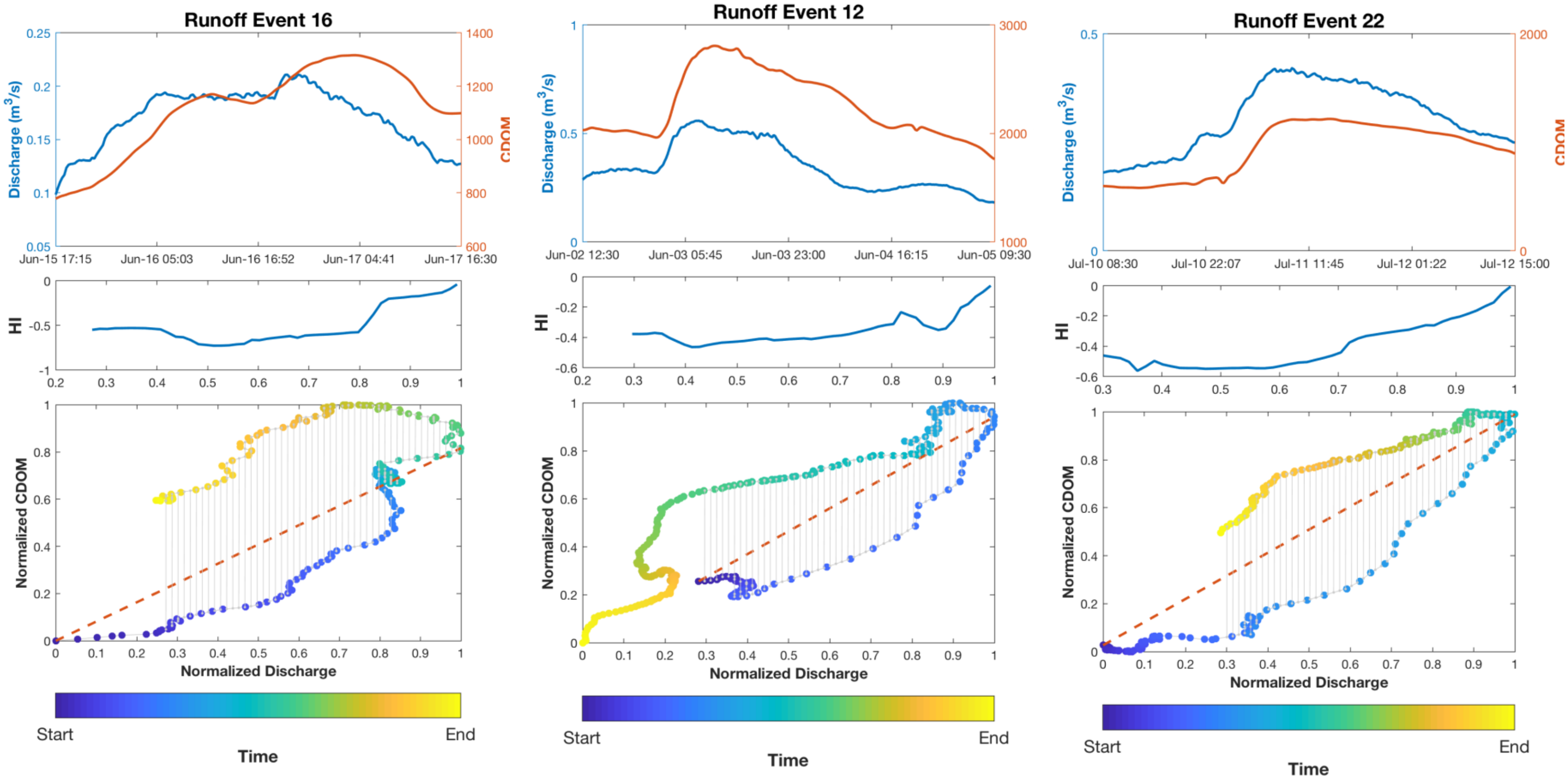
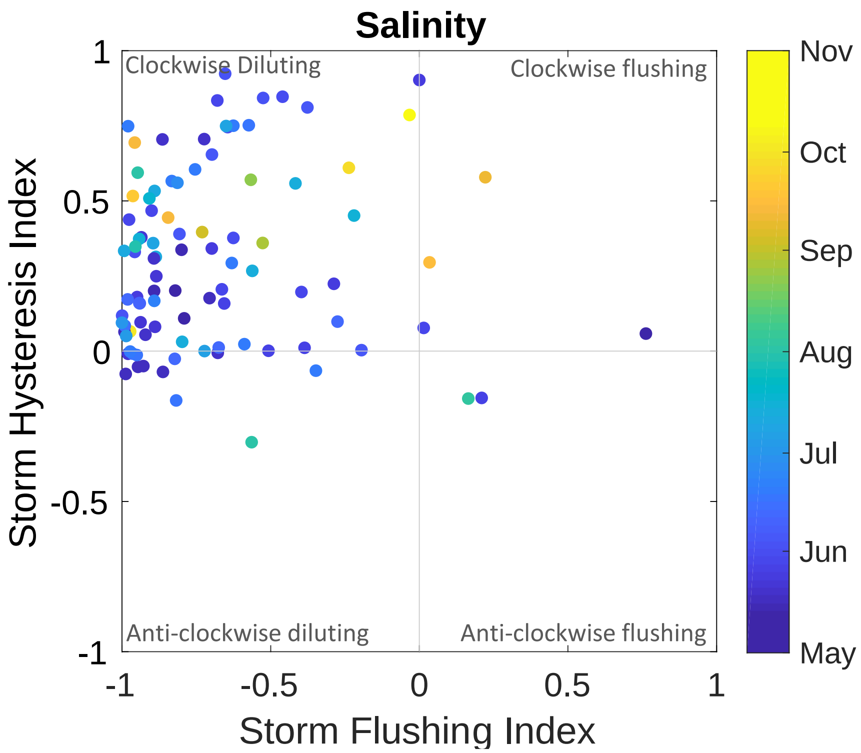
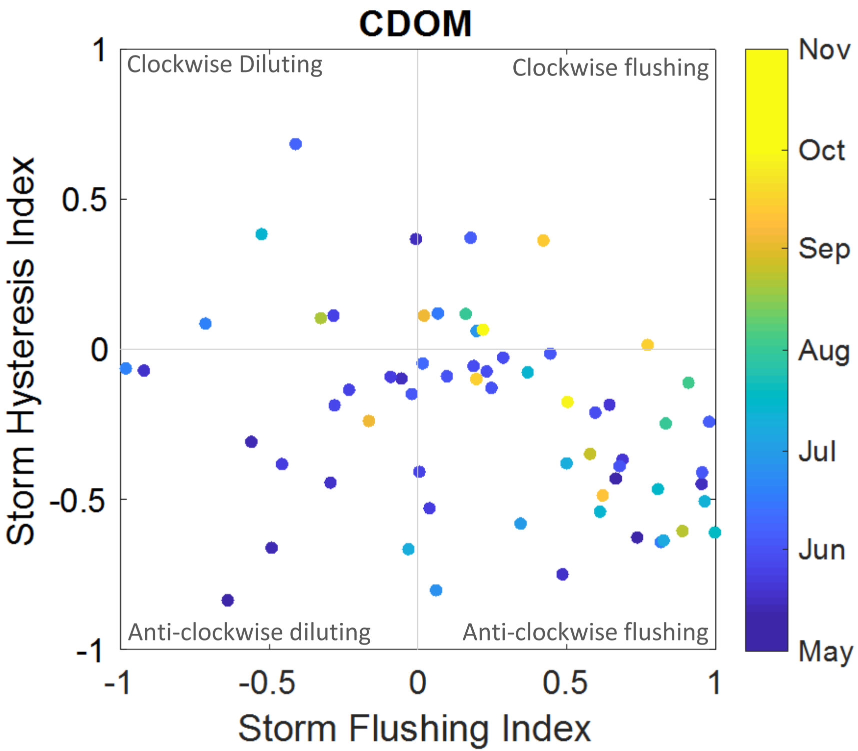
Event analysis - CDOM



