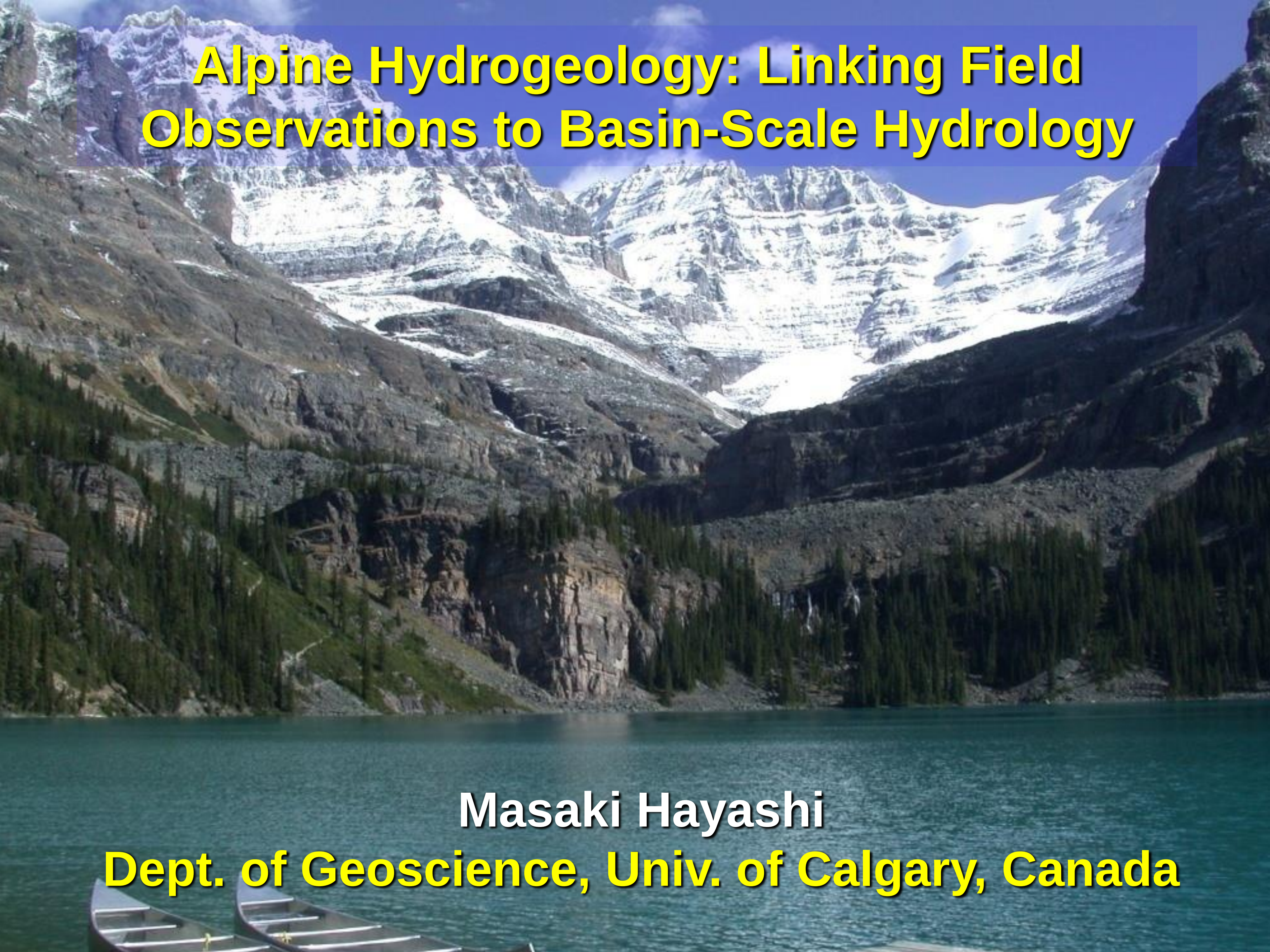


Alpine Hydrogeology: Linking Field Observations to Basin-Scale Hydrology

Masaki Hayashi
Dept. of Geoscience, Univ. of Calgary, Canada

Acknowledgements

Students, Technicians, Post-docs, Colleagues

Jaime Hood, Greg Langston, Danika Muir, Andrius Paznekas, James Roy, Alastair McClymont, Larry Bentley, Nathan Green, Kate Forbes, ….

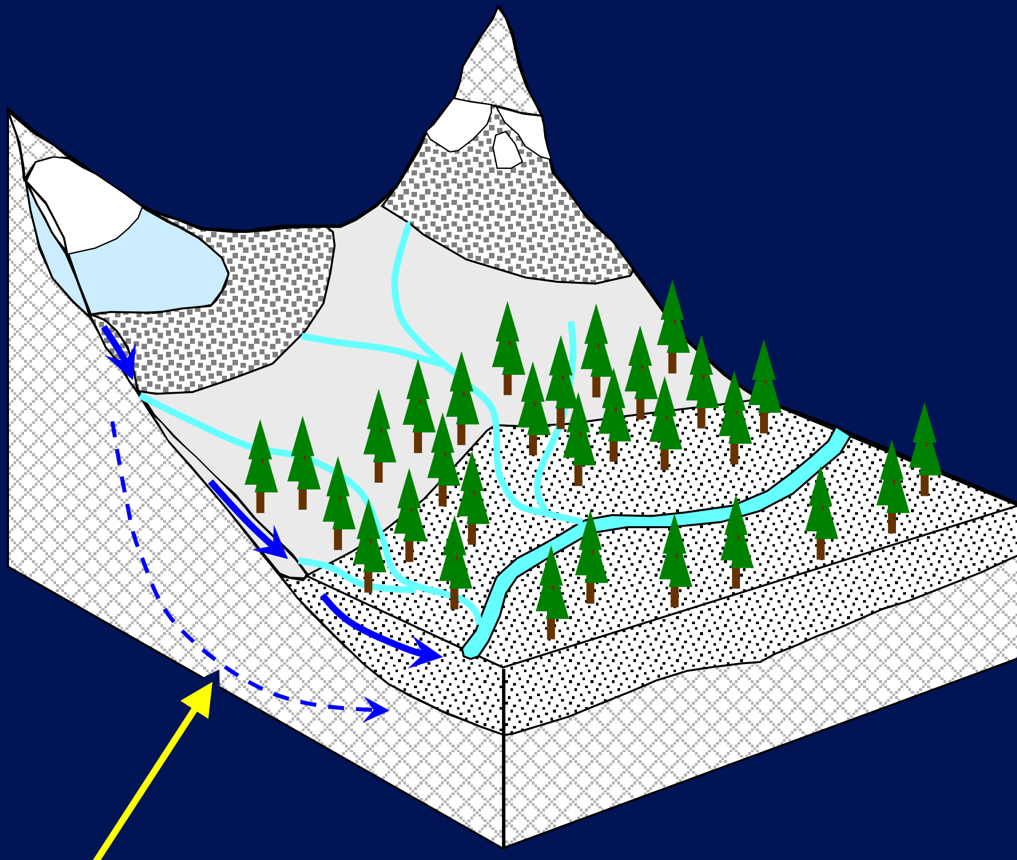
Funding Support

Biogeoscience Institute (Univ. of Calgary)
Alberta Ingenuity Centre for Water Research
Canadian Foundation for Climate and Atmospheric Science (IP3 Network)
Environment Canada

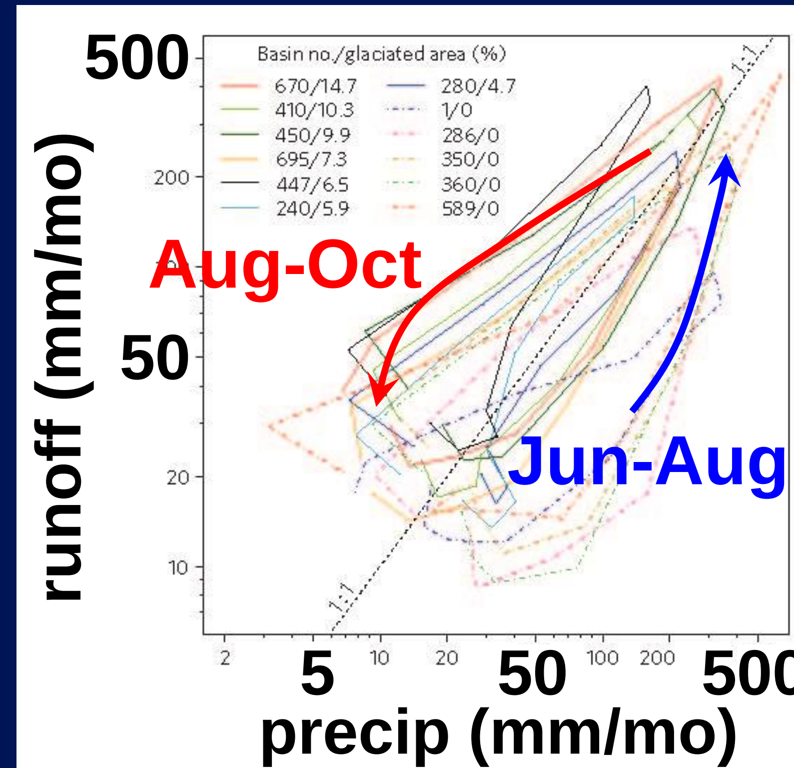
Logistical Support

Lake O’Hara Lodge
Parks Canada

Mountain Groundwater



Himalayan River Basins

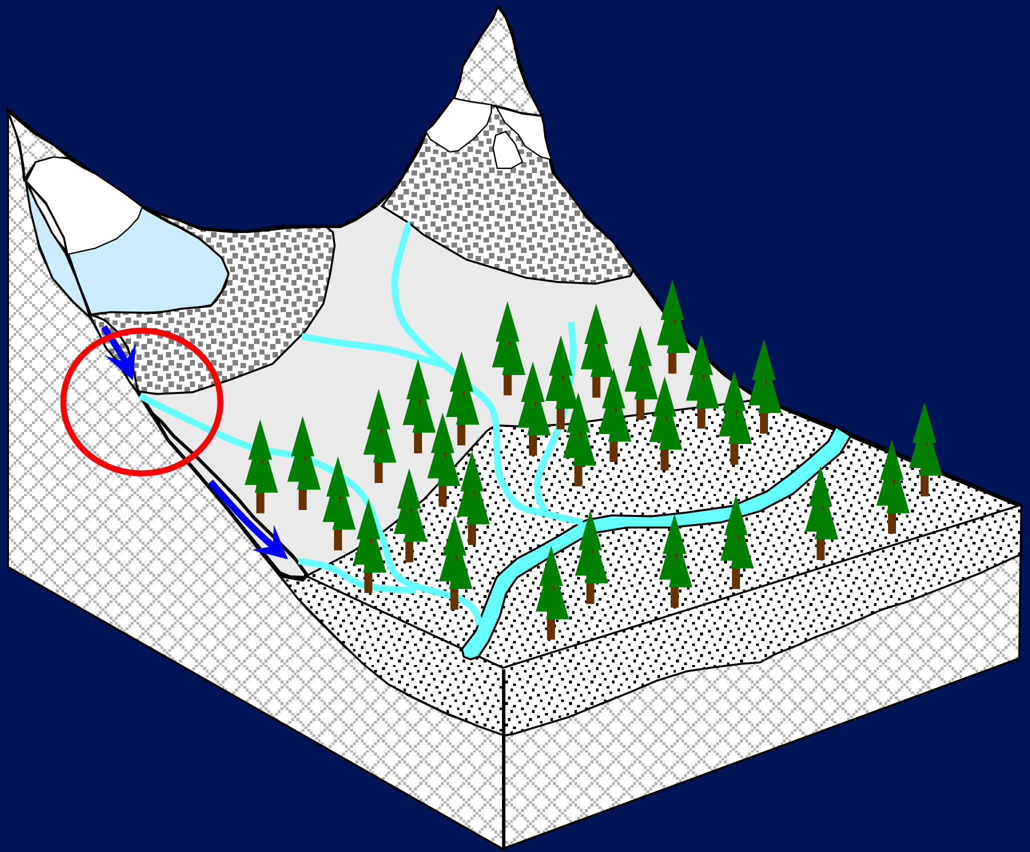


Andermann et al. (2013, *Nature GS*)

Mountain block recharge

- Manning and Solomon (2005, *Water Resour. Res*.)
- Ajami et al. (2011, *WRR*)
- Welch and Allen (2012, *WRR*)

