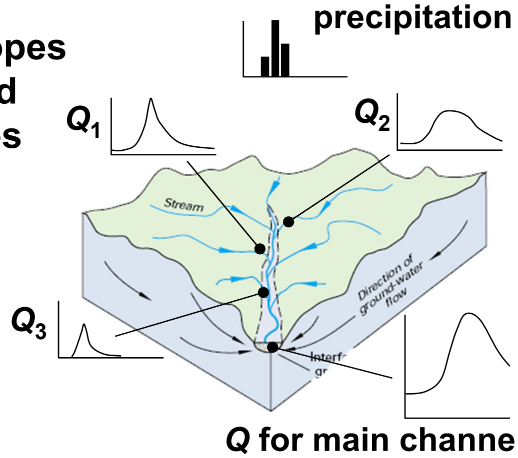
Hillslope Hydrology

Streams are the 'conduits' of the surface and subsurface runoff generated in watersheds. SW-GW interaction needs to be understood from the watershed perspective.

During a storm event, different hillslopes generate runoff at different timing and amounts. The main channel integrates hillslope inputs.

Hydrology of 1st-order streams are controlled by hillslope processes. Channel processes are more important in higher-order streams.



Objectives

1. **Understand hillslope runoff processes.**
2. **Understand the contribution of groundwater to storm runoff.**

Runoff mechanisms

In this lecture, we take a broad view of hillslope – any parts of a watershed that can potentially generate runoff.

'Rain' in the following refers to the fraction of rain that reaches the ground after interception loss.

1. Horton overland flow, or infiltration excess overland flow

The rainfall intensity exceeds the infiltrability of soil surface, even though the underlying soil is still unsaturated (see next page).

The lower bound of soil infiltrability is the saturated hydraulic conductivity, which is usually > 10^{-5} m s^{-1} in undisturbed soil. Rainfall intensities of most storm events are smaller than 20-30 mm/hr.

→ Horton overland flow is rare in most environments.

Exceptions?

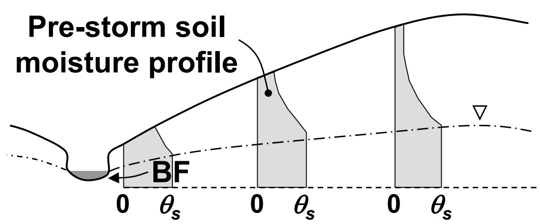
Horton overland flow during an intense (≅ 50 mm/hr) rain event in Tanzania.

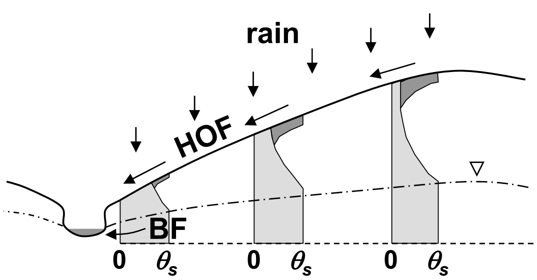
Soil was unsaturated under the sheet flow.

Horton overland flow over the frozen soil near Calgary, Canada

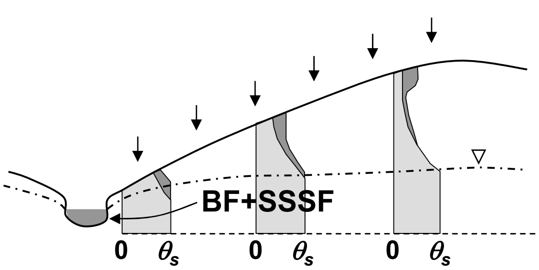
2. Subsurface storm flow

During non-storm periods, the flow of 1st order stream is sustained by baseflow (BF).





Horton overland flow (HOF) may occur when the soil surface is severely disturbed or frozen, but such cases are rare.