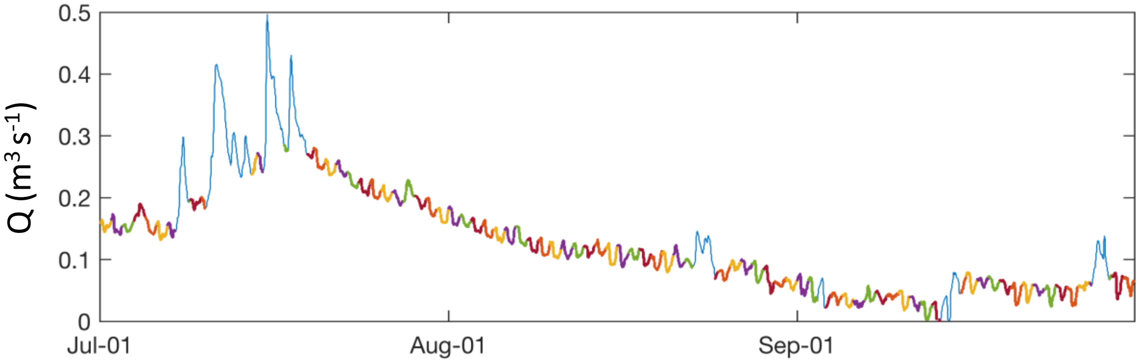
Summary Indices

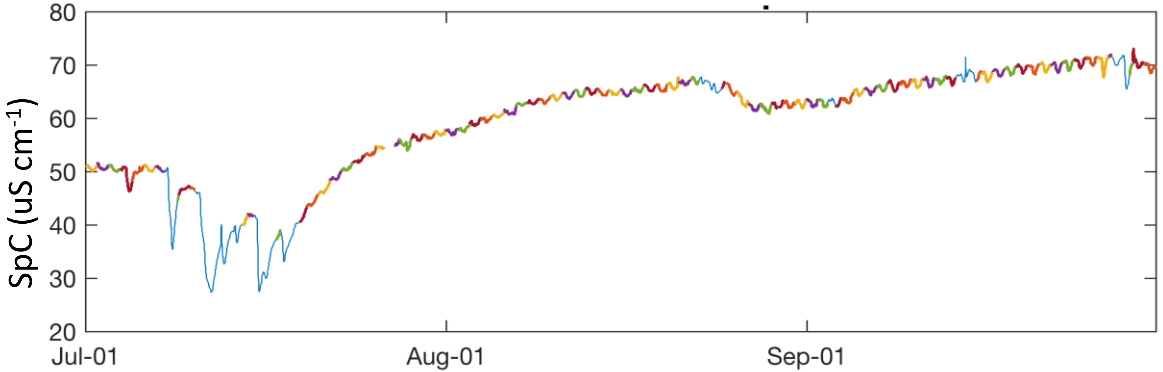


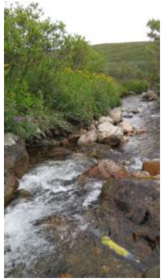


Diel signatures

- Q and SpC from July 1 to Sept 30







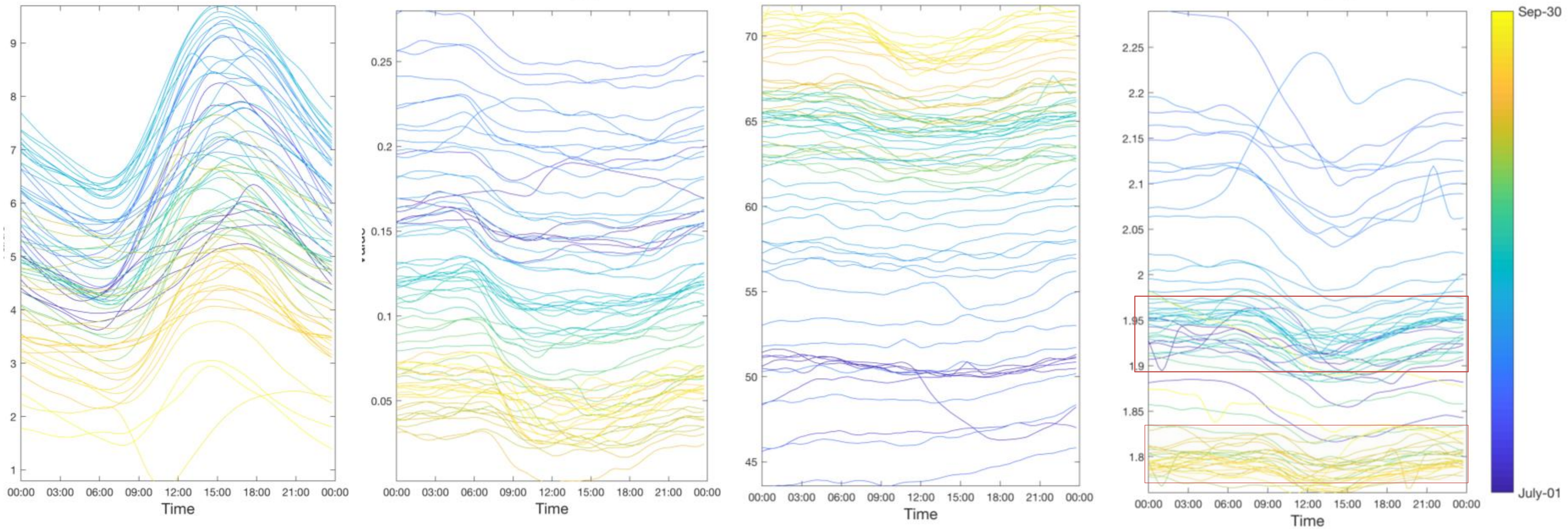
Diel signatures

Water Temp

Discharge (Q)