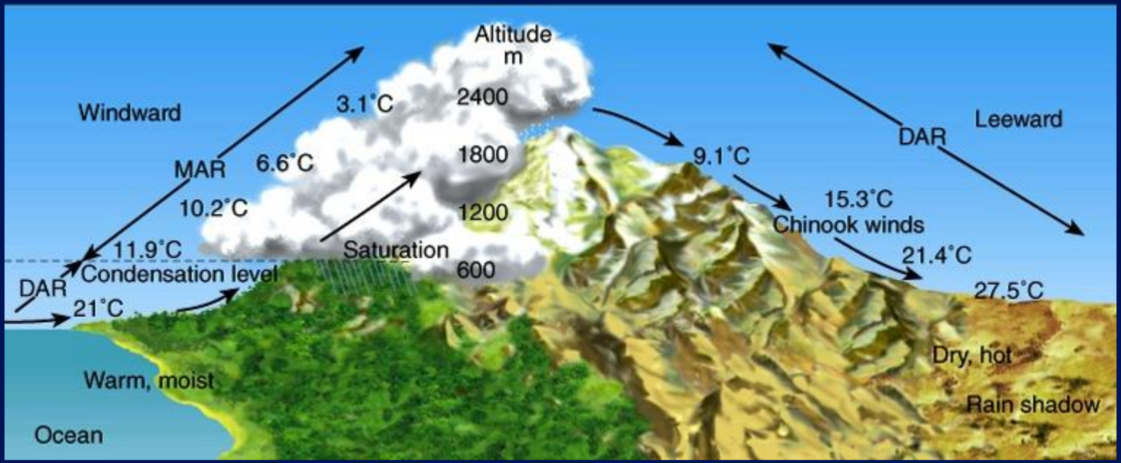
Mountain Groundwater



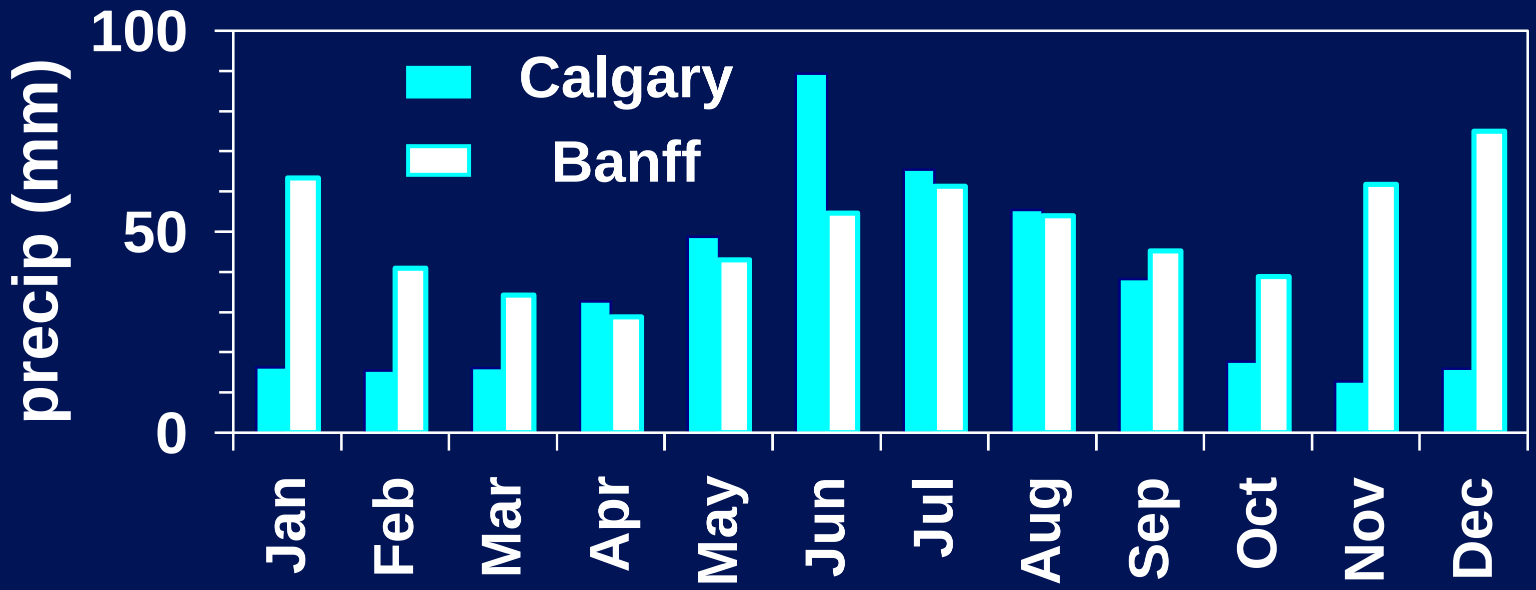
Alpine groundwater sustains critical habitats.

- **Lowry et al. (2011, *WRR*)**
- **Brown et al. (2009, *Freshwater Biol*)**

Mountains as 'Water Tower'

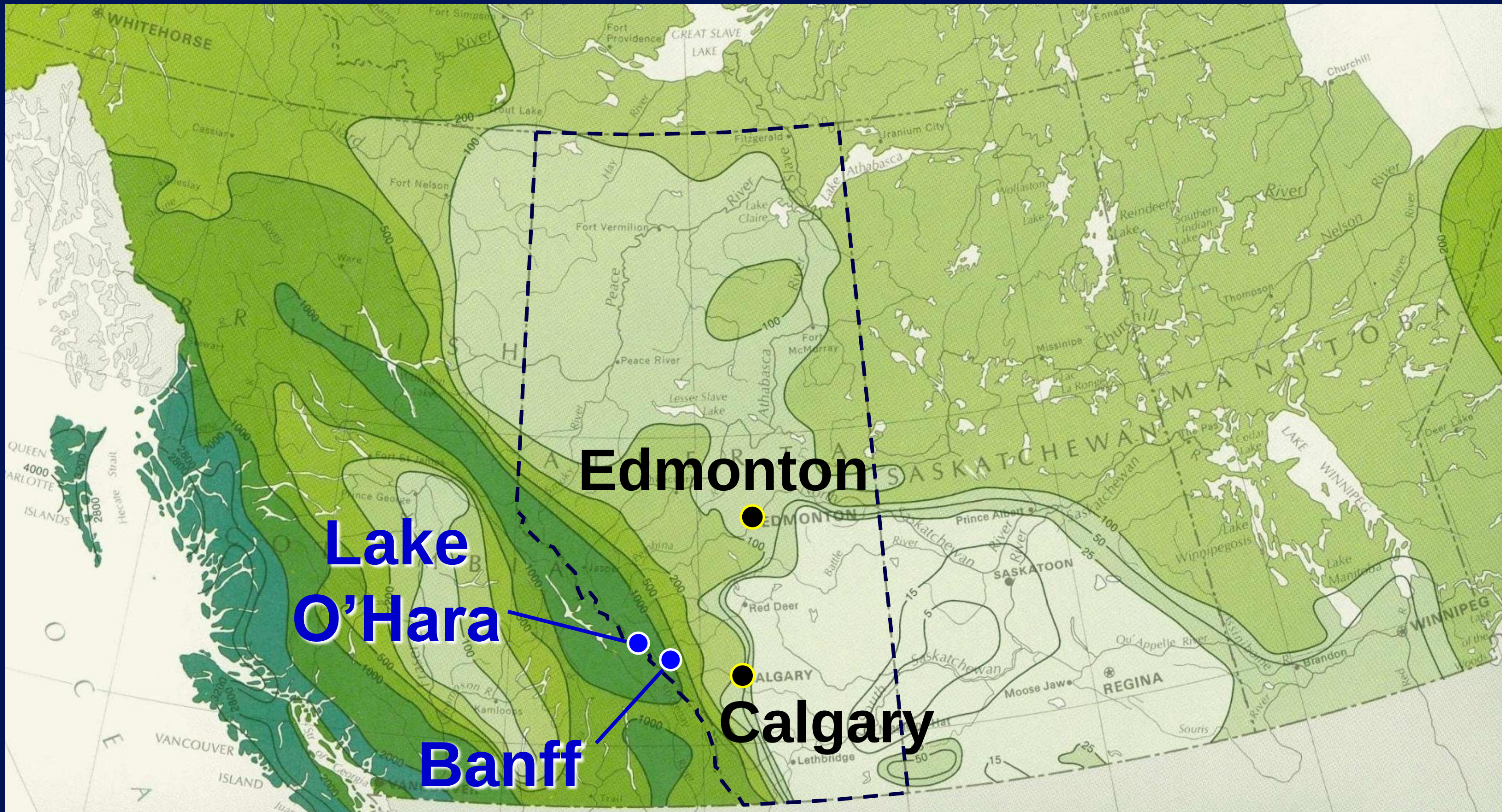


Christopherson (2000)



Mountain Rivers Provide Water Supply

Annual Average Runoff

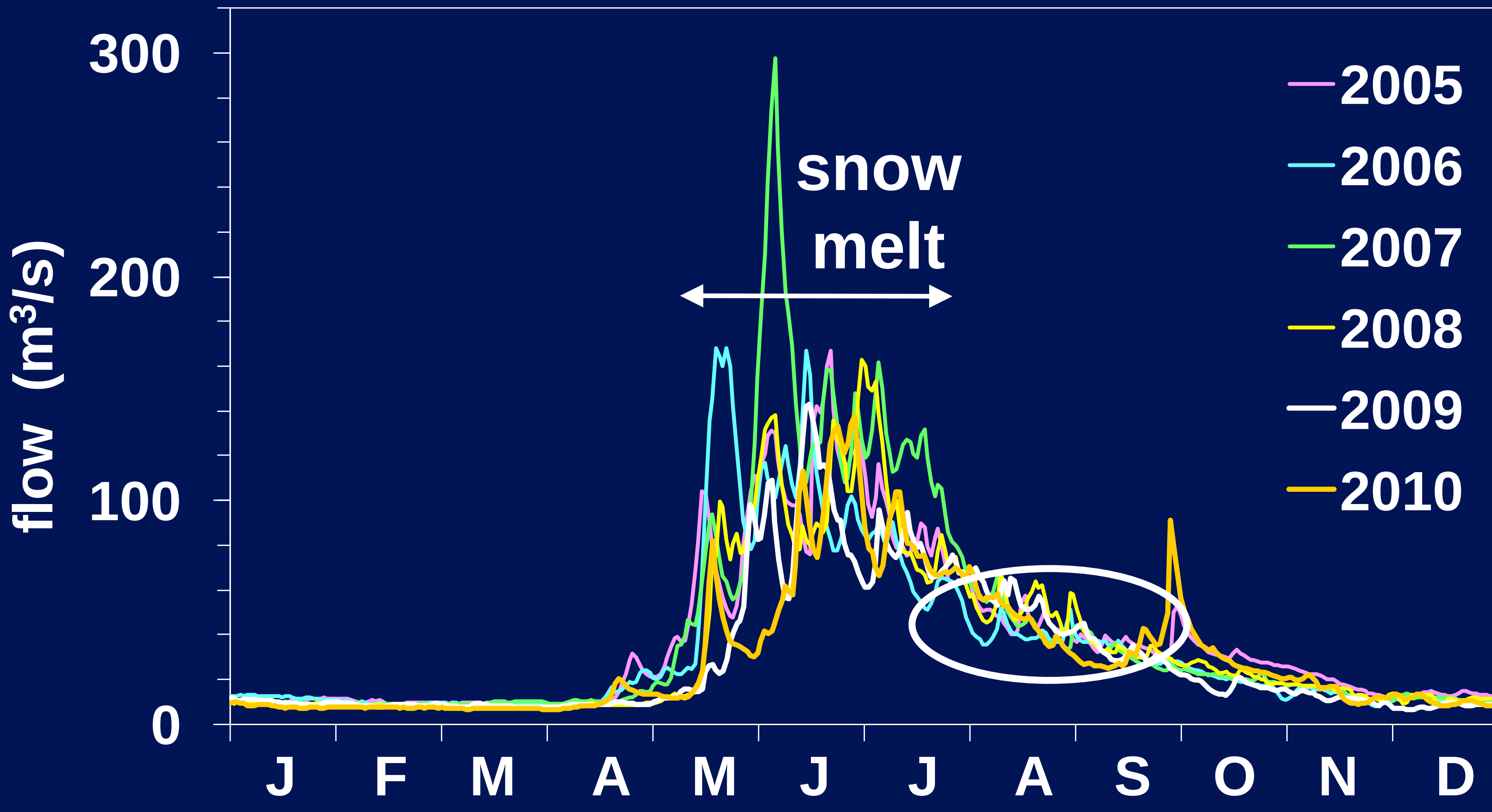


0 25 100 200 500 1000 2000 mm/yr

Hydrological Atlas of Canada (1978)

Bow River in the Canadian Rockies

Discharge at Banff (2200 km^2, unregulated)



Data: Water Survey of Canada

Lake O'Hara Hydrological Observatory (14 km^2)