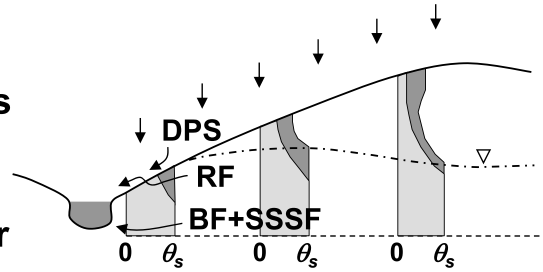


Modified from Dunne and Leopold (1978. *Water in Environmental Planning*. p.263)

Infiltration causes the WT to rise, particularly in the areas where the capillary fringe is close to the surface. This increases the hydraulic gradient, resulting in subsurface storm flow (SSSF).

3. Saturation overland flow

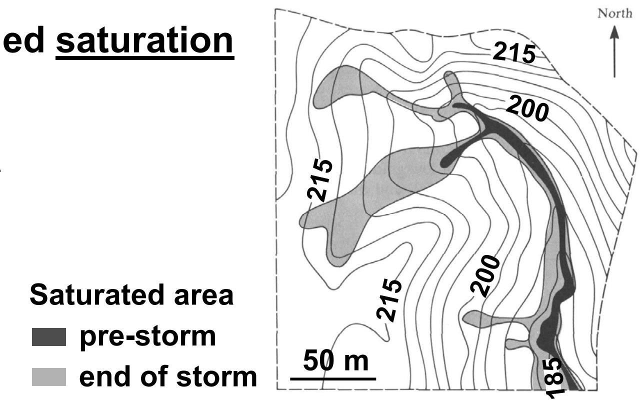
As the storm continues, the WT keeps rising and eventually reaches the surface in riparian areas. This causes a further increase in SSSF, and return flow (RF) of groundwater to the surface.



In addition. any rain falling on saturated areas becomes surface runoff, called direct precipitation onto saturated area (DPS).

The sum of RF and DPS is called <u>saturation overland flow</u>.

Saturated areas grow during a storm, meaning that runoff is generated in <u>variable source areas</u>. The extent of saturated areas also has seasonal variability.



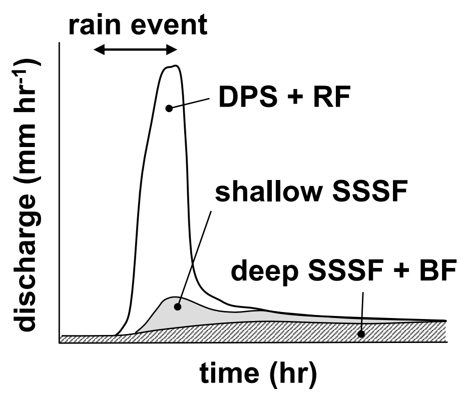
Modified from Dunne and Leopold (1978, p.268)

Contribution of surface and subsurface runoff

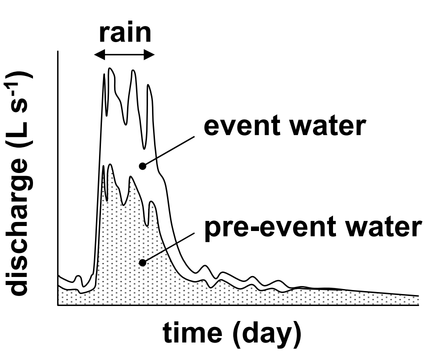
Different runoff mechanisms contribute different amounts (and quality) of water at different timing.

Return flow (RF), subsurface storm flow (SSSF), and baseflow (BF) all occur under the WT. → Groundwater!

The physical distinction between storm flow and baseflow is fuzzy.



Modified from Dunne & Leopold, p.266.



Modified from Buttle (1994. *Progress in Physical Geography*, 18:26)

Using stable isotopes (^{2}H, ^{18}O), 'event' water, resulting from the storm, can be distinguished from pre-event water from the storage.