SpC

DOC



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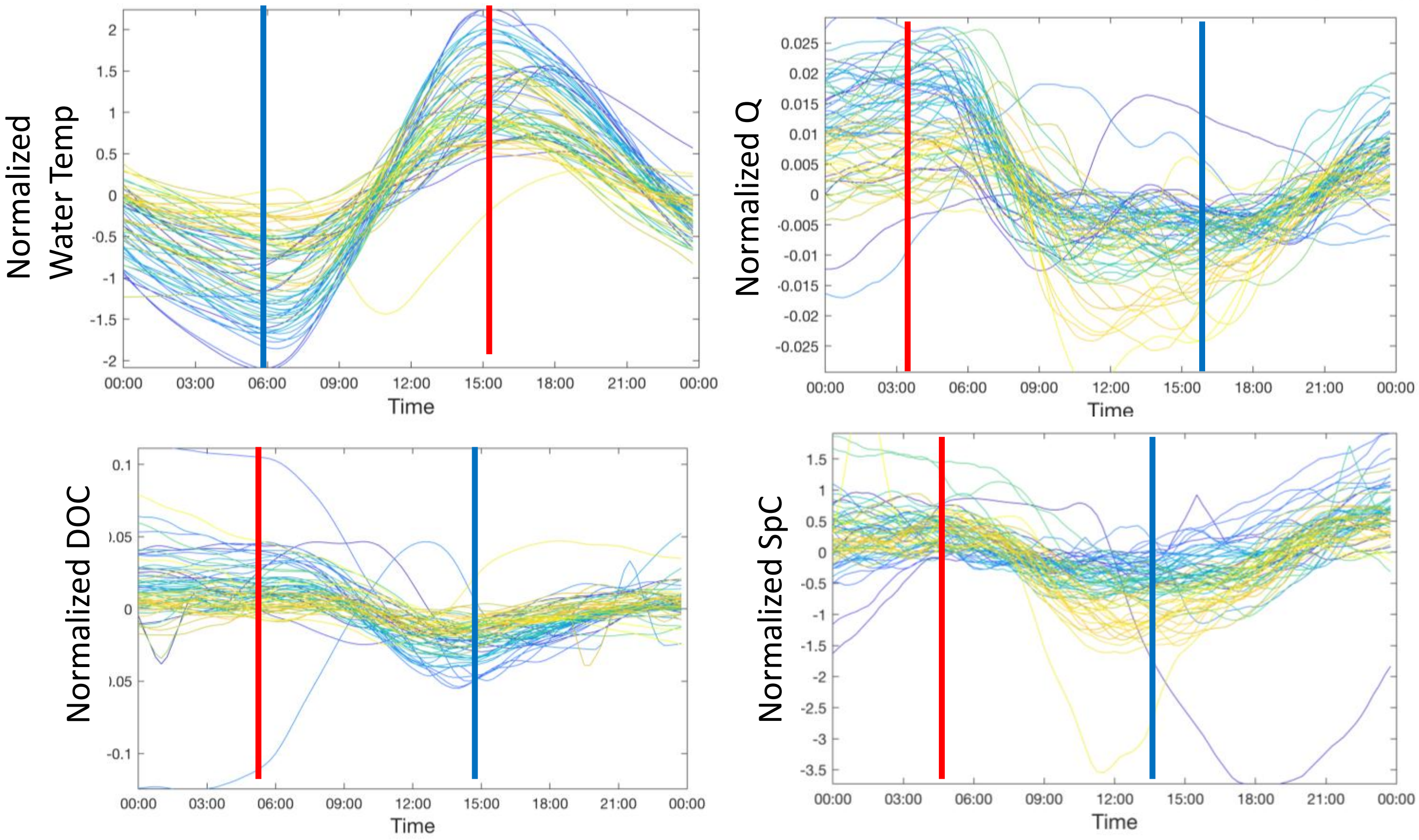
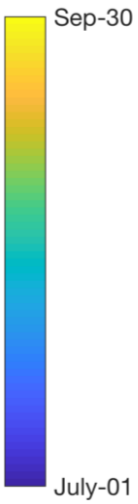
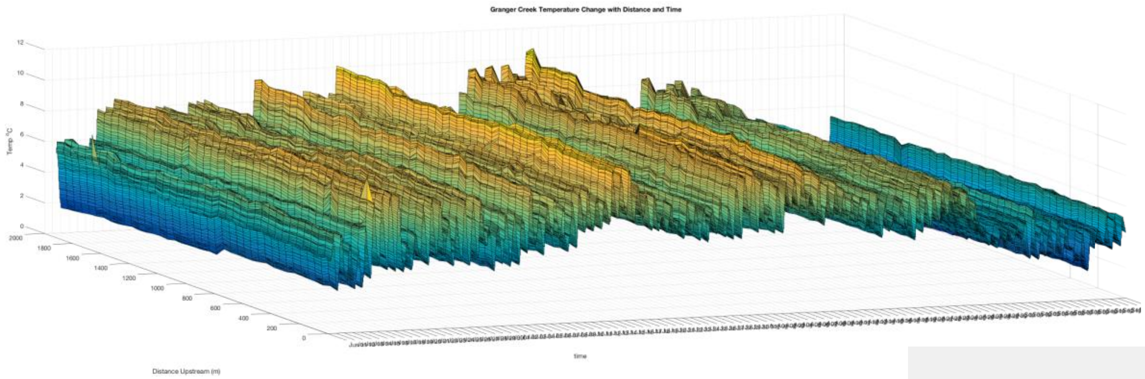
Diel signatures