Elevation: 2000-3500 m

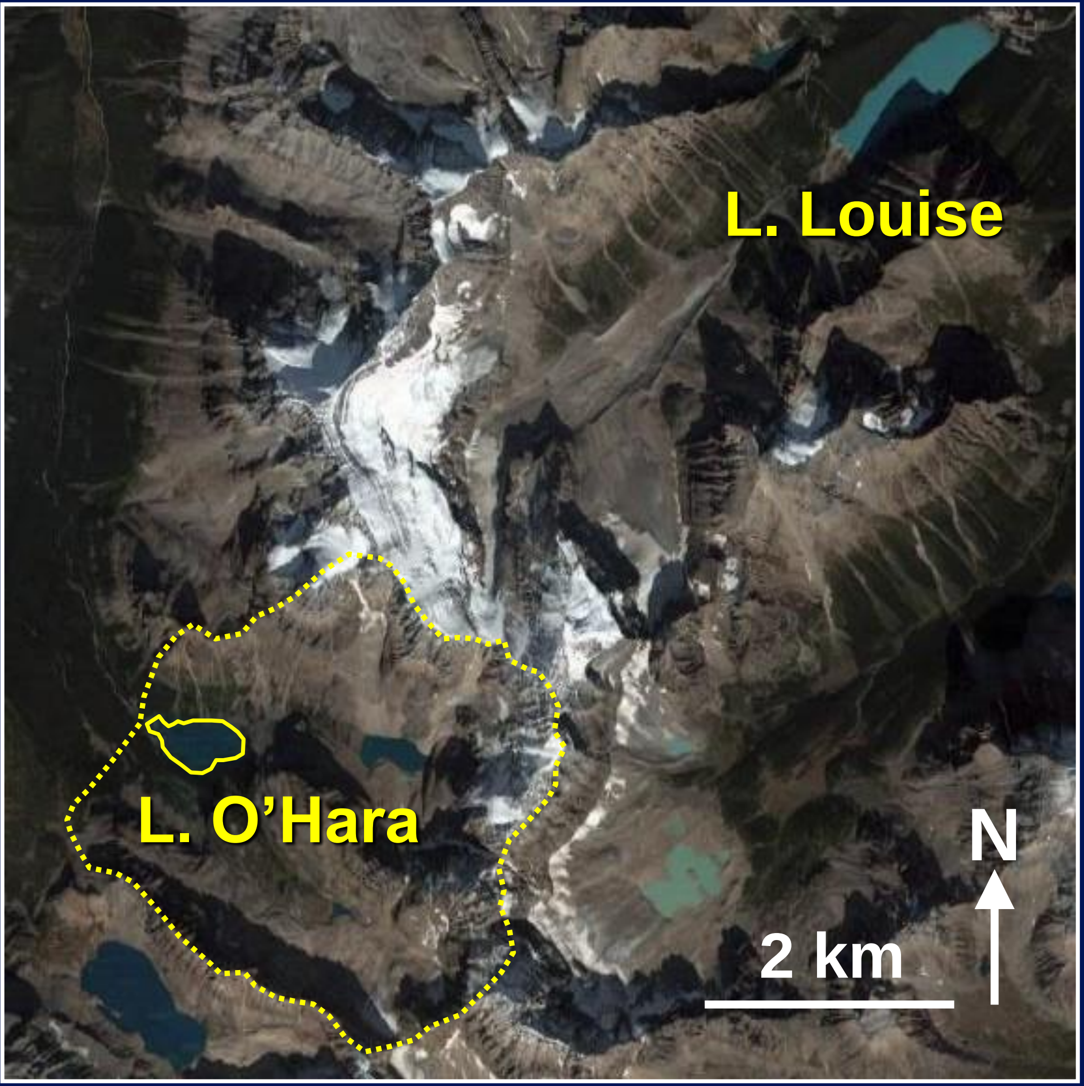
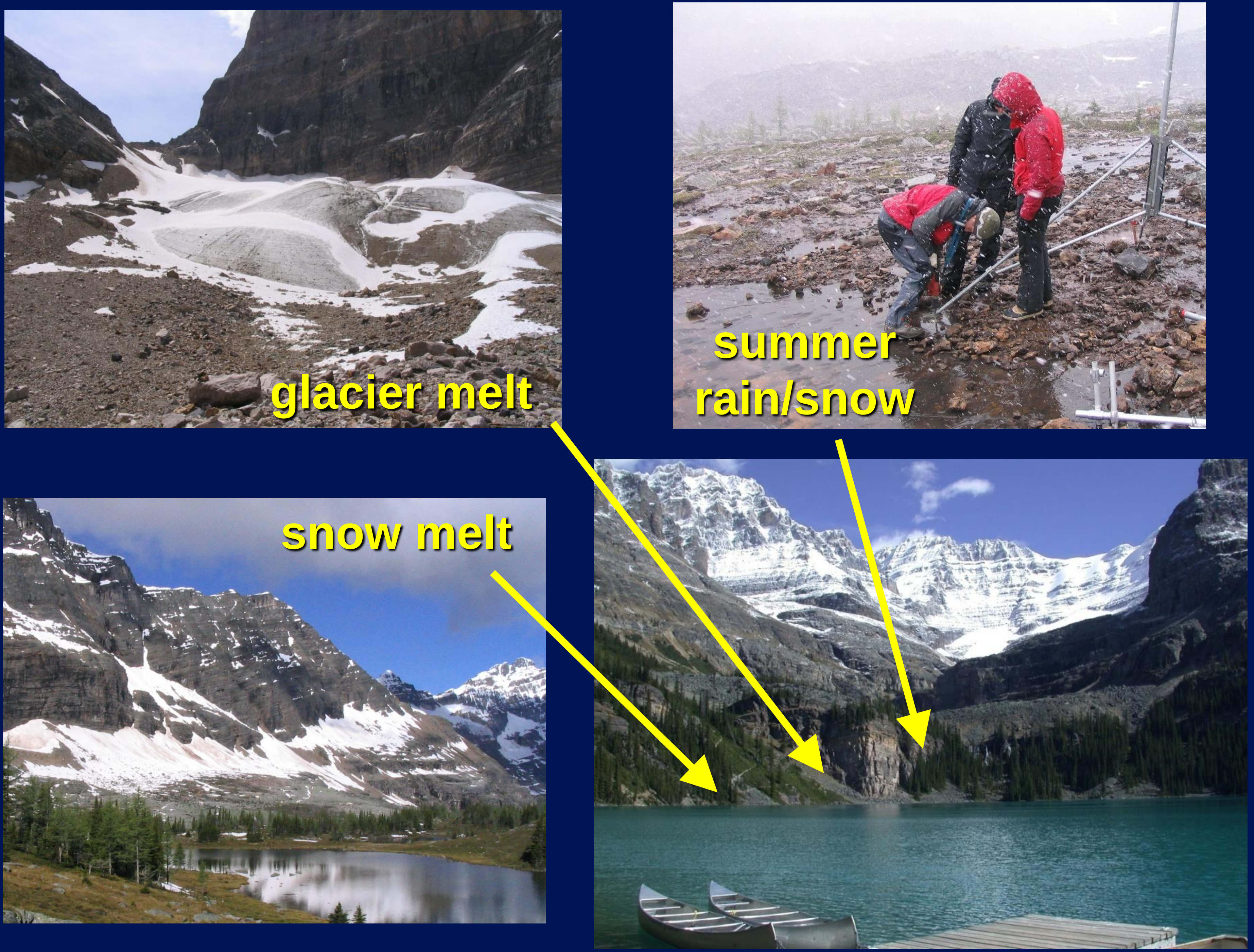
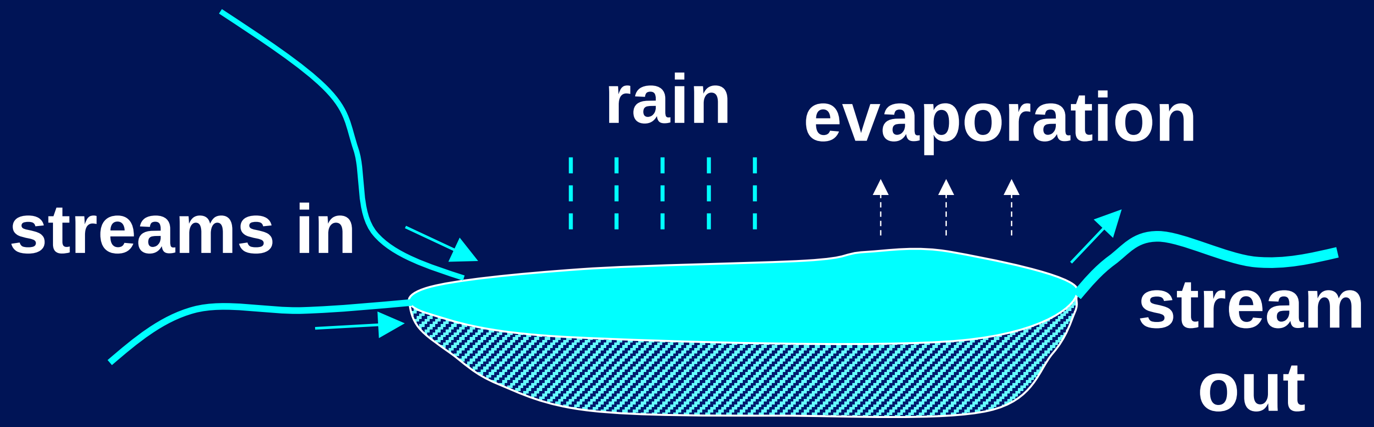


Image from Google Earth

- Weather stations
- Water level gauges
- Stream flow gauges
- Other instruments


glacier melt
summer
rain/snow
snow melt

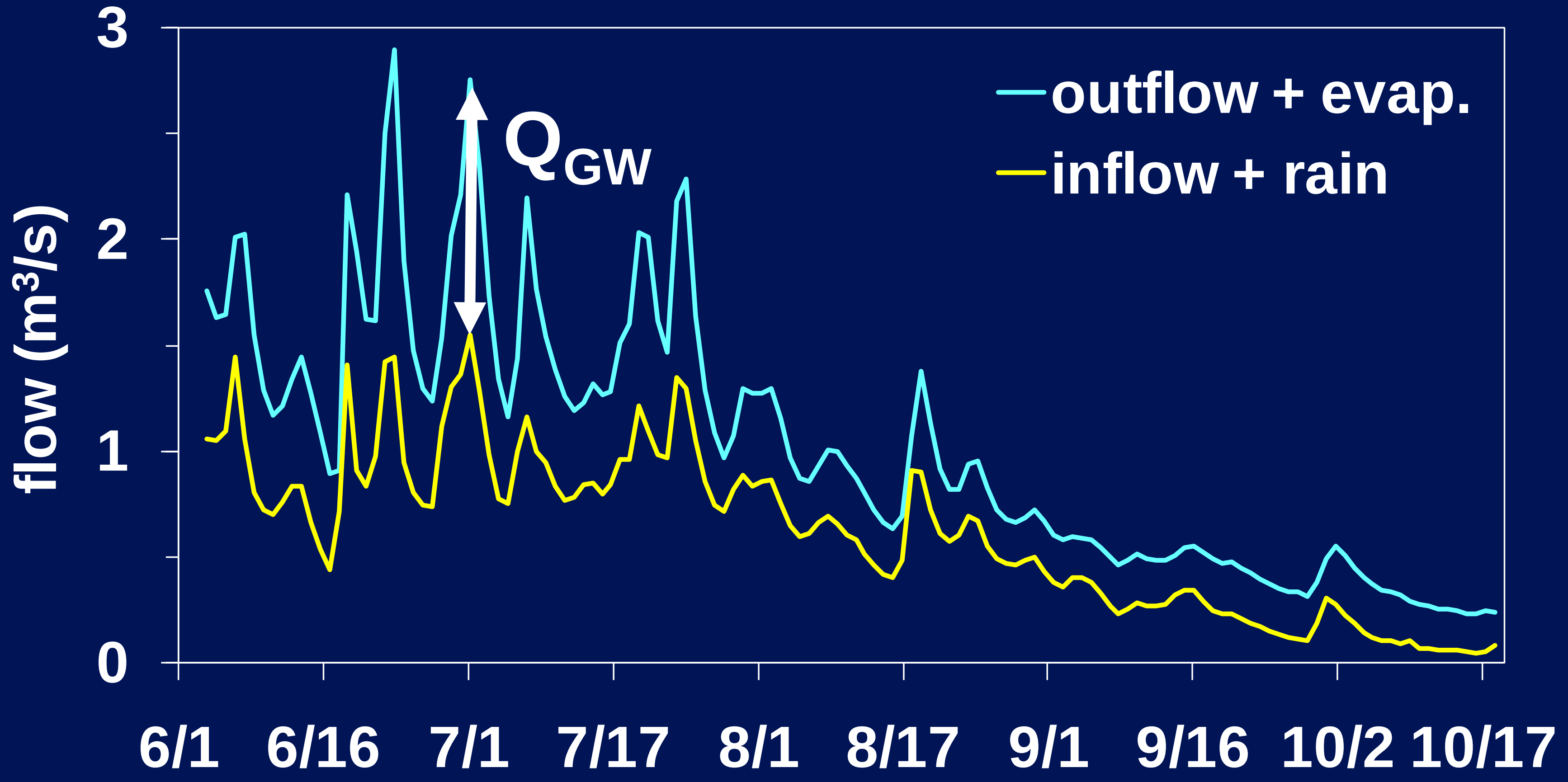
Lake Water Balance



If there is no groundwater flowing in or out,

streams in + rain = stream out + evaporation

The lake has more outflow than inflow.



Q_{GW} = groundwater inflow – outflow

30-70 % of water input is by groundwater.