Pre-event water contributes typically 50-75 % of storm flow in low-order watersheds (e.g., Buttle, 1994).

There must be some processes that push the pre-event water very quickly from the soil (and groundwater) to streams. One of the biggest challenges in today's hillslope hydrology is to understand these processes (Weiler and McDonnell, 2004. *J. Hydrol*. 285: 3-18).

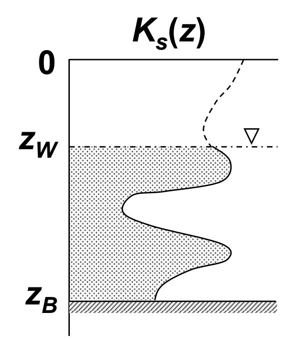
Transmissivity feedback

In classical hydrogeology, transmissivity T ($m^2\ s^{-1}$) is defined by:

$$T = K_s \times \text{(aquifer thickness)}$$

When $K_s(z)$ varies with depth, the definition is modified to:

$$T(z_W) = \int_{z_W}^{z_B} K_s(z)dz$$

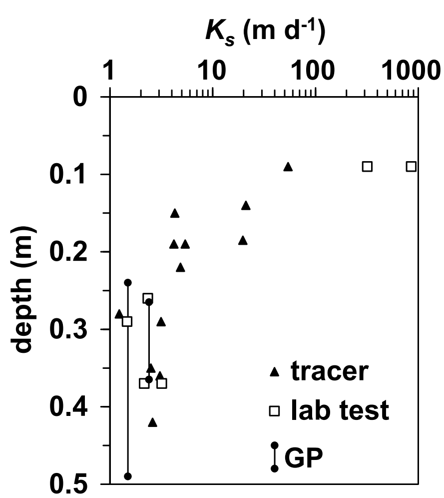


K_s is integrated from the WT to a relatively impermeable surface, e.g., unweatherd bedrock, clay, permafrost, etc. Note that T increases as the WT rises toward the surface.

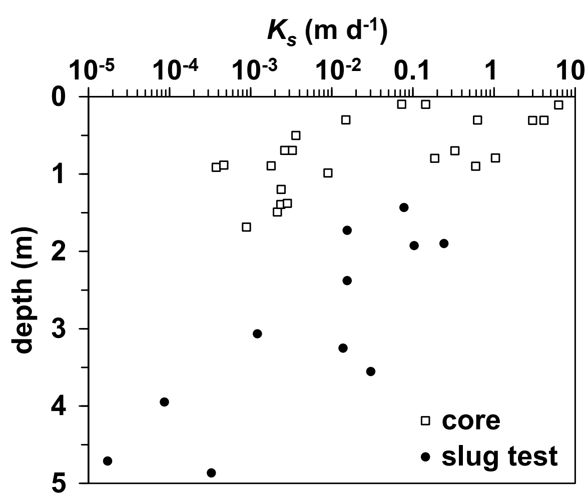
Why do we not include unsaturated K?

In general K_s in shallow (< 5 m) sediments decreases with depth (e.g., Buttle, 1994). Below are examples of organic soils from the subarctic region (left) and glacial tills from the prairie region (right) in Canada, measured by various methods.

K_s decreases dramatically with depth.
→ $T(z_W)$ is very sensitive to z_W, especially near the surface.

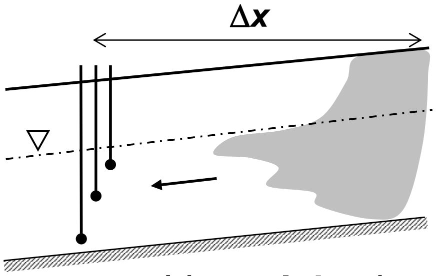


Quinton et al. (2008. *Hydrol. Process*., 22:2829)



Parsons et al. (2004. *Hydrol. Process*., 18:2011)