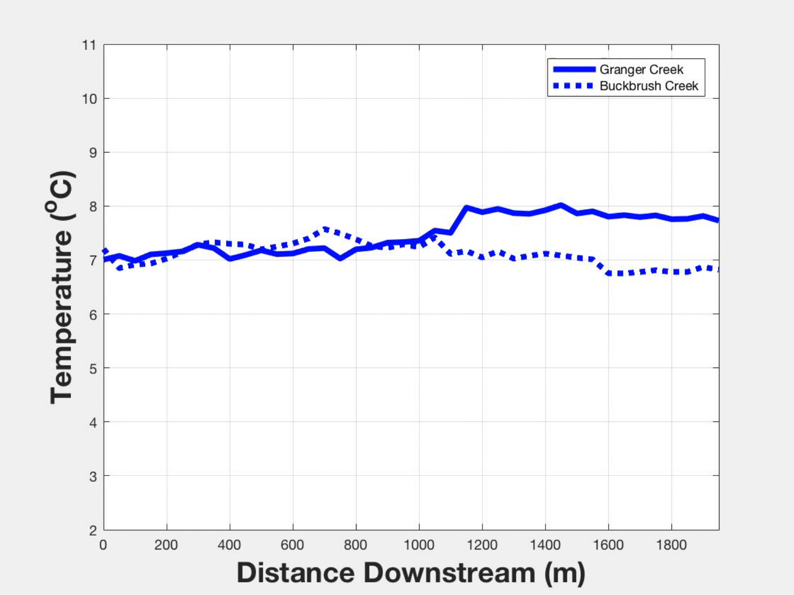


- Water temp out of phase means viscosity is not a driver



Stream temperature to understand groundwater





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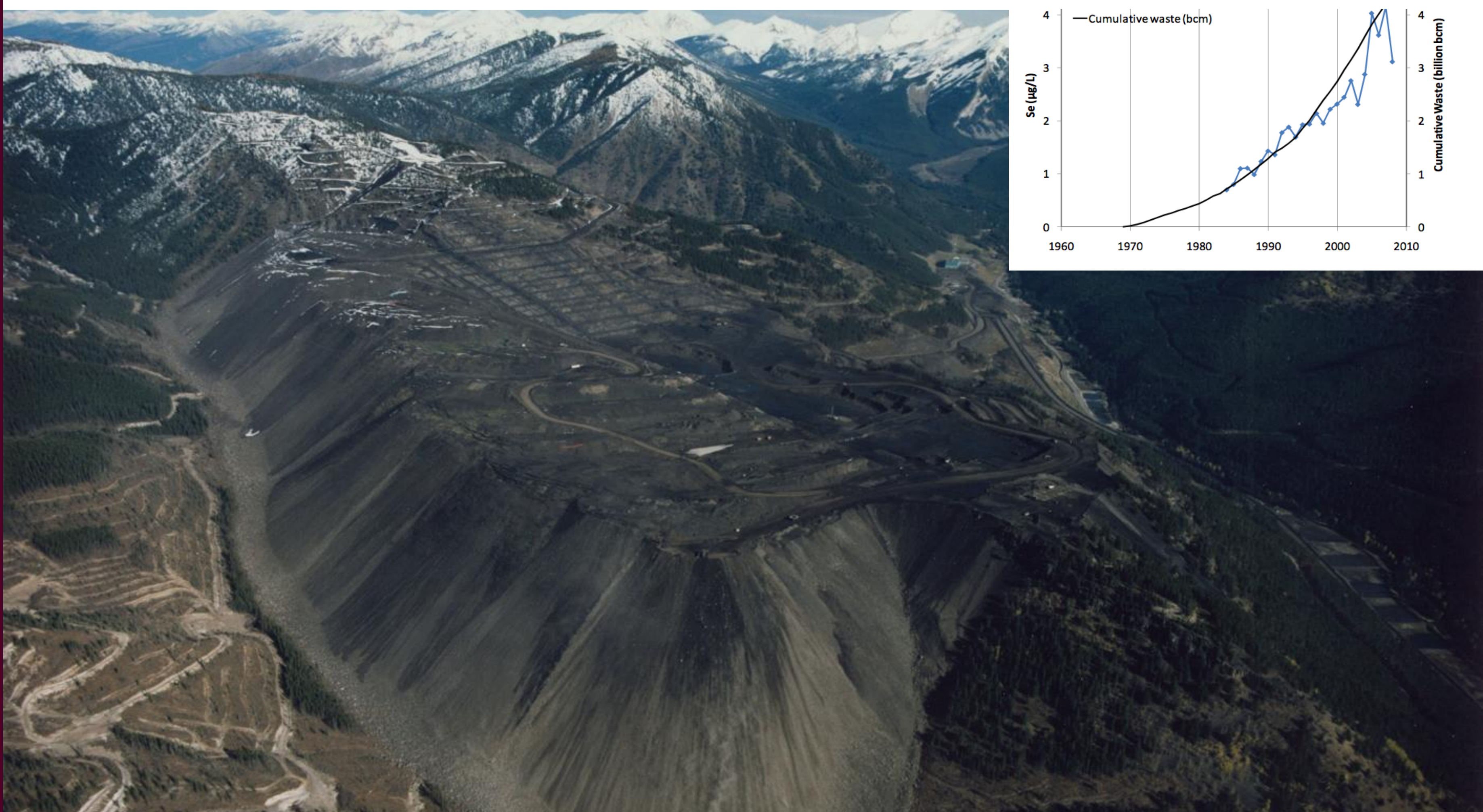
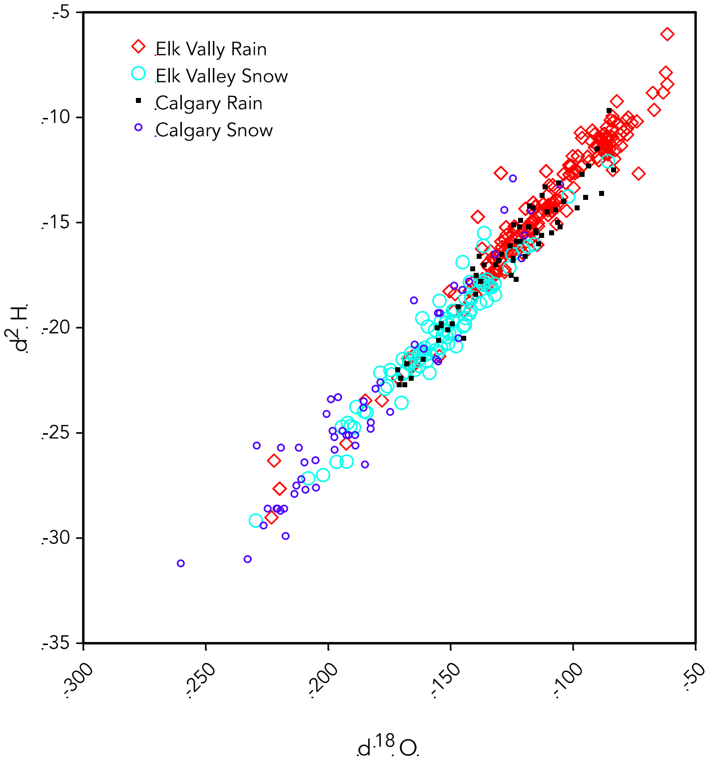
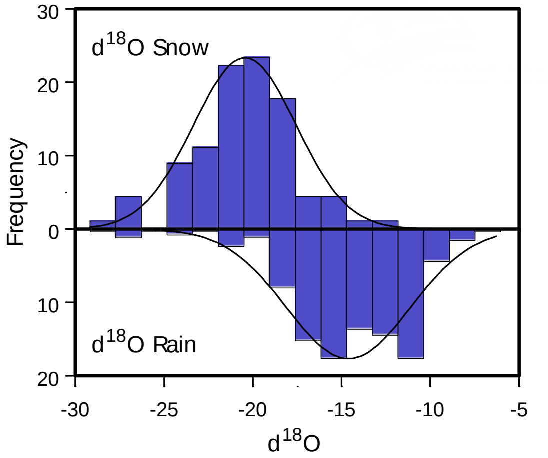
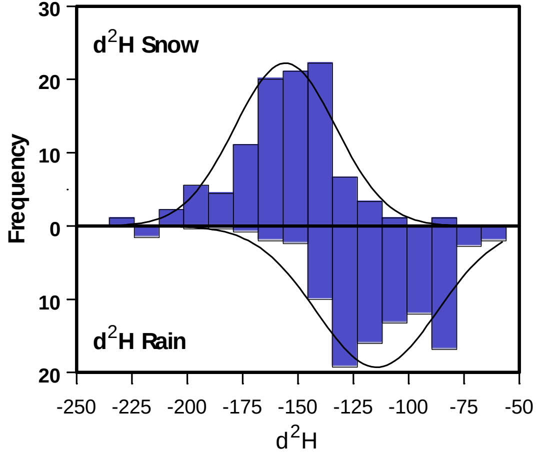
Isotopes and the dark arts



Stable Isotopes







⇒ LMWL similar to Calgary
⇒ Distribution of snow and rain

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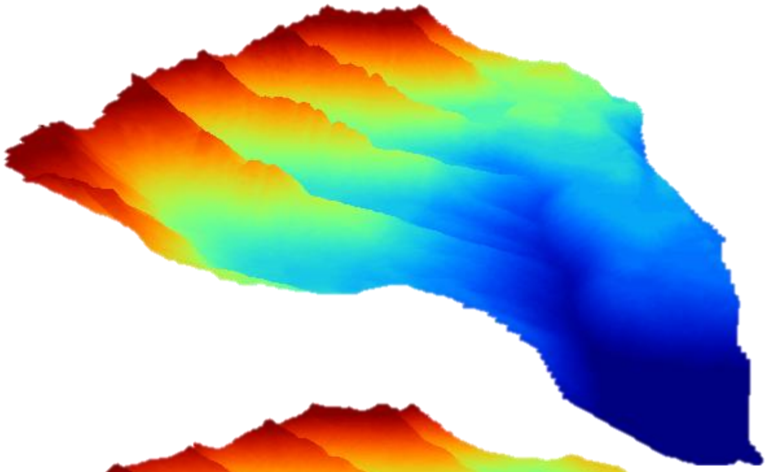
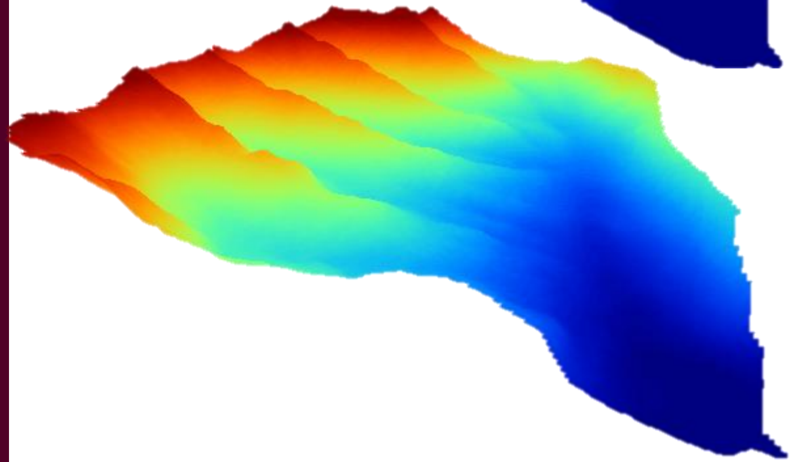
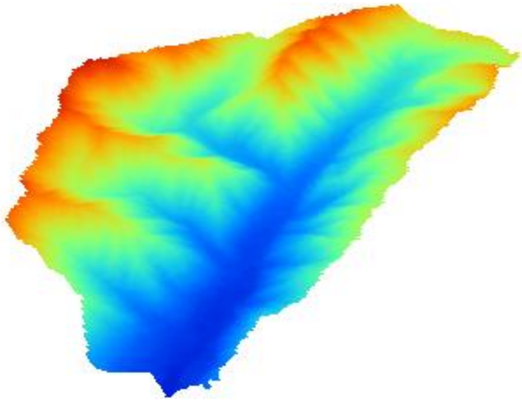
West Line and Dry Creek