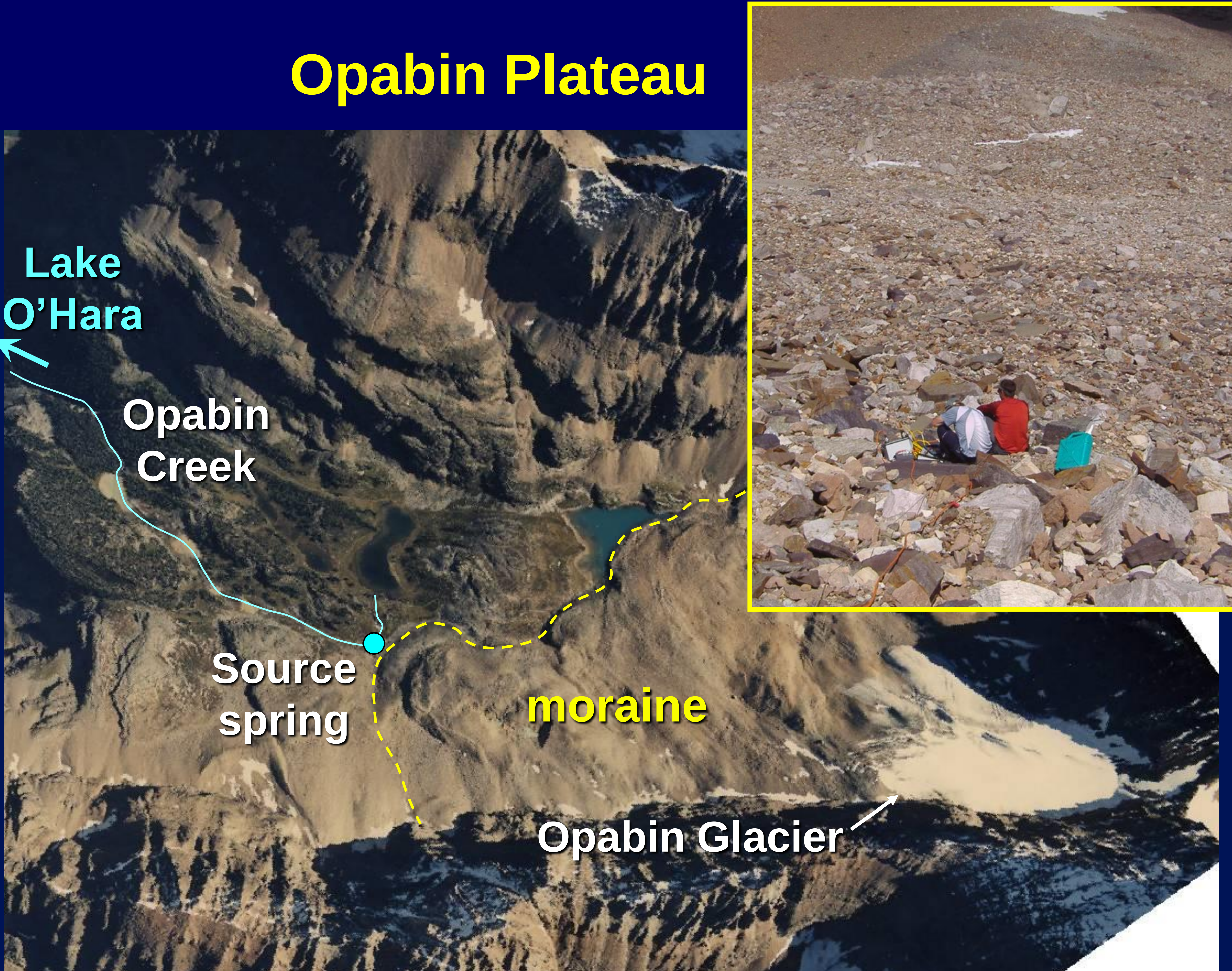
Hood et al. (2006, *Geophys. Res. Lett*., 33, L13405)

Opabin Creek Sub-Watershed (5 km^2)

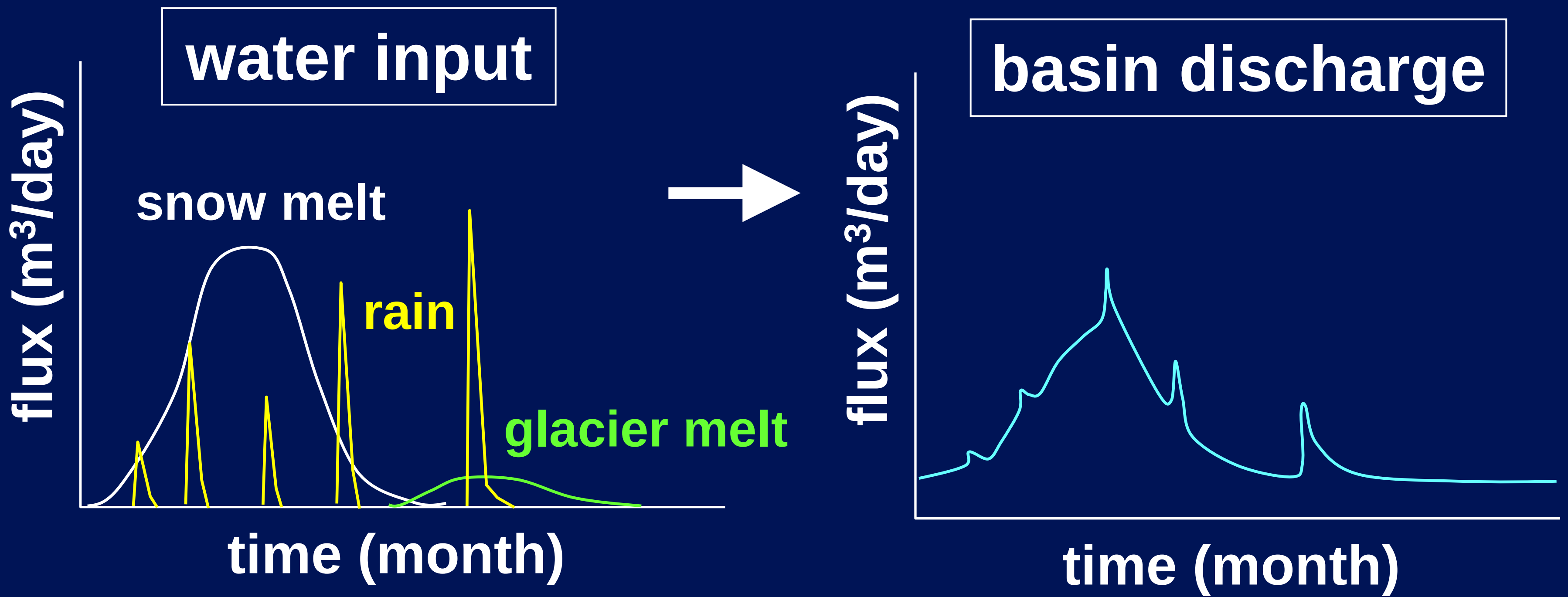
Opabin Creek entering Lake O'Hara

Opabin Creek source: Groundwater spring

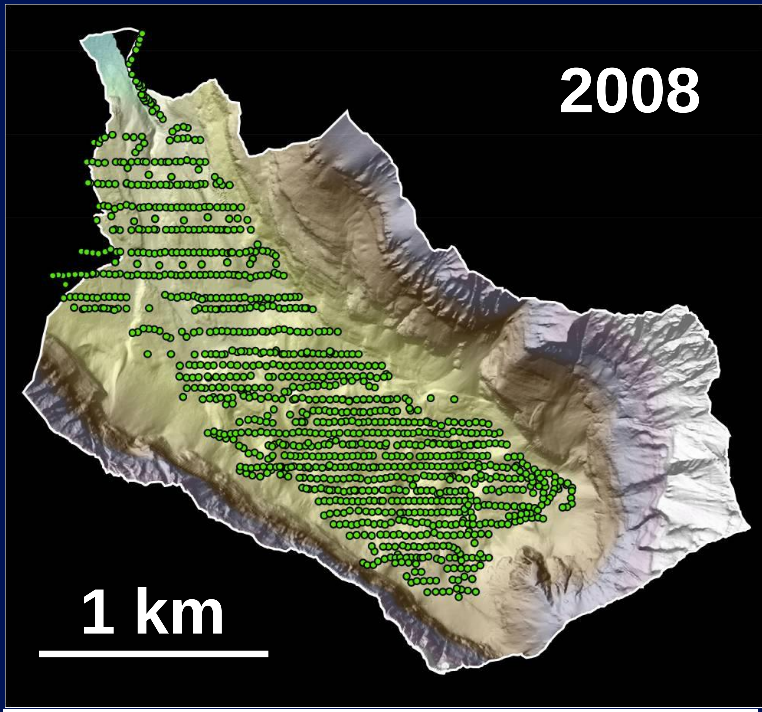
Opabin Plateau

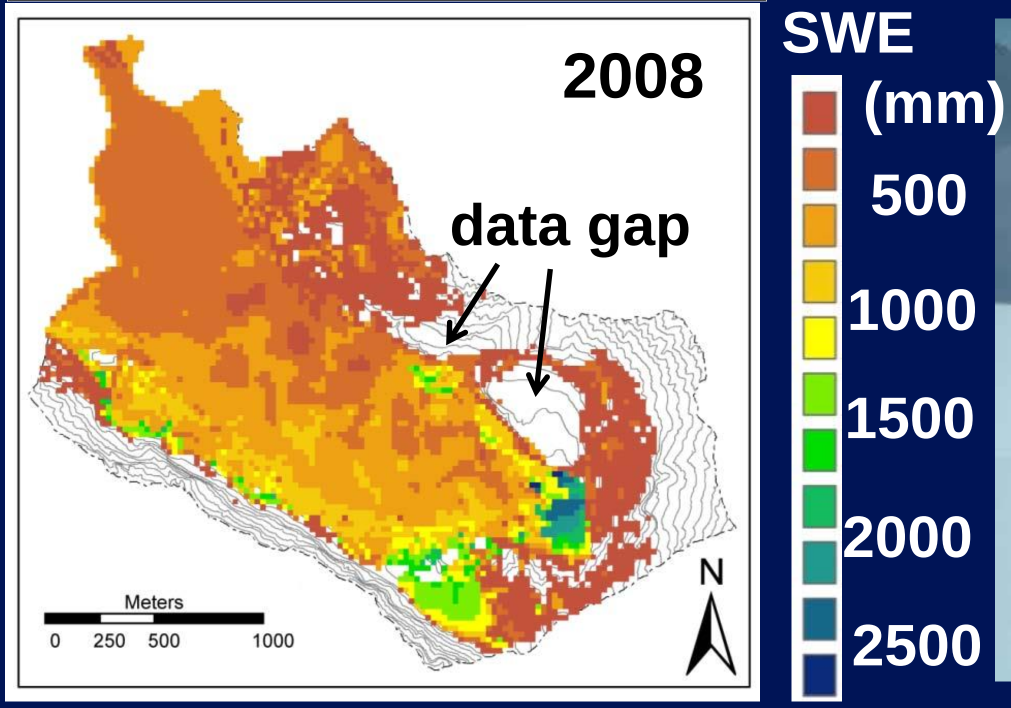


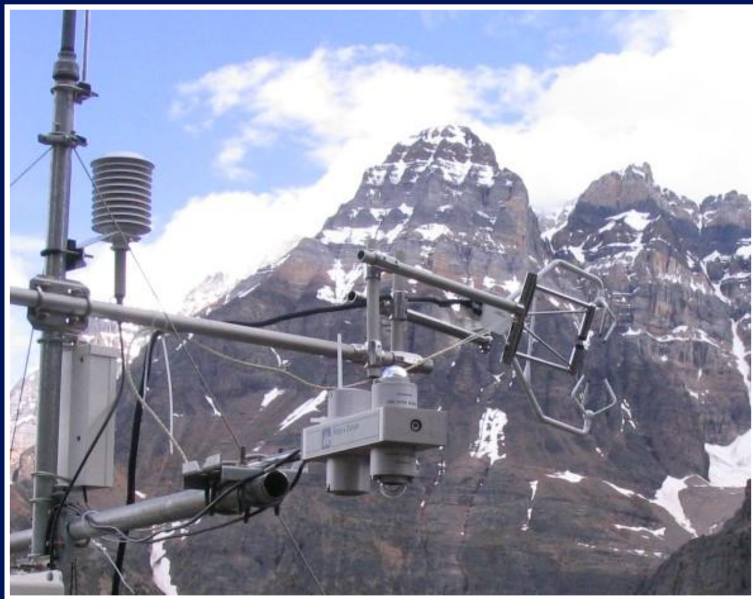
Water Input and Output in the Opabin Watershed



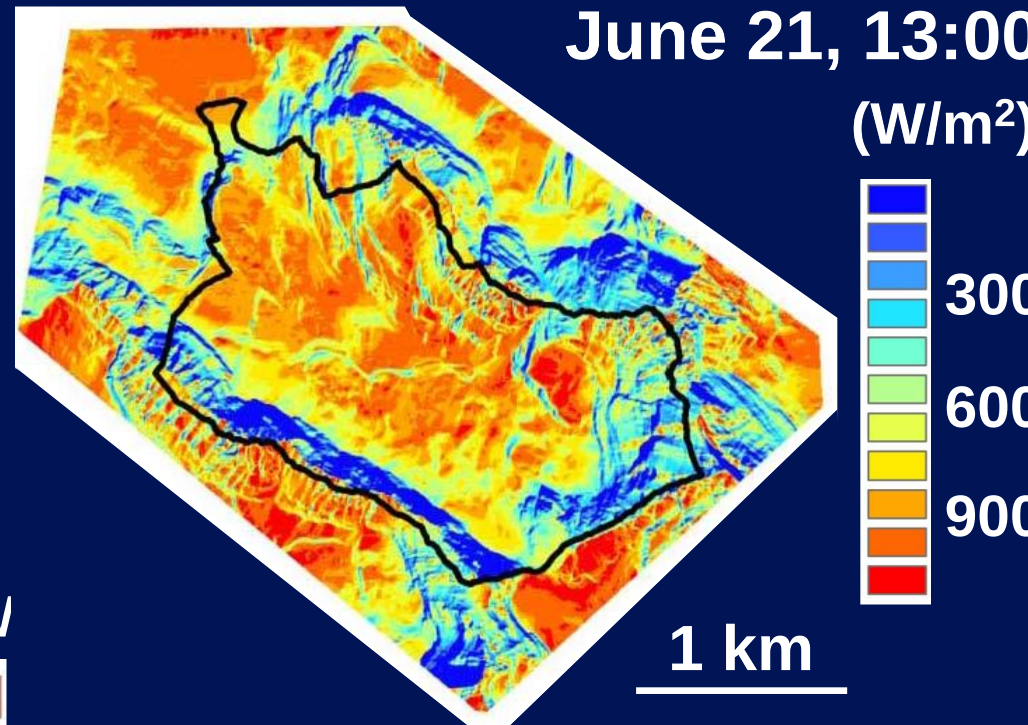
Groundwater provides temporary storage.