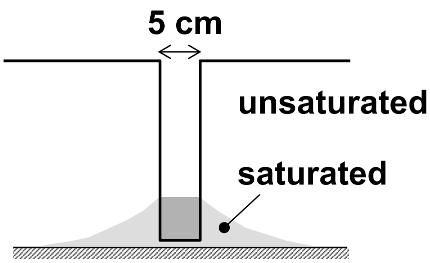
Tracer Tests
(Quinton et al., 2008)



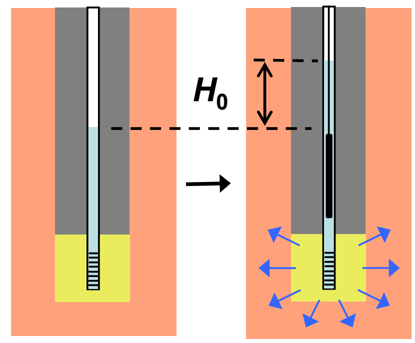
$v = \Delta x$ / (travel time)
$n_p v = K_s \, \Delta h/\Delta x$
$K_s = n_p v \, / \, (\Delta h/\Delta x)$

Lab tests: 'Cube' method
(Beckwith et al. 2003, *Hydrol. Process.*, 17: 89)

Guelph permeameter (GP)
Hayashi & Quinton (2004. *Can. J. Soil Sci.*, 84: 255)



Piezometer slug test

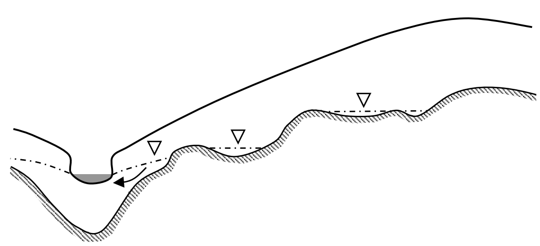


In many hillslope studies, K_s was shown to be very high near the surface due to macropores, piping, etc., and decrease exponentially.

→ Rapid rise in the WT during a storm causes a fast flow of pre-event water. This is called <u>transmissivity feedback</u>.
(e.g., Bishop et al., 2011, *Hydrol. Process*. 29: 3950-3959)

<u>Fill and spill mechanism</u>

Hillslopes commonly have relatively impermeable boundaries restricting groundwater flow, such as unweathered bedrock.



The storage in bedrock 'hollows' must be filled to the top before the continuous flow pathways for subsurface storm flow (and return flow) develop.

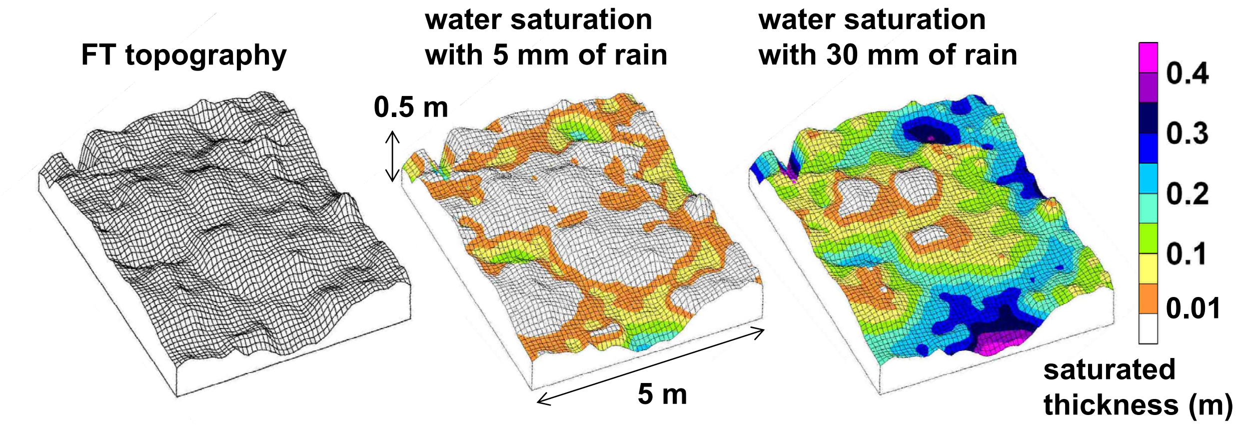
This process is called 'fill and spill' runoff in the recent literature.
(e.g. Freer et al., 2002: *Water Resour. Res.*, 38, 1269; Spence and Woo, 2003. *J. Hydrol.*, 279: 151).