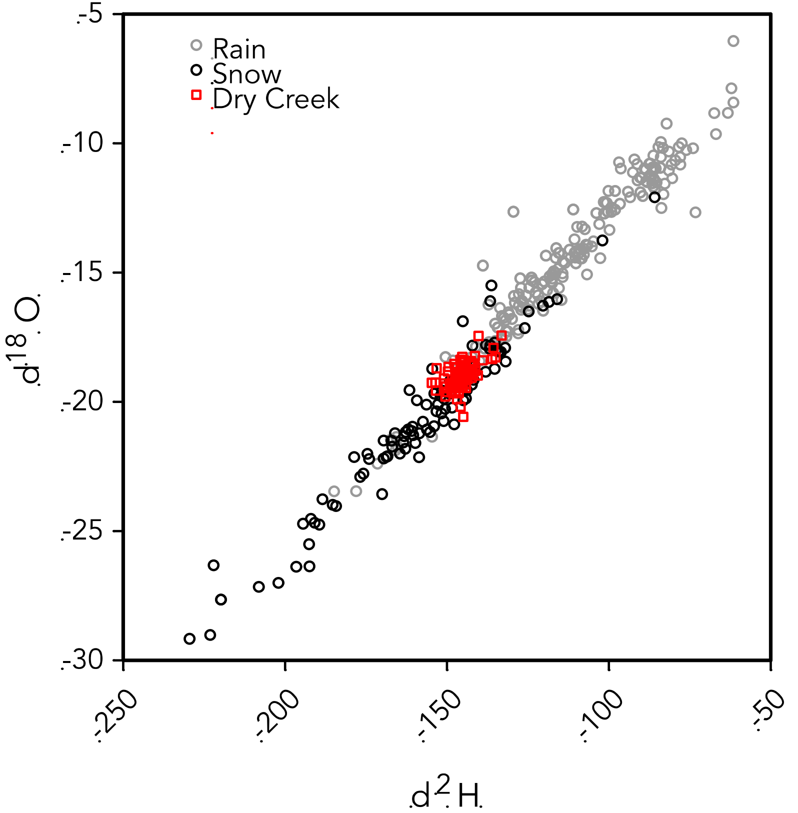






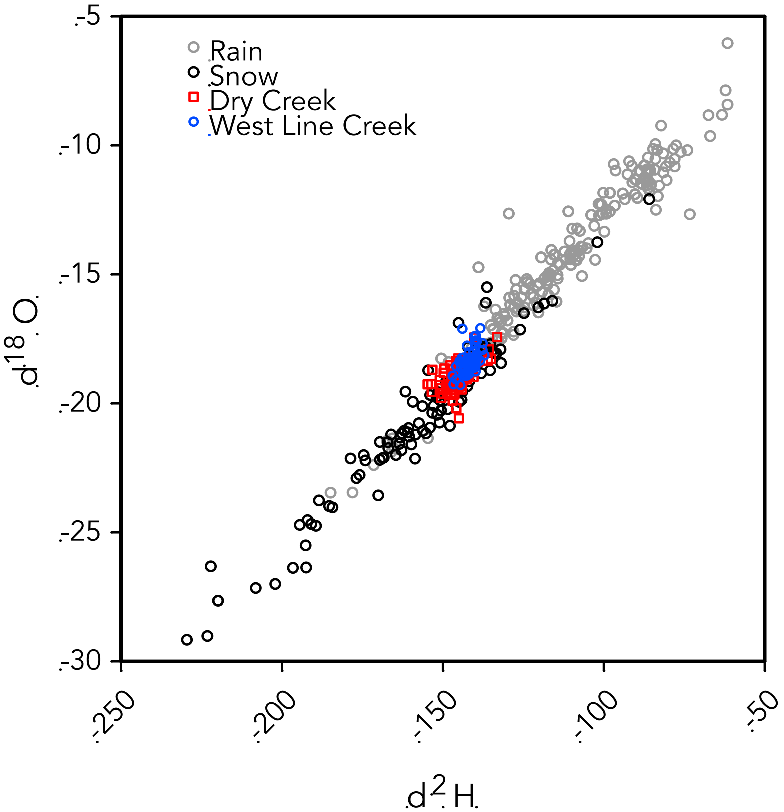
N50˚02.016’ W114˚48.867'

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

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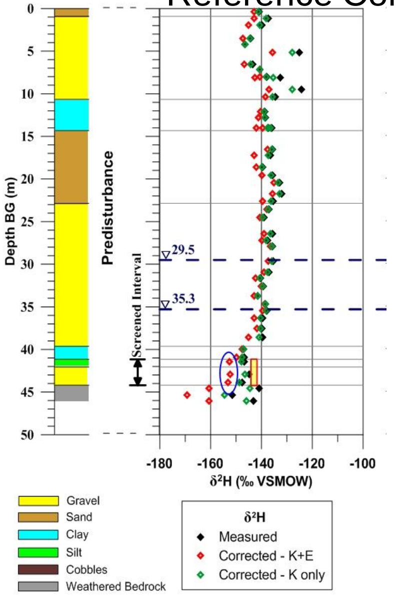
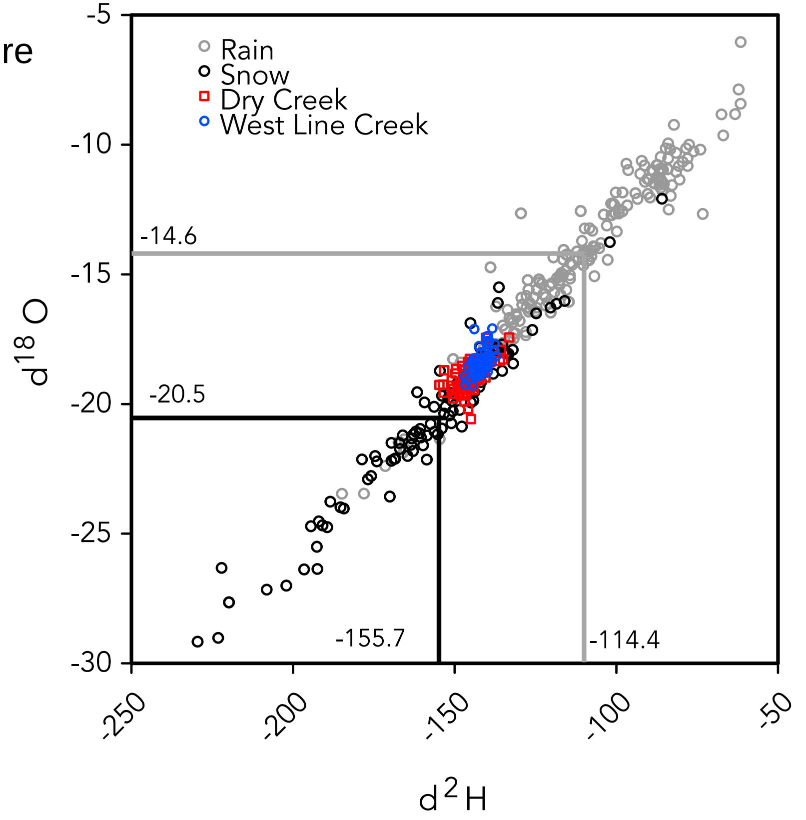
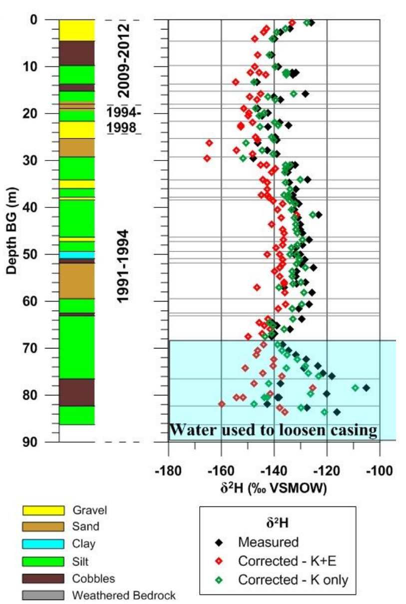
Stable Isotopes