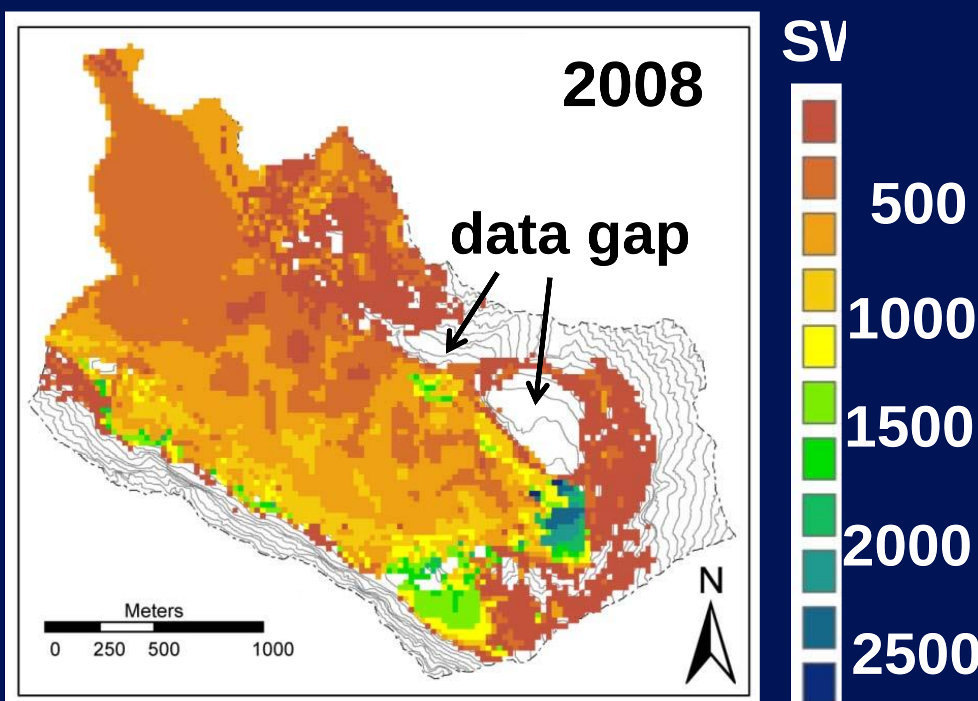

2008
1 km


2008
data gap
Meters
0 250 500 1000
N
SWE
(mm)
500
1000
1500
2000
2500



Shortwave radiation June 21, 13:00

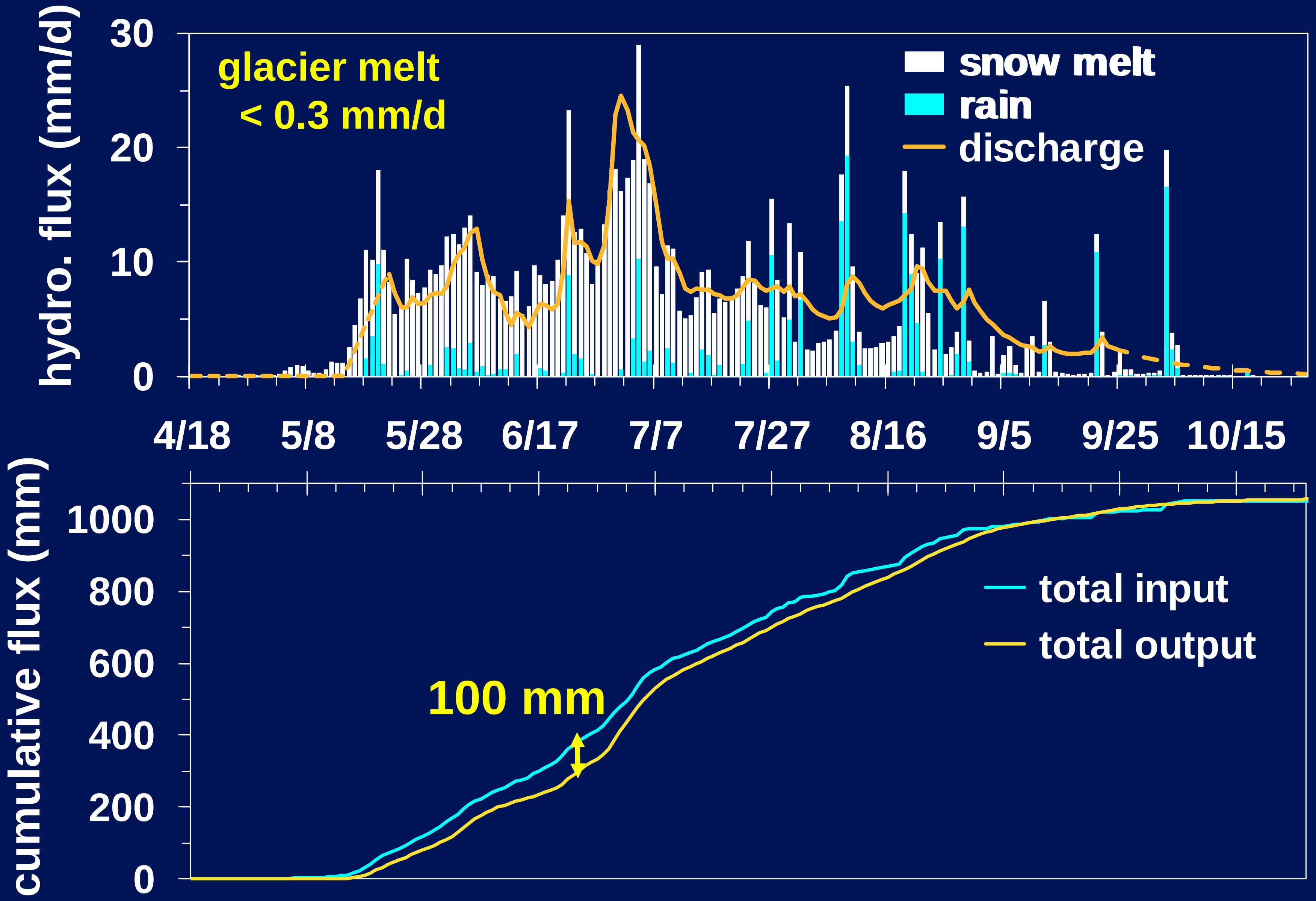




Snowmelt model

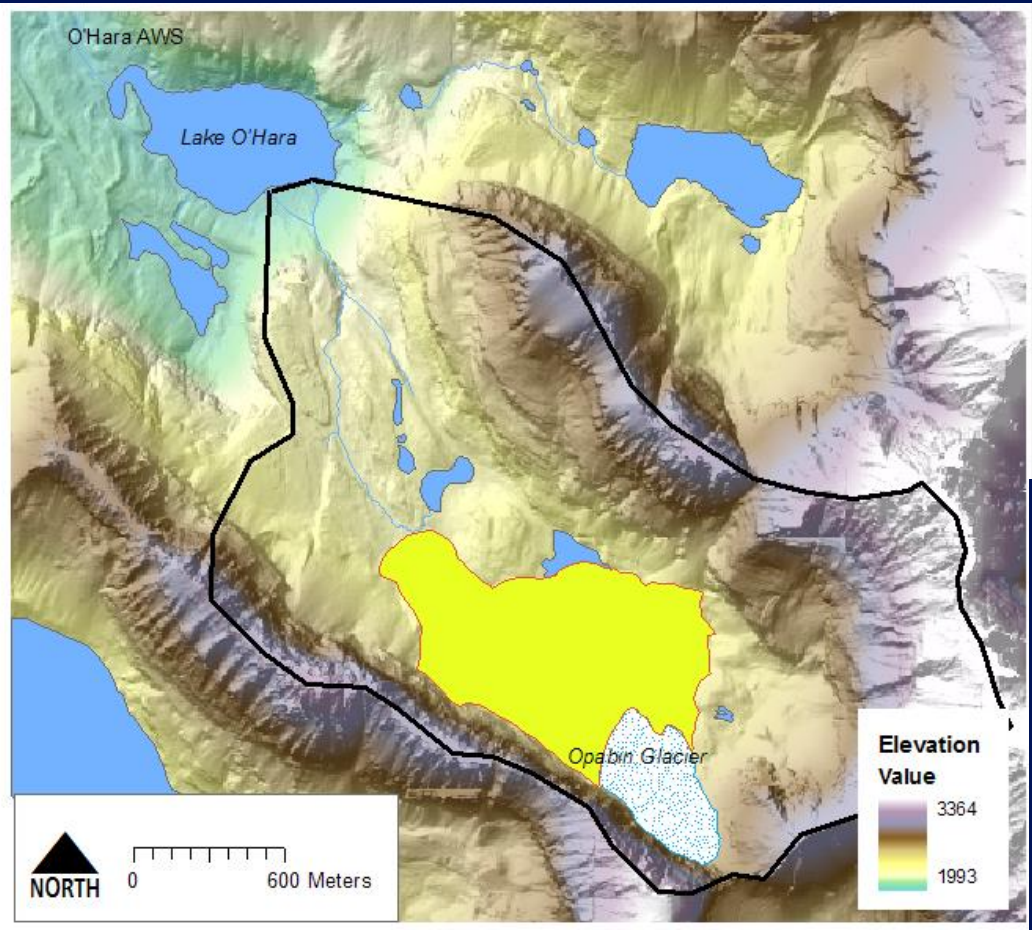
- Utah Energy Balance
- Hourly time step
- 50 m grid cells

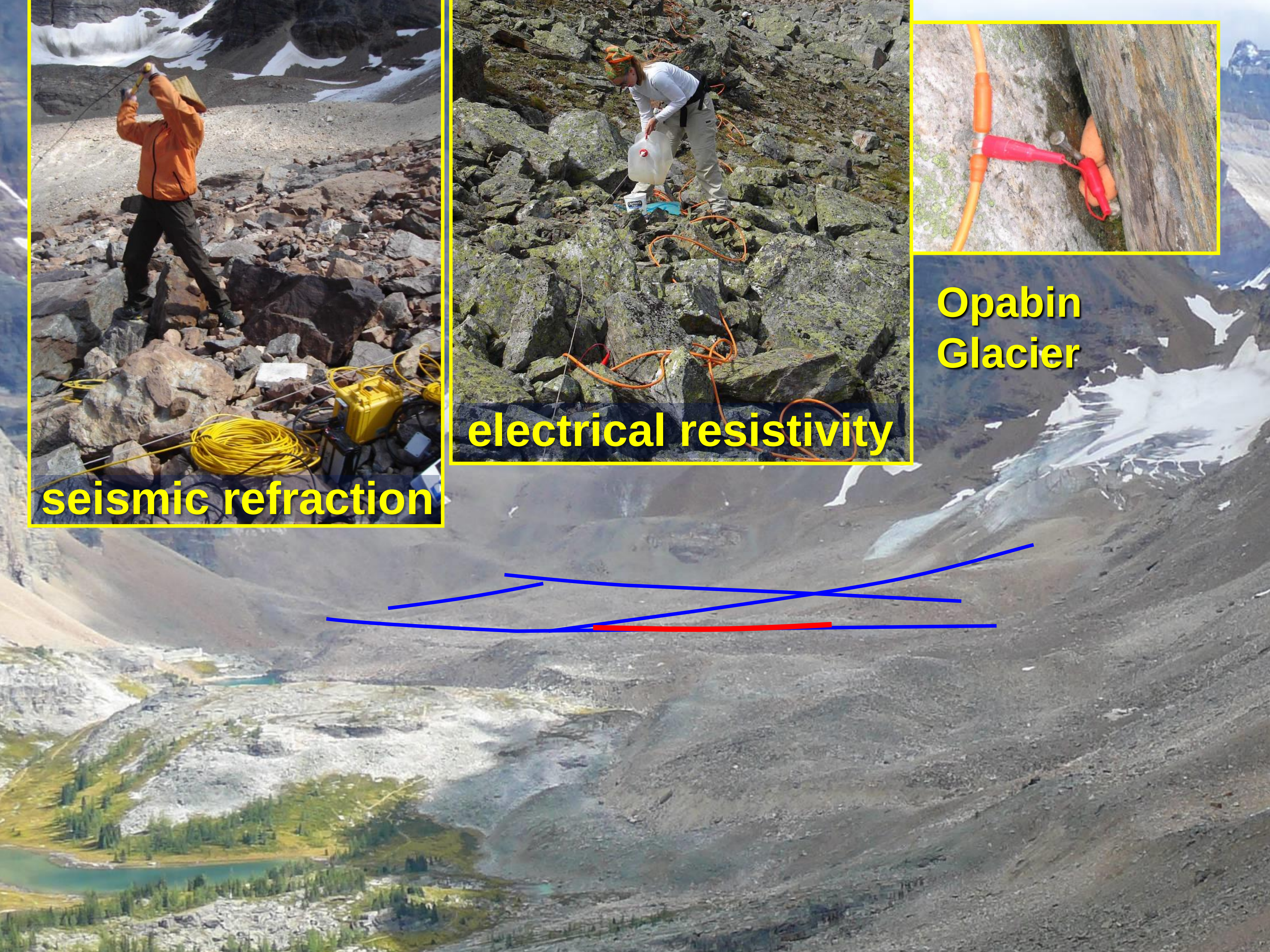
Opabin Basin Water Balance (2008)