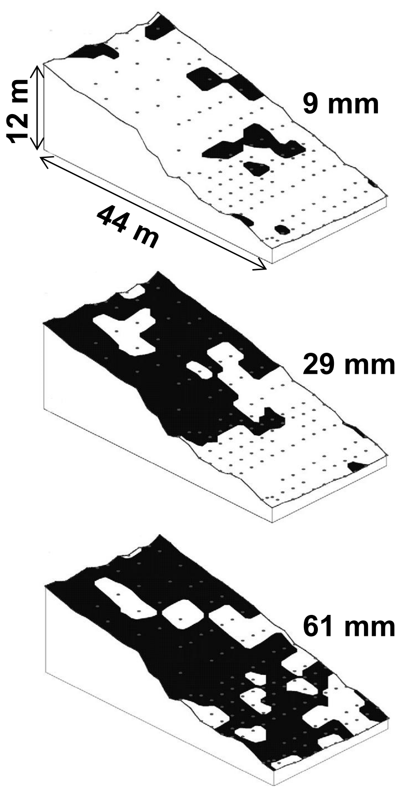
Scotty Creek watershed in Northwest Territories, Canada

This hillslope is underlain by permafrost, which thaws in summer to 0.5-1 m below the ground surface.

The frost table (FT) has irregular shape.
(Wright et al., 2009. *Water Resour. Res.*, 45: W05414)

Fill-and-spill model simulations for a gentle slope (not in the photo) is shown below.

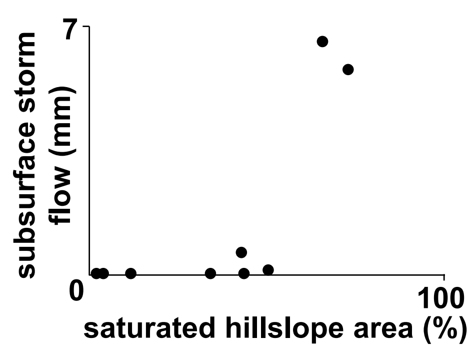




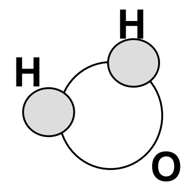
Detailed study in Panola Mountain watershed in Georgia, USA (Tromp-van Meerveld and McDonnell, 2006. *Water Resour. Res.*, 42, W02411).

Larger storm events caused saturation of larger areas of bedrock hollows and channels.

There seems to be a threshold (50%?). Above this value, subsurface channels may become connected.



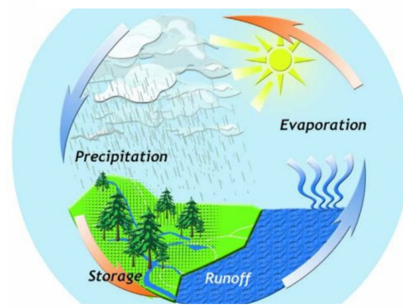
Stable isotope ratio in natural water



Water is H_2O.
H has an atomic weight of 1, O has 16.
→ 1+1+16 = 18 for 'normal' water.

Some O has a weight of 18 → ^{18}O isotope.