Reference Core





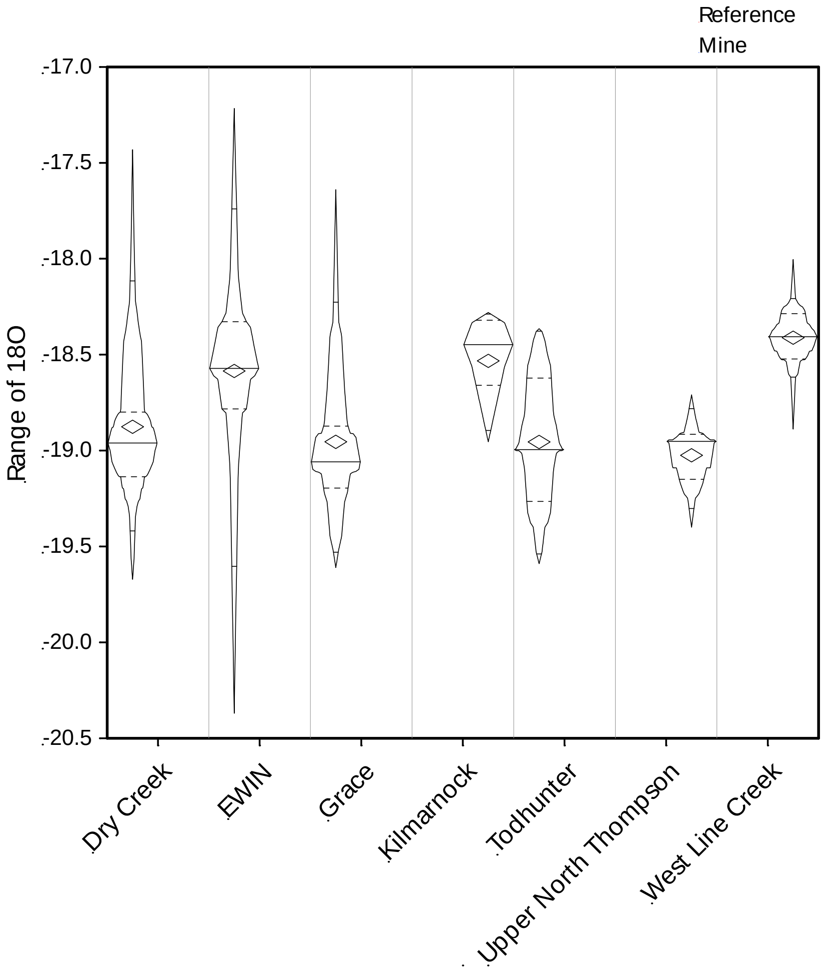
Waste Rock Core



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

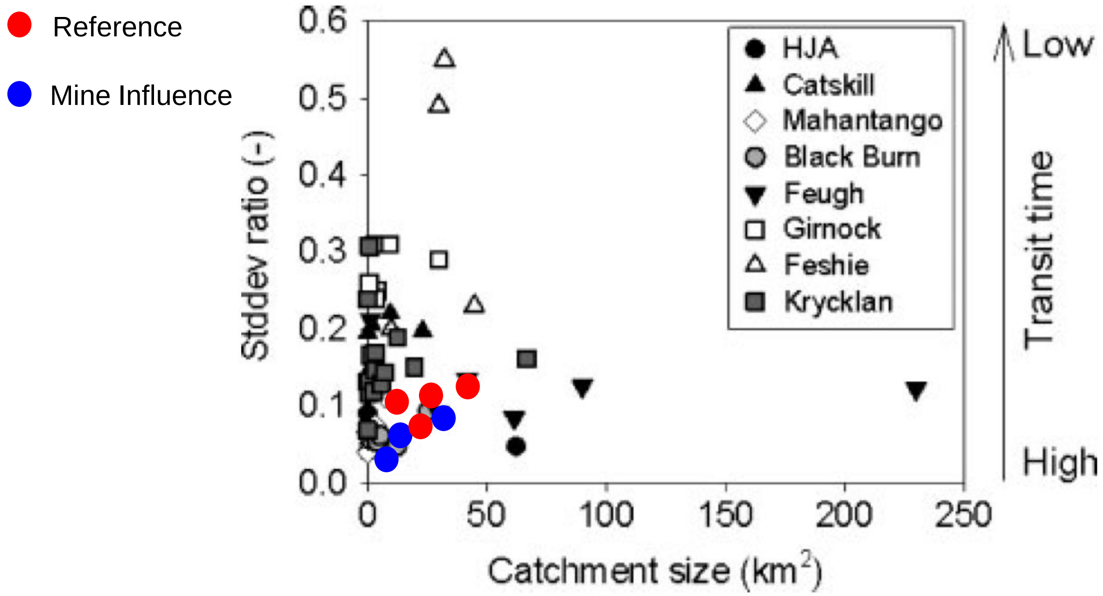


Figure 5. Relationship between catchment size and the inverse transit time proxy ITTP (ratio of standard deviations of $\delta^{18}O$ measurements of stream water to precipitation) for the eight catchments and their associated sub-catchments

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]