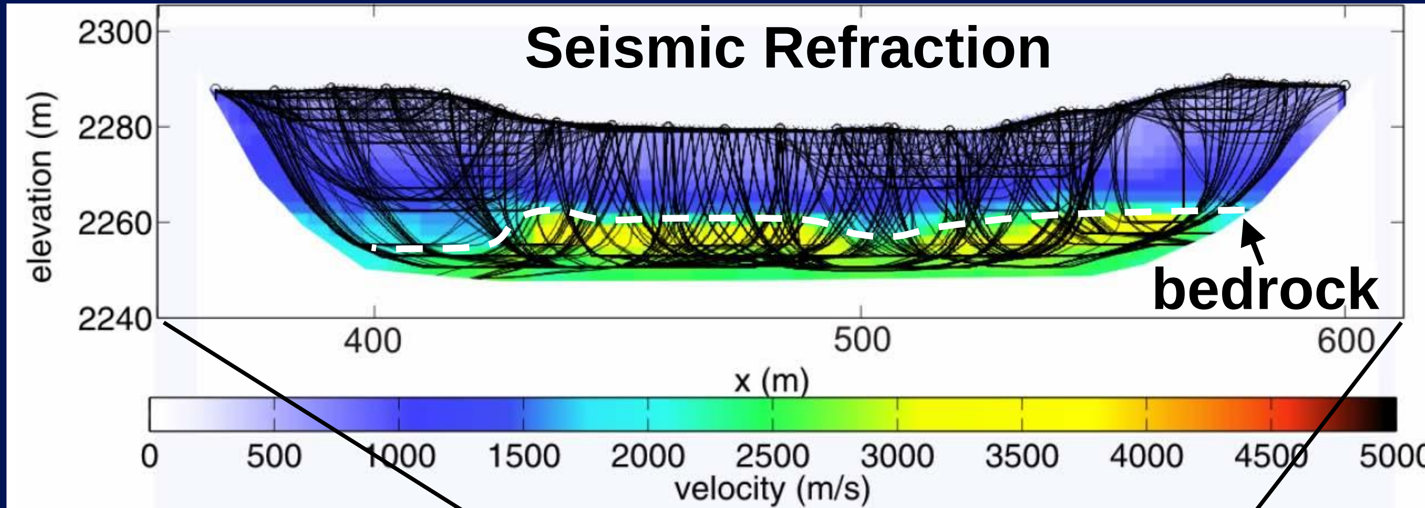


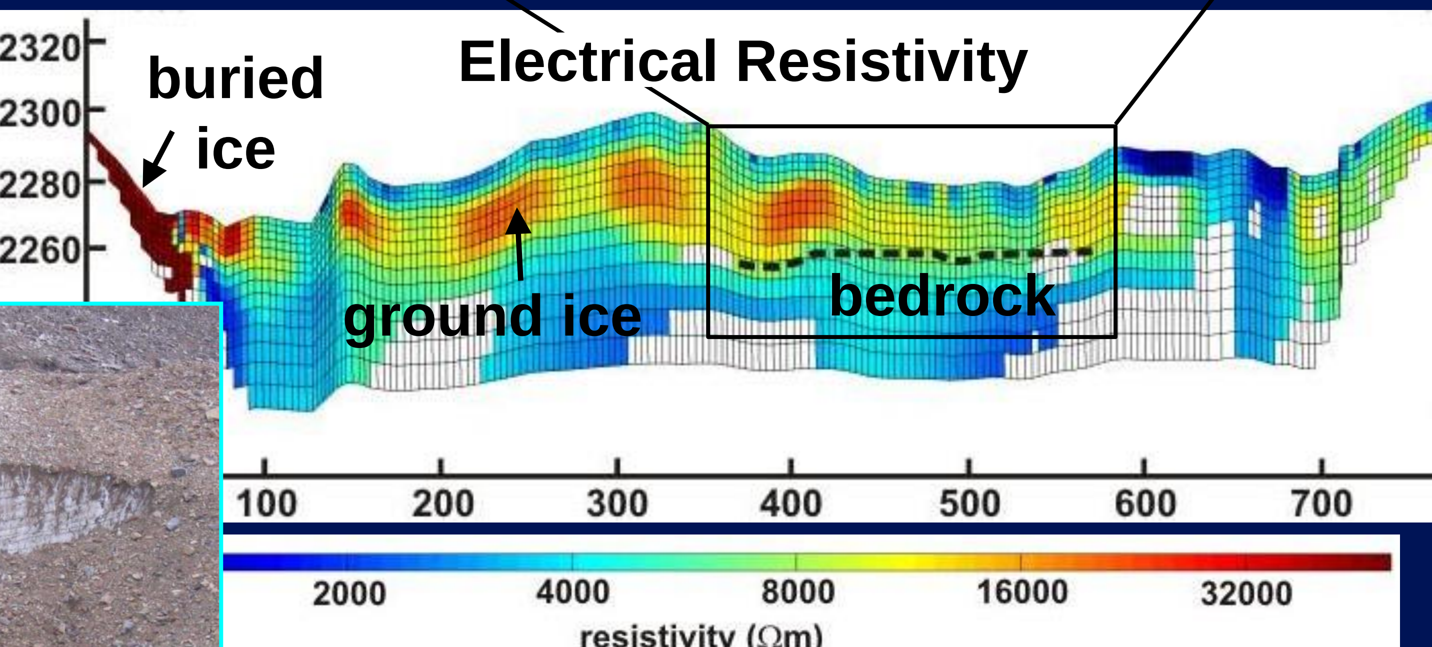
Hydrogeological Response Units

- Bedrock (hard quartzite)
- Proglacial moraine




seismic refraction
electrical resistivity
Opabin
Glacier

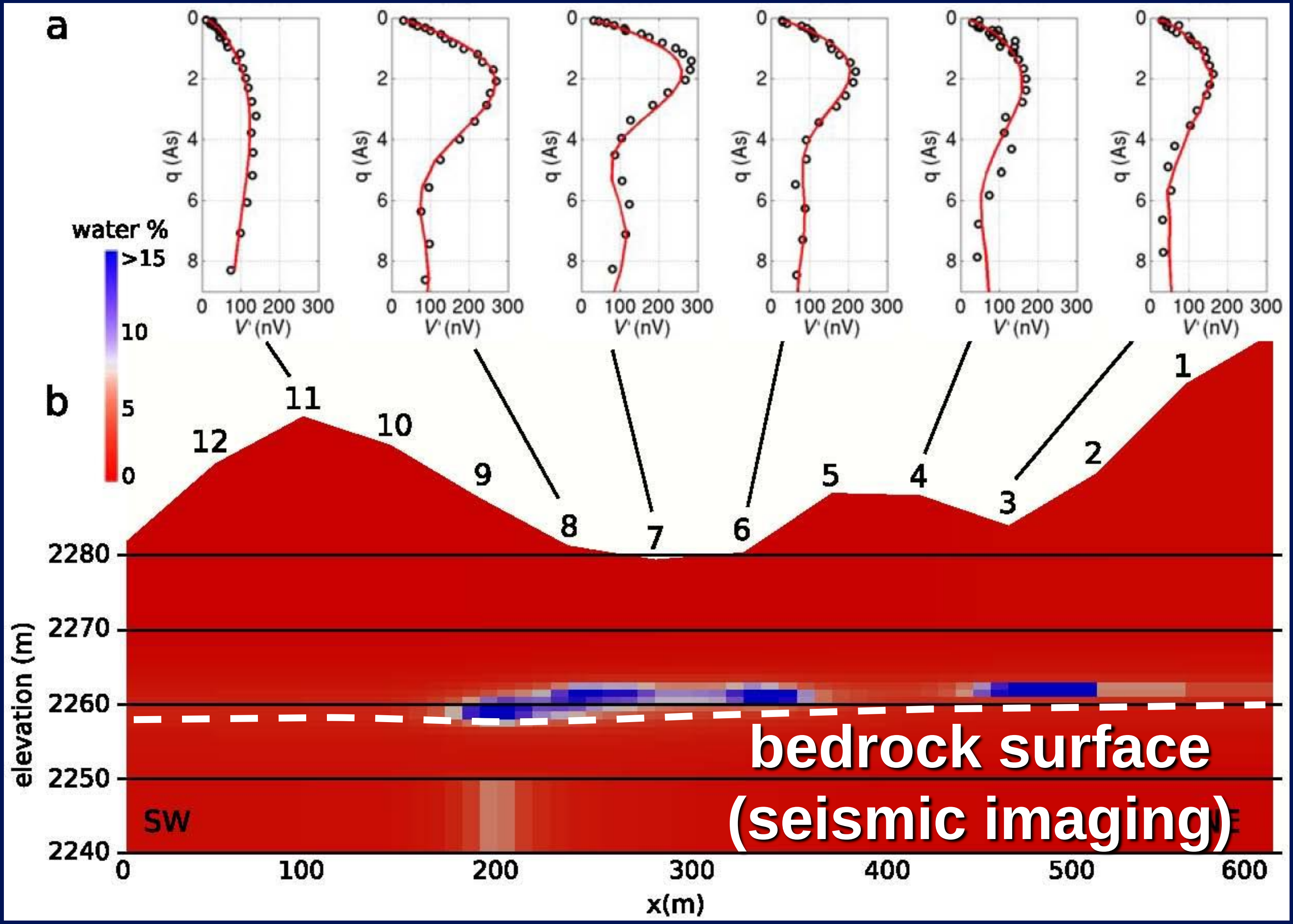




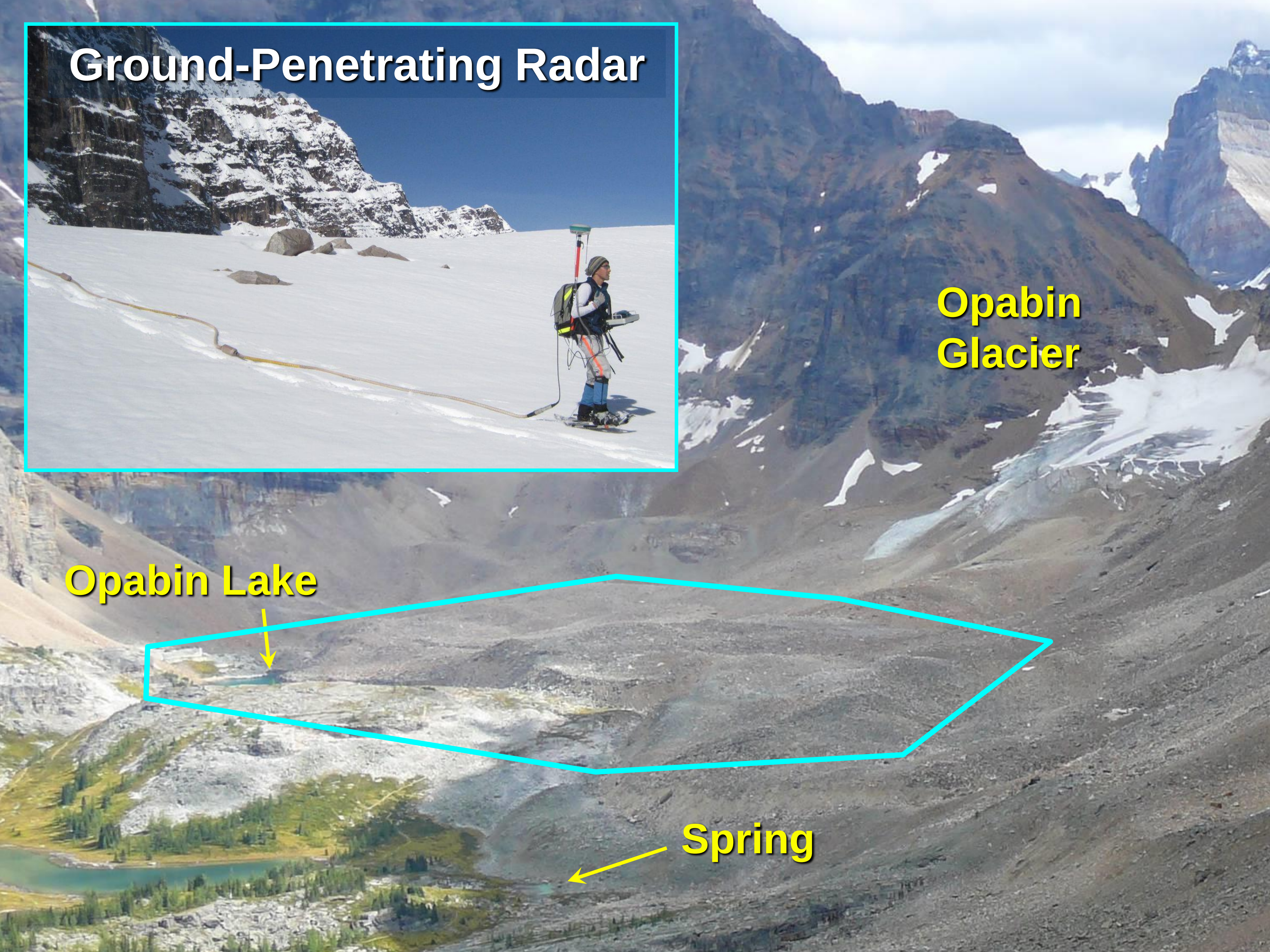
Langston et al. (2011, *Hydrol. Process*. 25: 2967)