Isotope concentration is a natural tracer of water through the hydrologic cycle.



http://www.gewex.org

Concentration of stable isotopes is given by the molecular ratio:

e.g., R_{18} = (# of $H_2{}^{18}O$ molecules) / (# of $H_2{}^{16}O$ molecules)

The ratio is expressed using the δ-notation:

$$\delta^{18}O = [(R_{18} - R_{18\_VSMOW})/R_{18\_VSMOW}] \times 1000 \quad (‰)$$

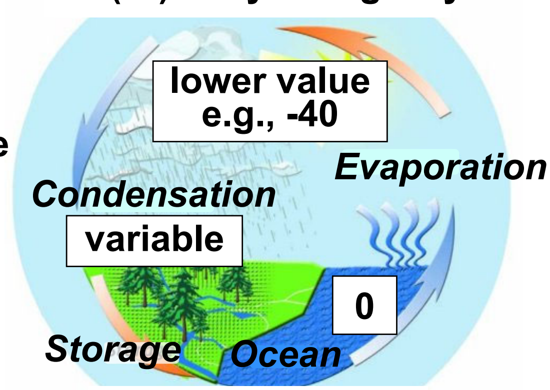
where R_{18_VSMOW} is the isotope ratio in the Vienna standard mean ocean water (VSMOW).

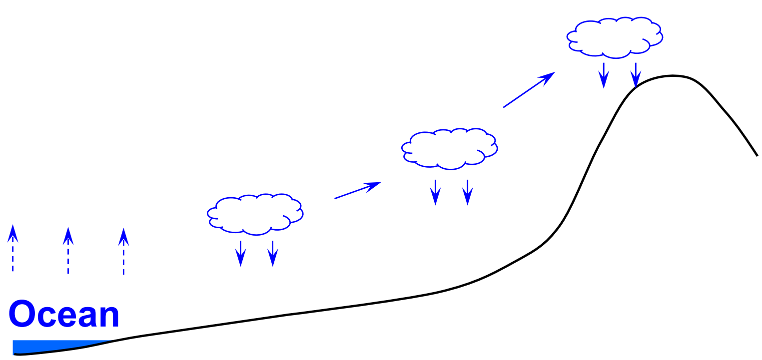
Isotopic fractionation

- **Lighter molecules ($H_2{}^{16}O$) evaporate more easily.**
- **Heavier molecules condensate more easily.**
  → Shift in $\delta^{18}O$, called fractionation

Degree of fractionation depends on:
- **Temperature (season)**
- **Geographic setting (e.g., altitude)**