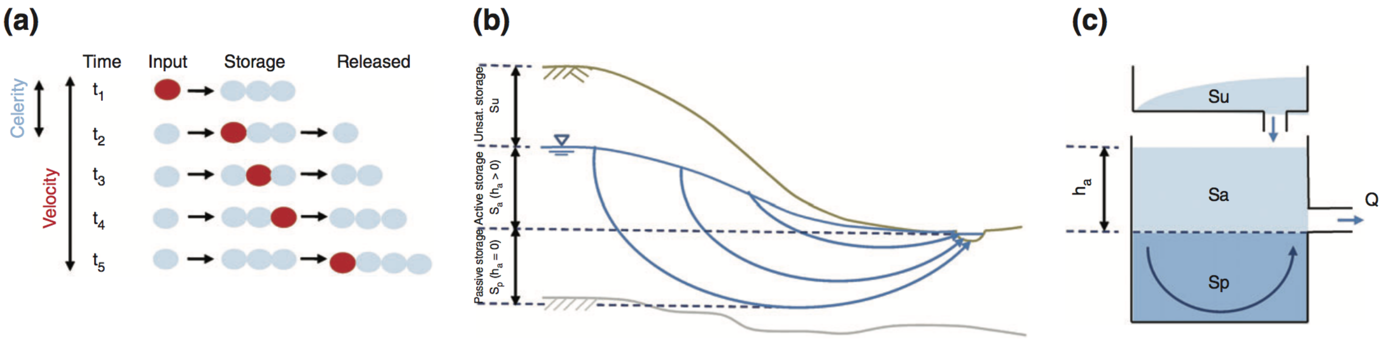
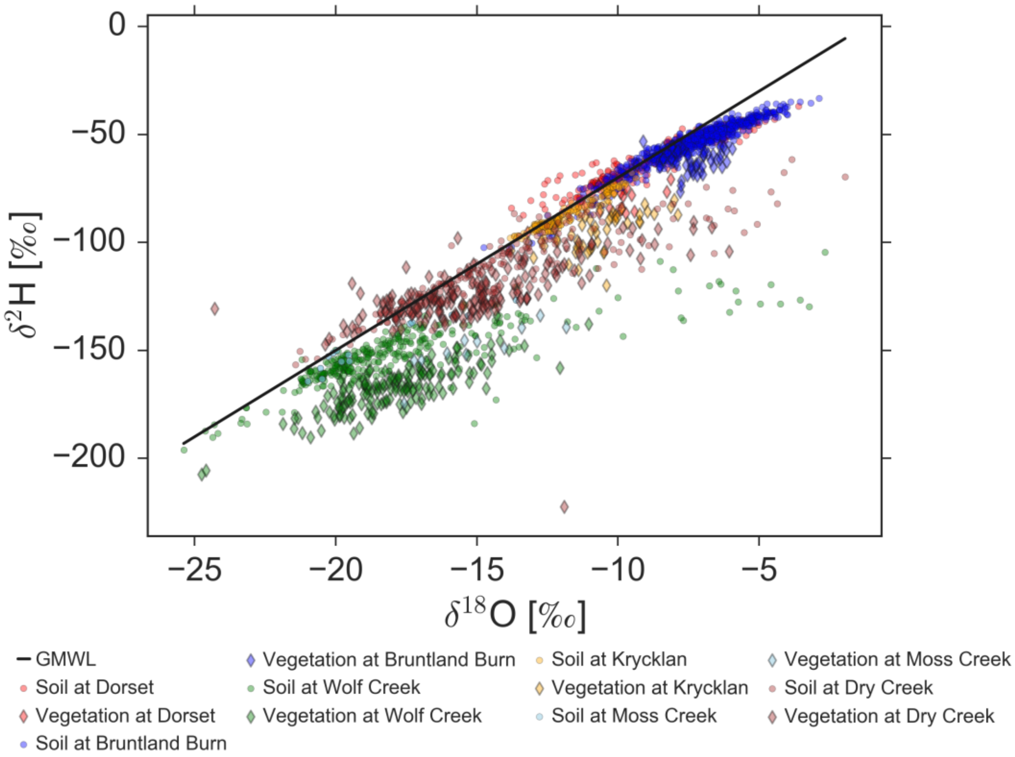
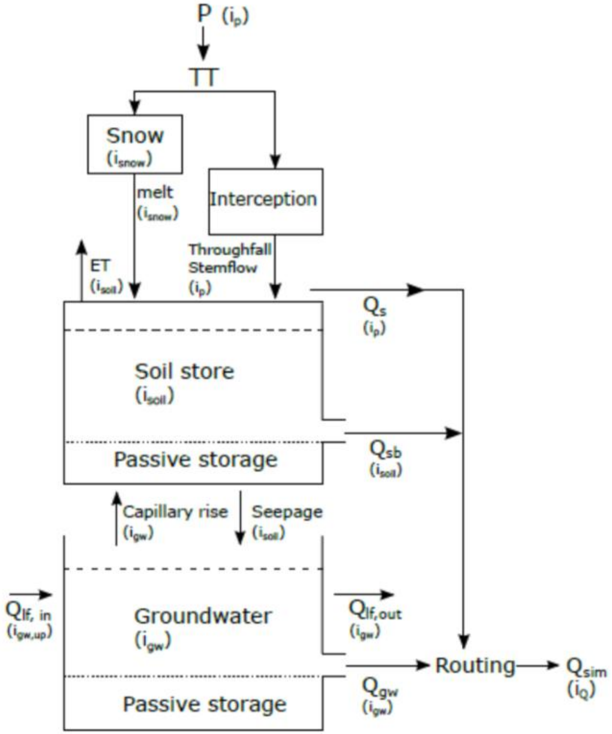


FIGURE 2 | (a) Conceptualization of the difference between celerity-driven hydrological response and velocity-driven transport processes using the analogy of a game of billiards. A new input at t_1 (red ball) causes a disturbance of the system that propagates with a celerity and that generates a response (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.

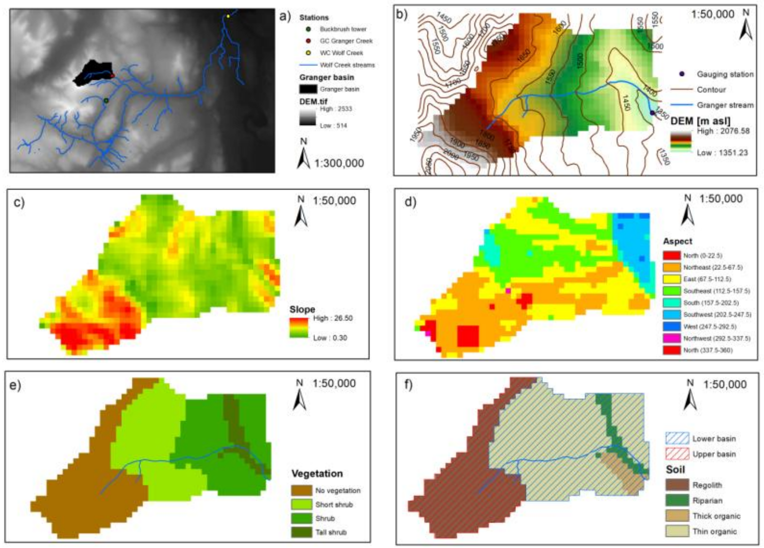
Stable isotopes of water

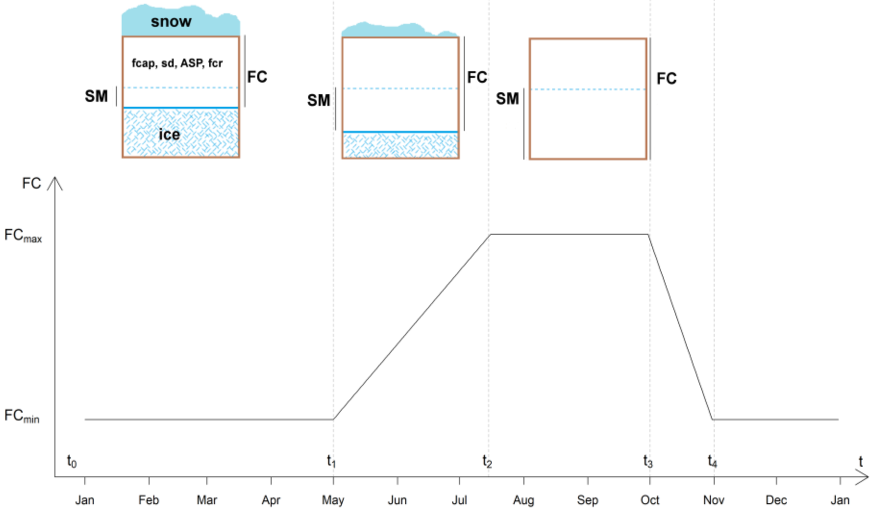




- VEWA – International inter-comparison project with common methodologies to trace water and isotopes through the soil-plant-stream continuum.