Nuclear Magnetic Resonance Imaging

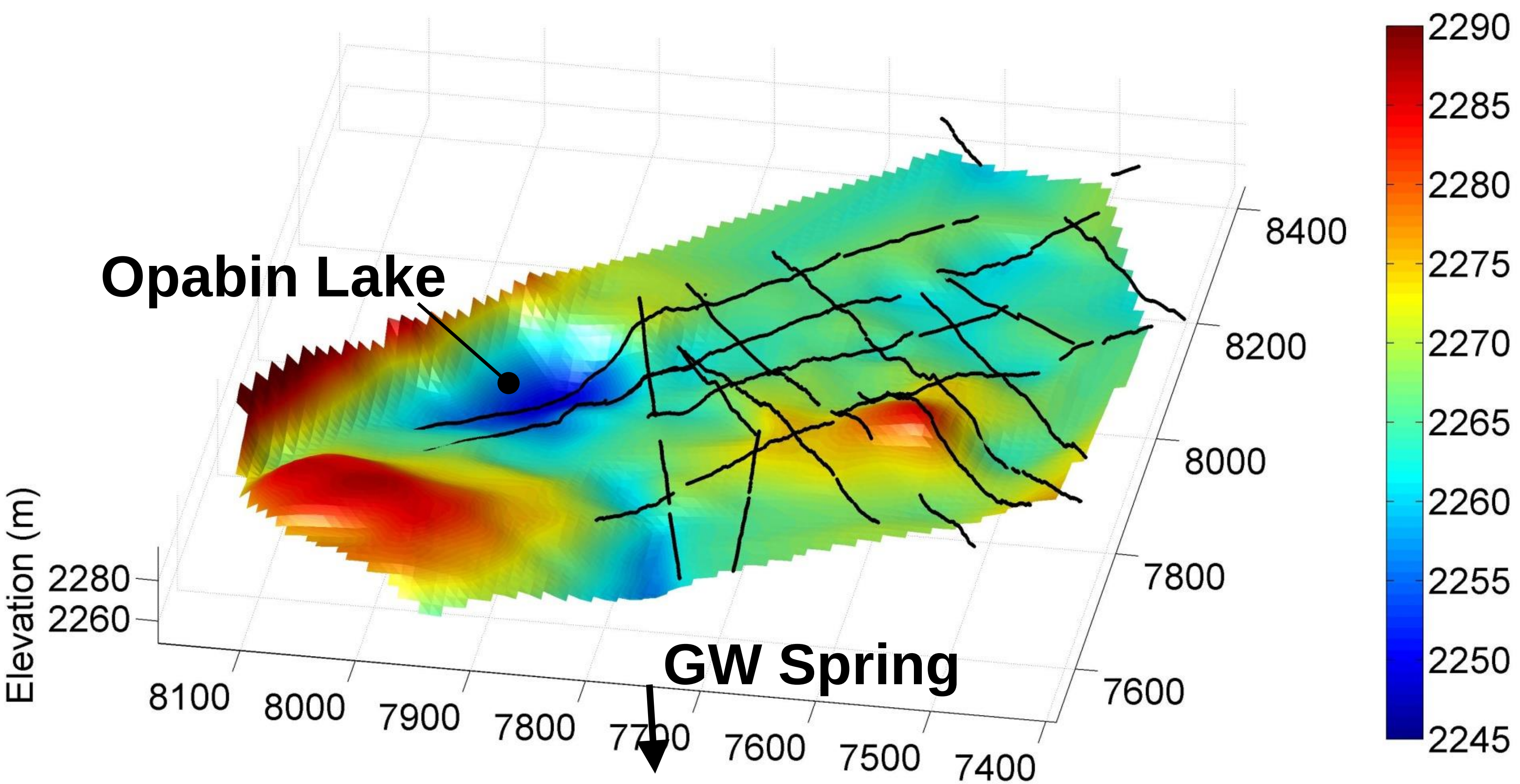
Blue colour indicates water molecules



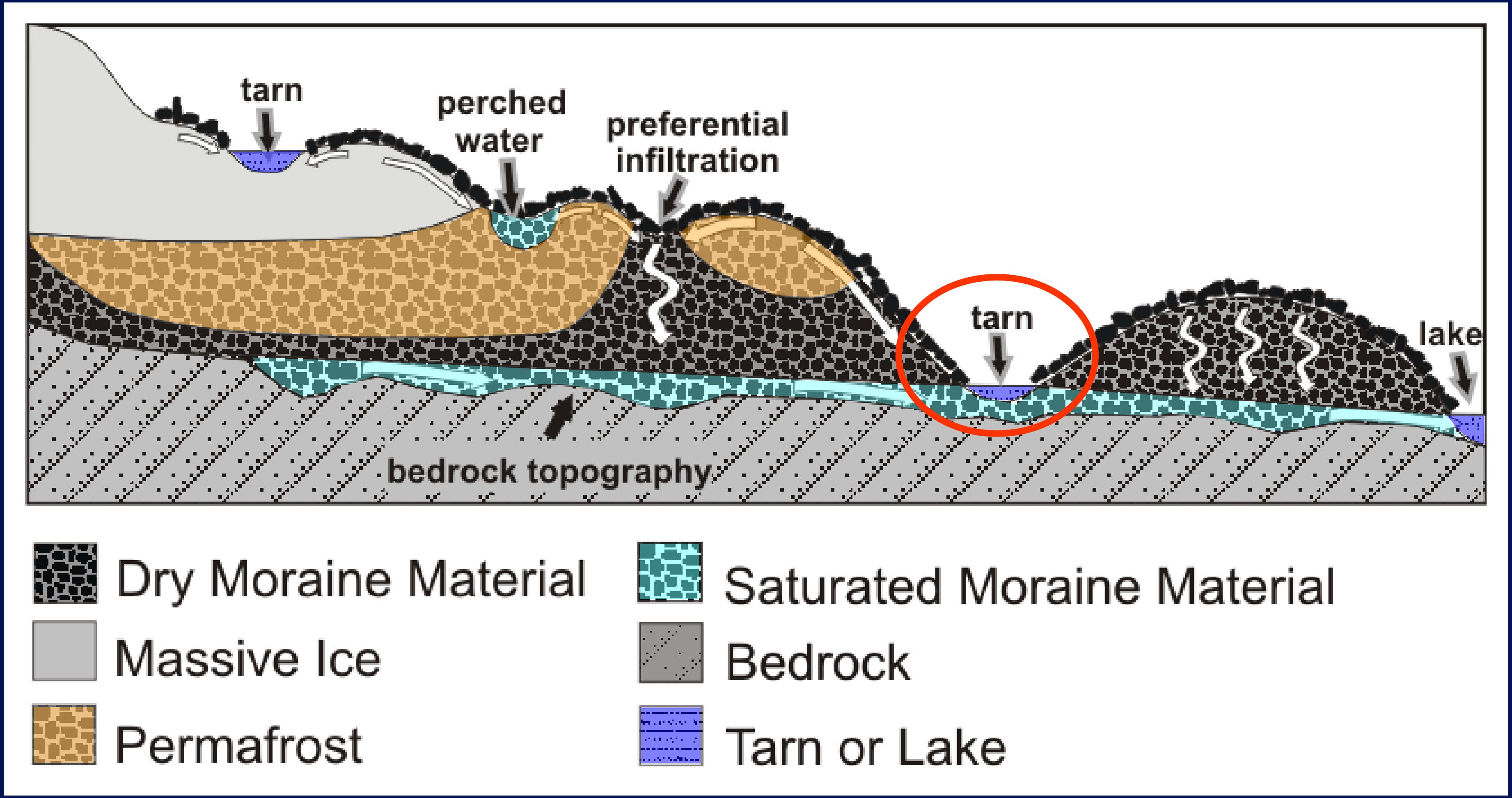
Lehmann et al. (2012. *Geophysics*, 76: B165)