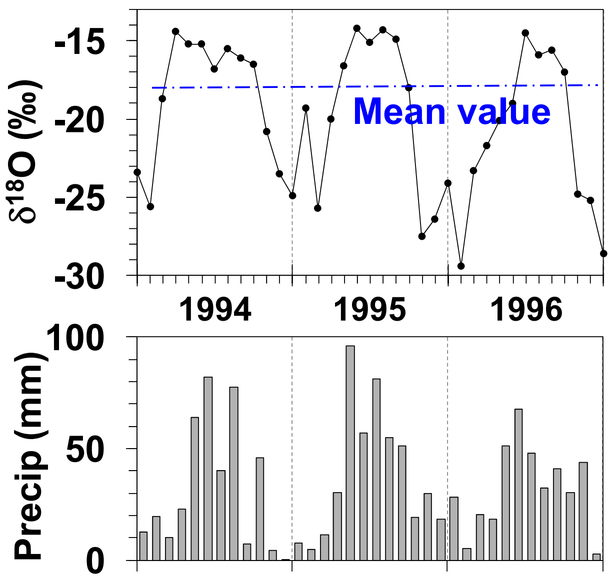
$\delta^{18}O$ (‰) in hydrologic cycle





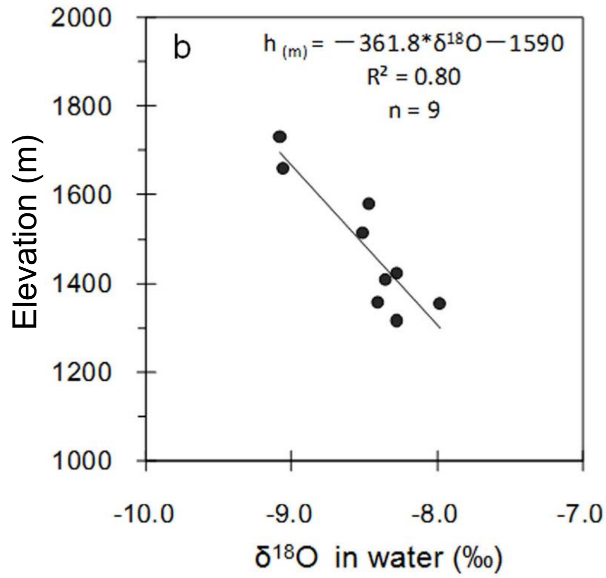
Examples of isotope ‘signature’

Precipitation in Calgary, Canada



Peng et al. (2004. *Tellus* 56B:147-159)

Springs in Kathmandu Valley, Nepal – Altitude effects



Tanaka et al. (2012. *Kathmandu Valley Groundwater Outlook, Ch.5*)