Isotope-aided models

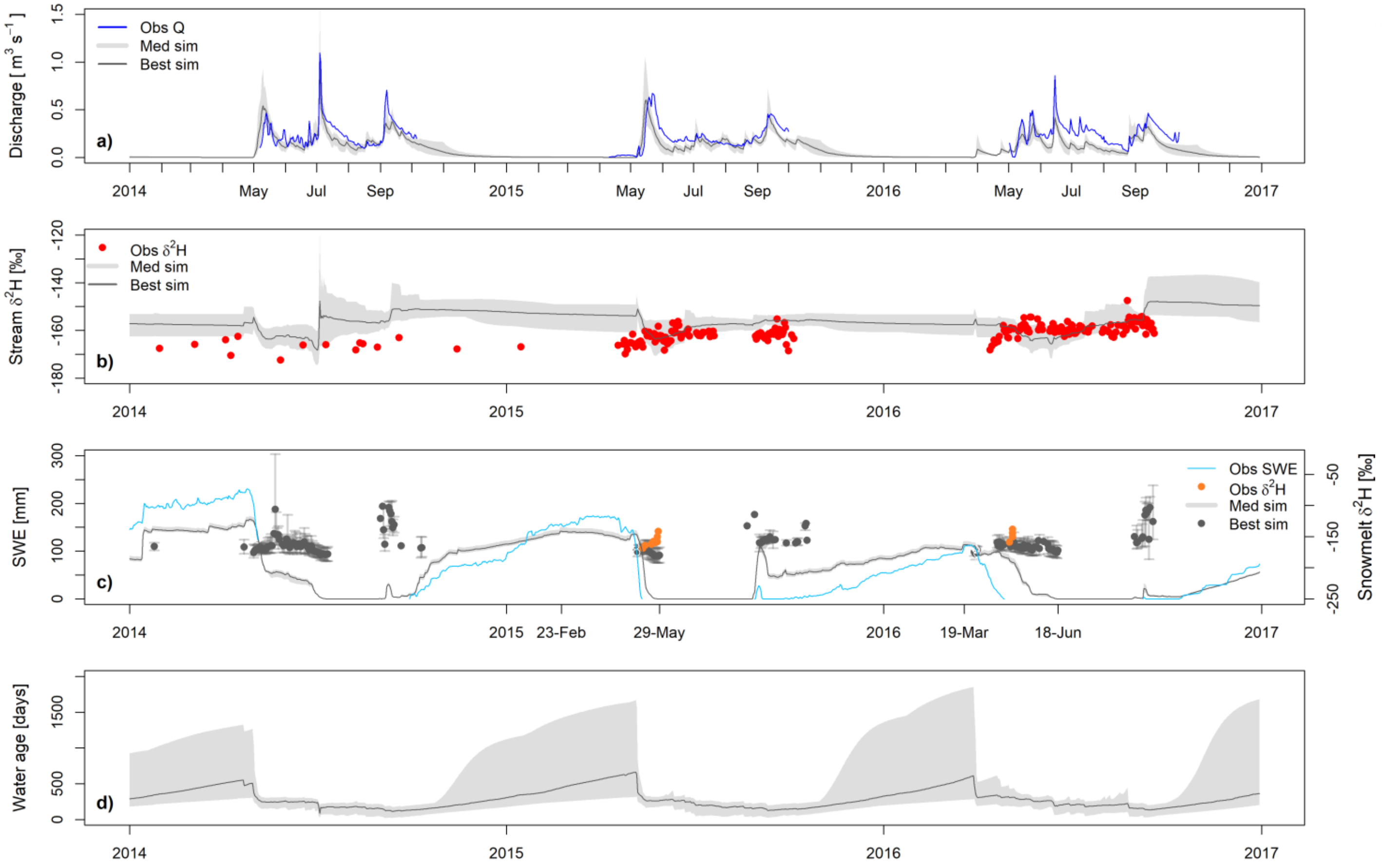




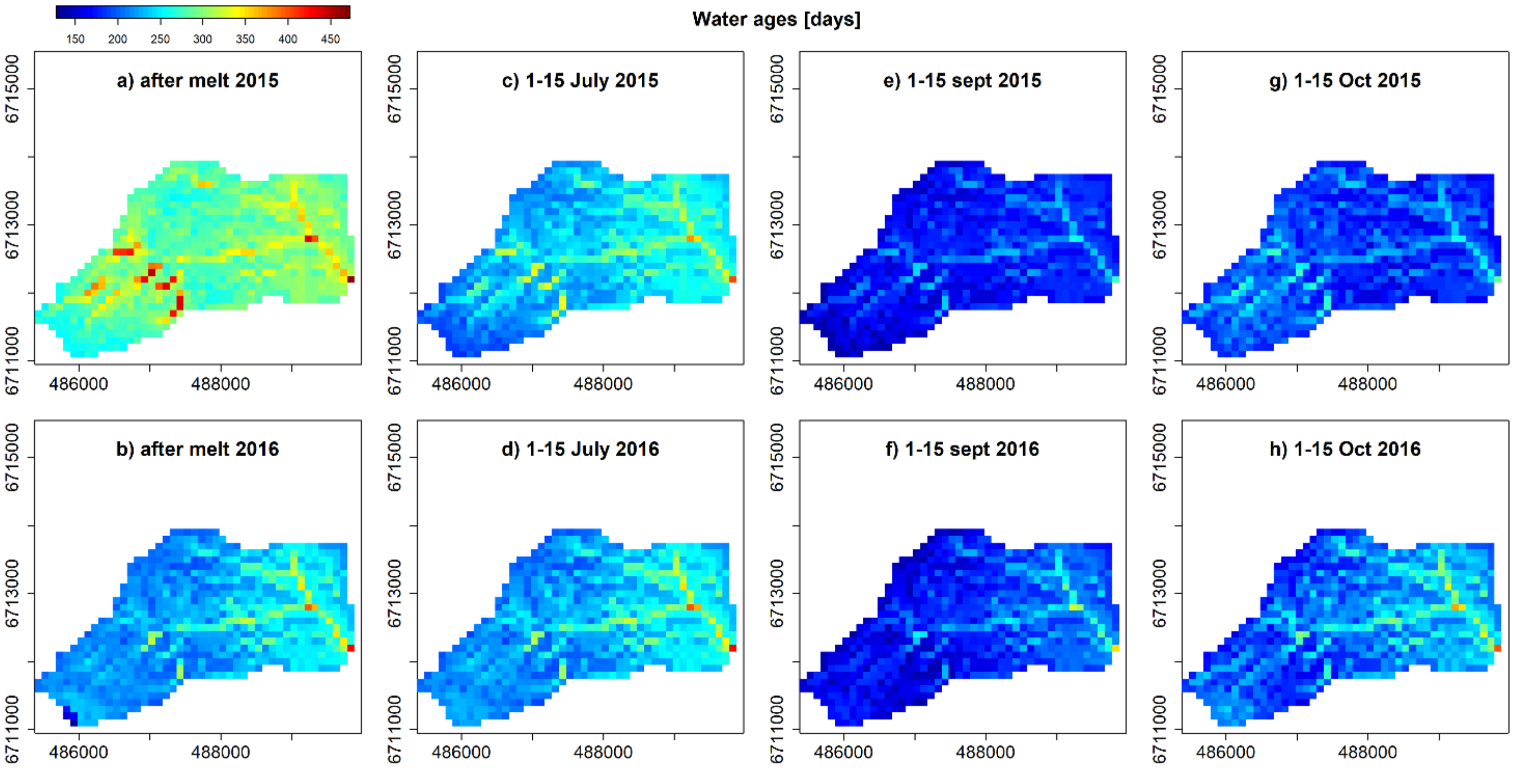
STARR - Ala-aho et a. (2017)

Runoff Processes in Alpine Catchments: Challenges and Opportunities

Isotope-aided models



Isotope-aided models



Thank you!