Example of Stable Isotope Tracer

Groundwater Discharge from Rock Glacier

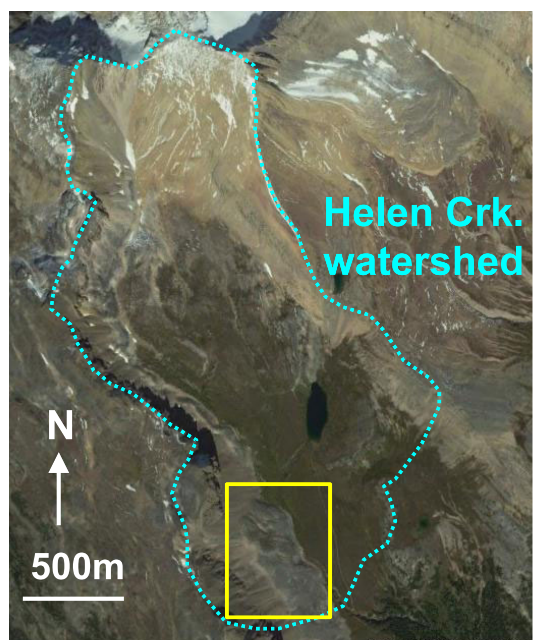
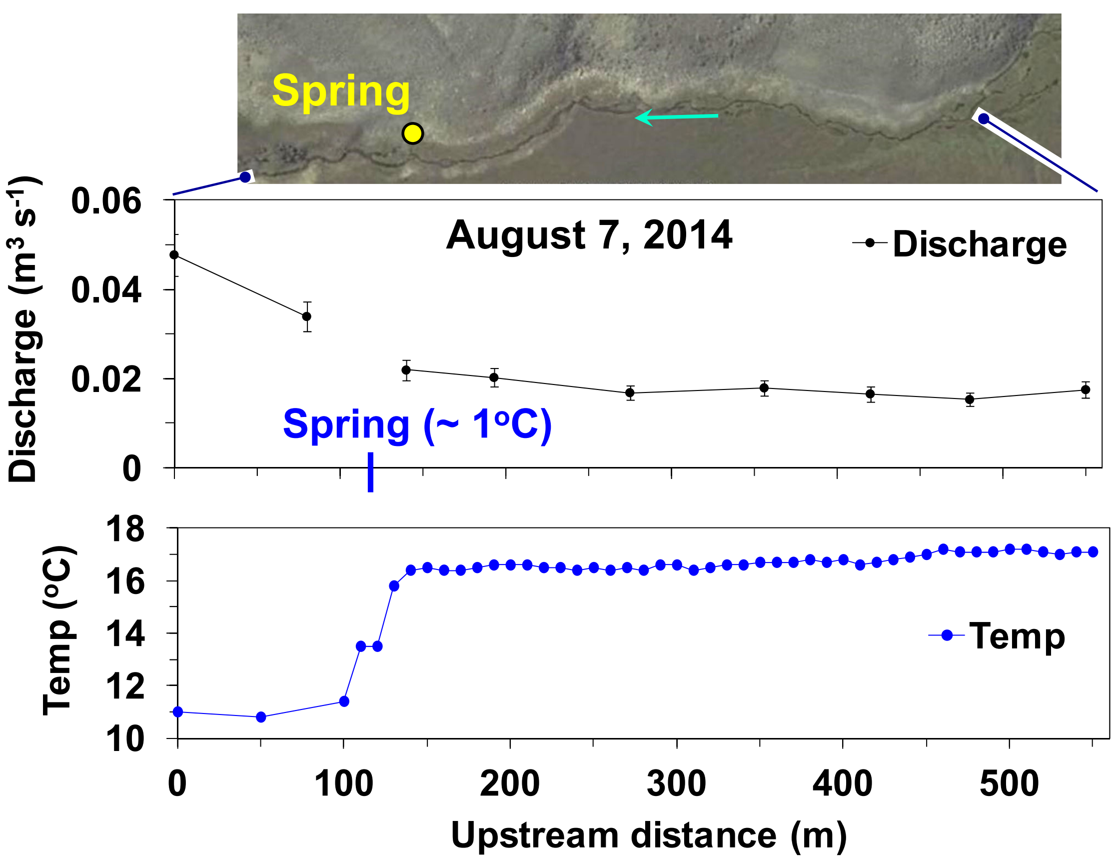
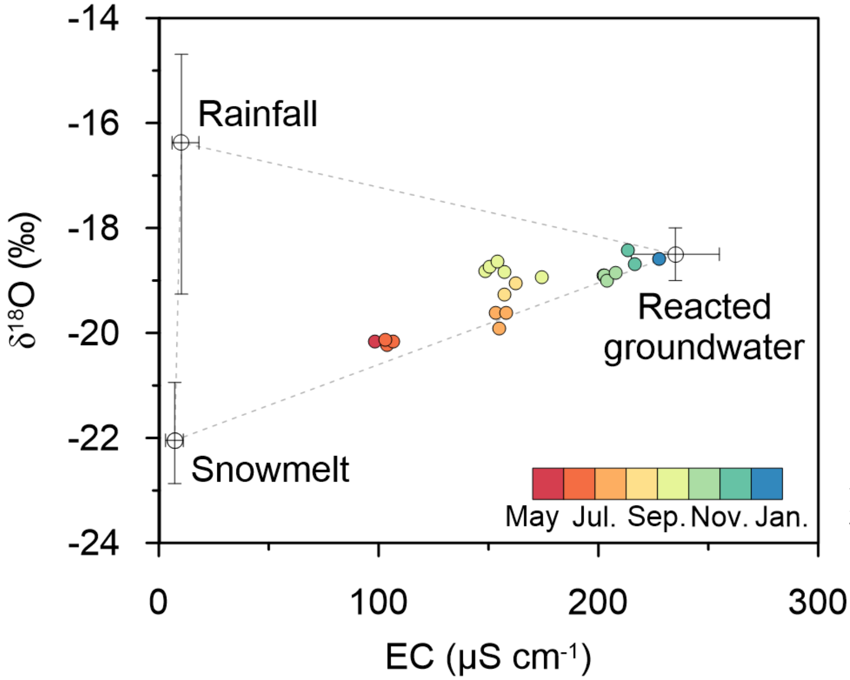


Image from Google Earth

Creek Discharge and Water Temperature



Three 'End-Members' of Spring Discharge



Harrington et al. (2018. *Hydrol. Process.* 32:3070-3088)

- **$^{18}O/^{16}O$ isotope ratio for snow/rain**
- **Electrical conductivity (EC) for residence time**