Ground-Penetrating Radar
Opabin Glacier
Opabin Lake
Spring

Bedrock Surface Map from Radar Data

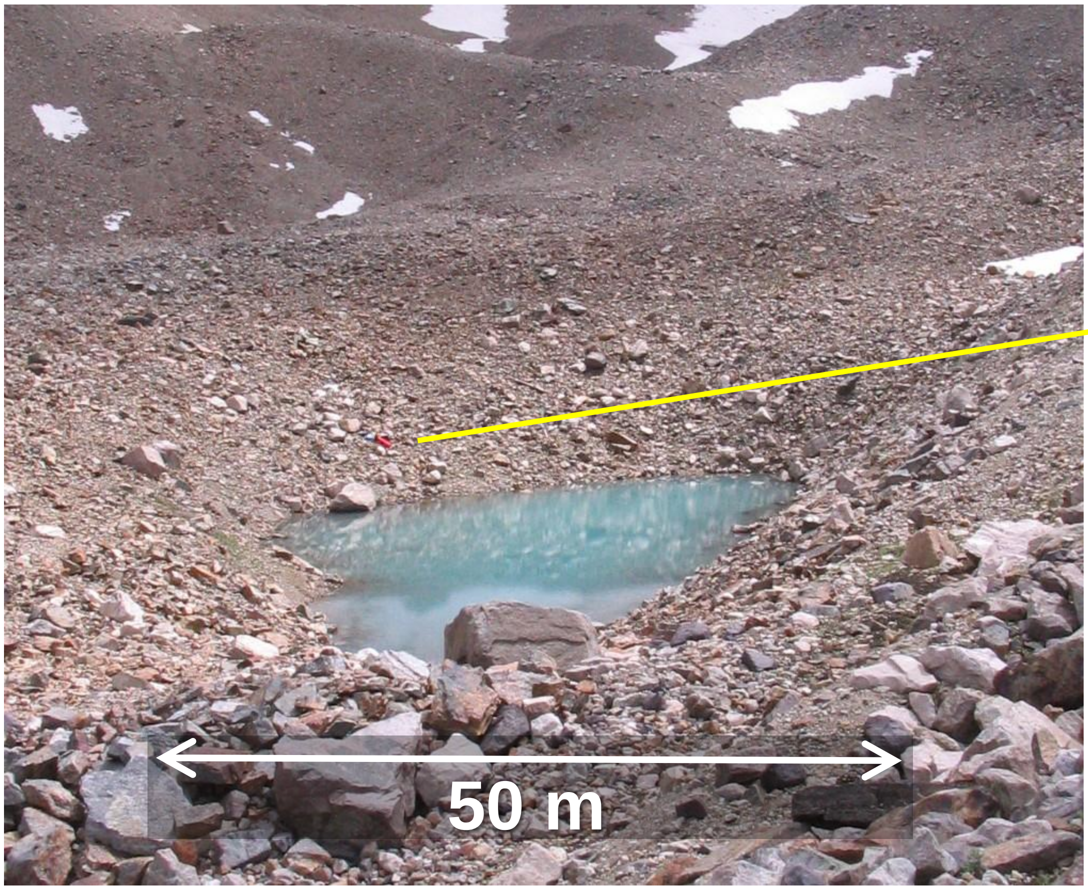


Emerging Conceptual Model



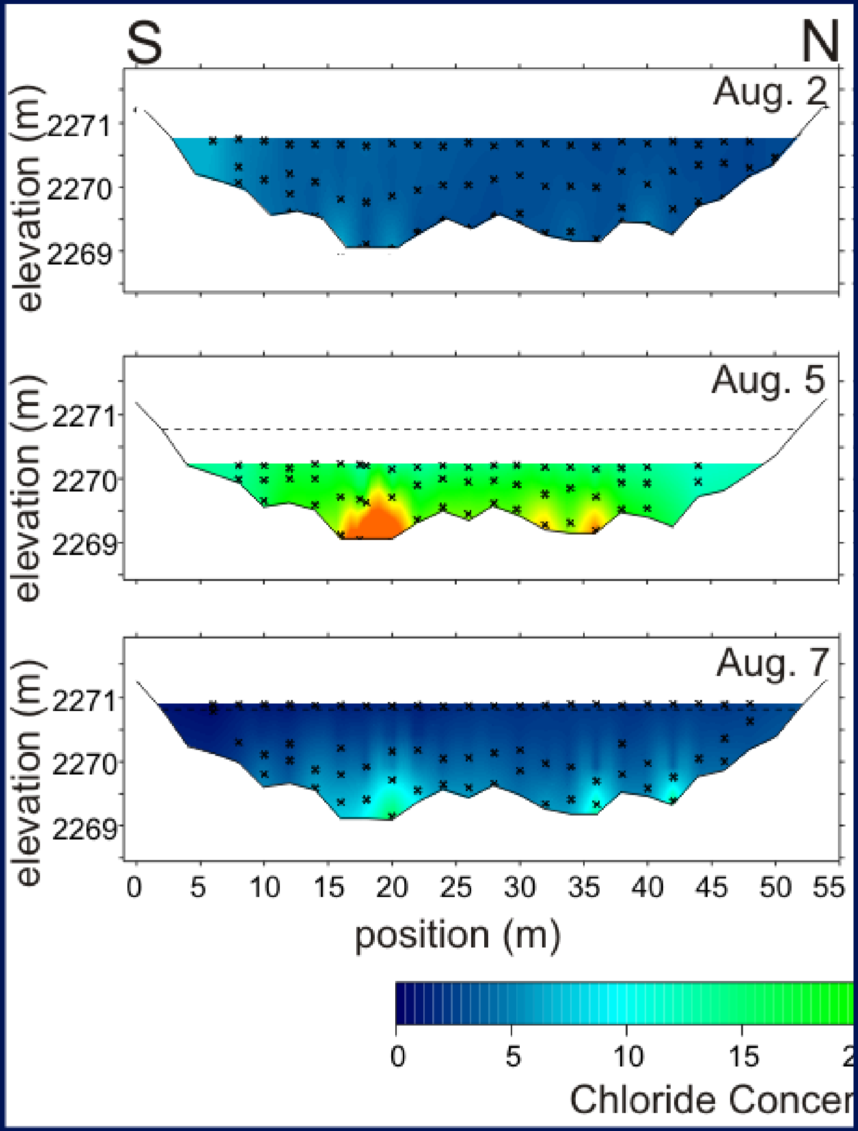
Langston et al. (2011, *Hydrol. Process*. 25: 2967)

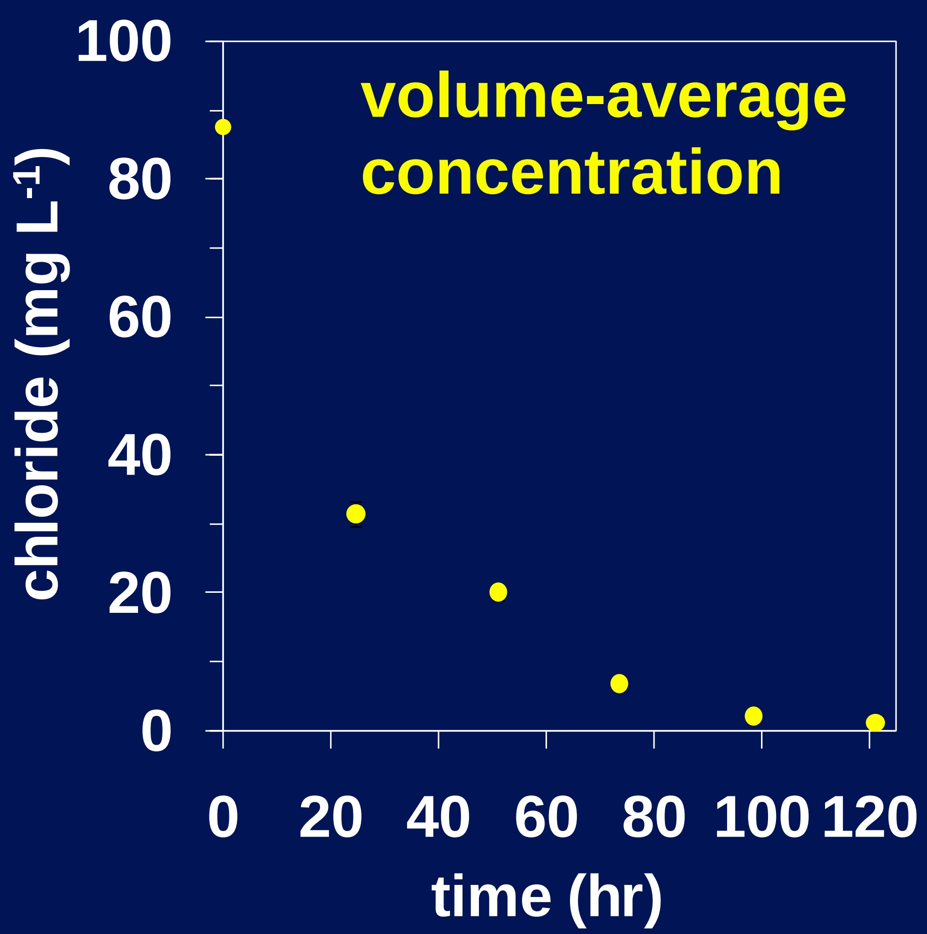
Estimating Hydraulic Conductivity of the Moraine



- Water balance equation
- Energy balance equation
- Tracer mass balance equation

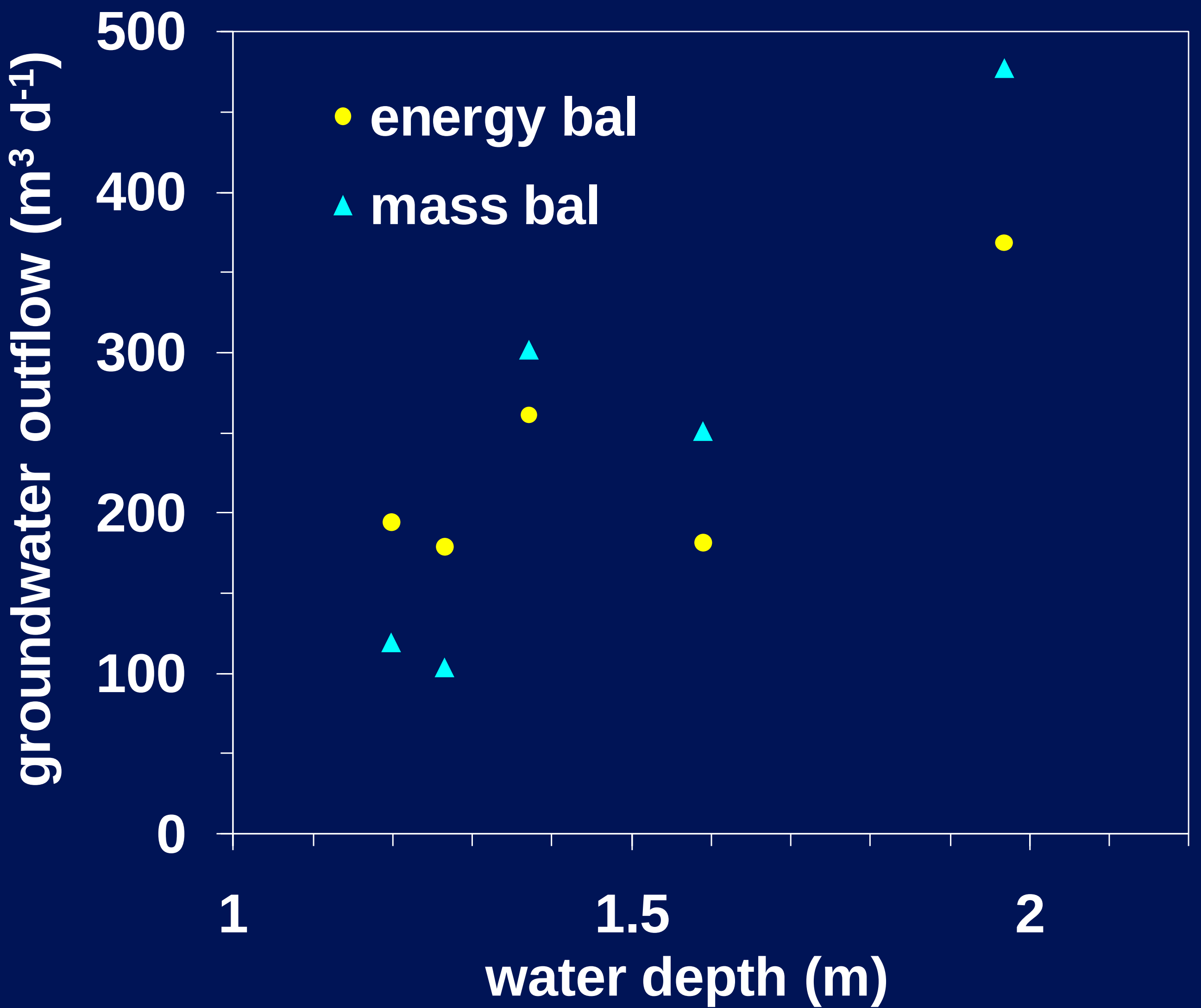
Chloride in the Tarn





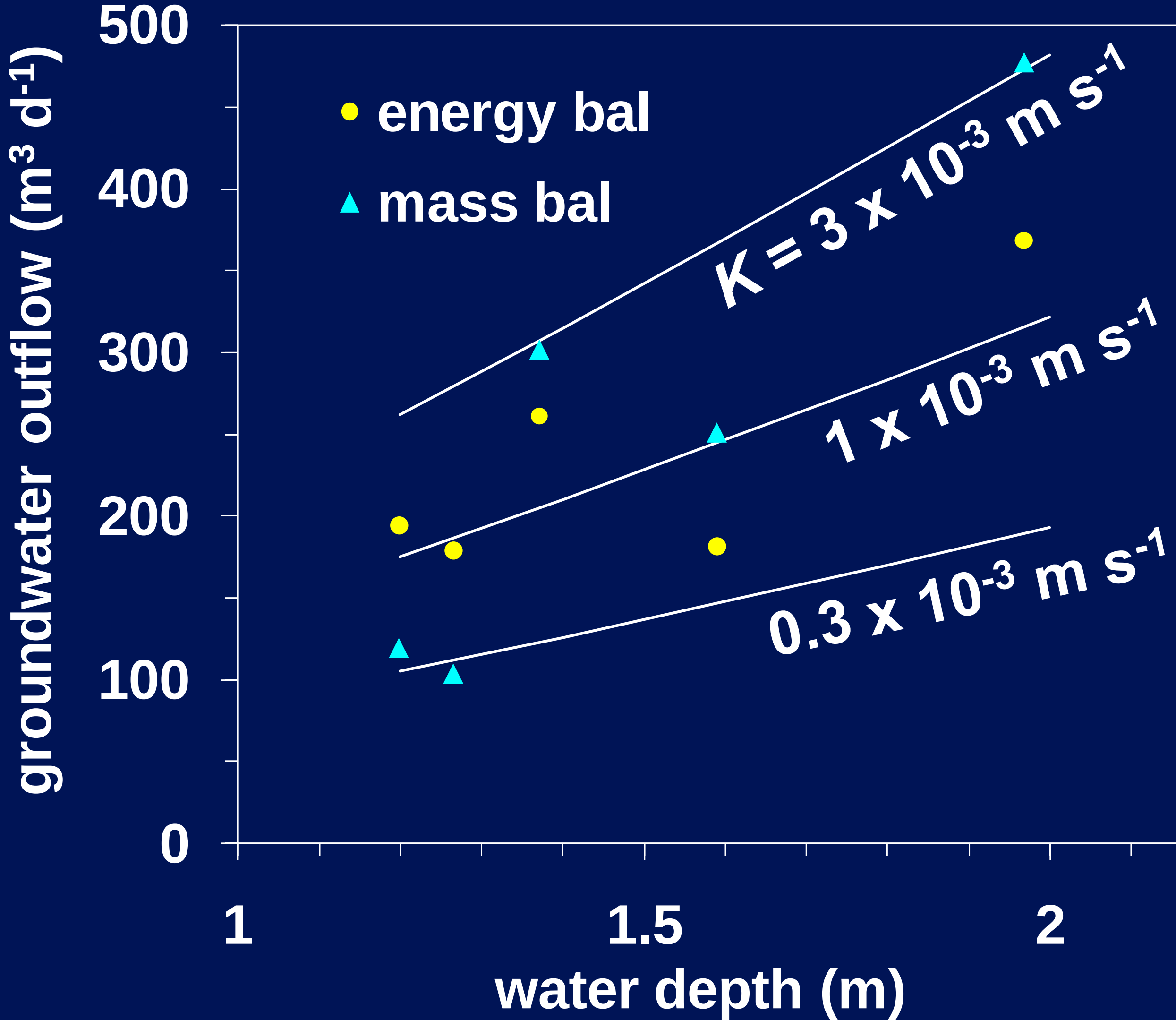
Langston et al. (2013, *Water Resour. Res*. 49: 5411)

Groundwater outflow from the tarn



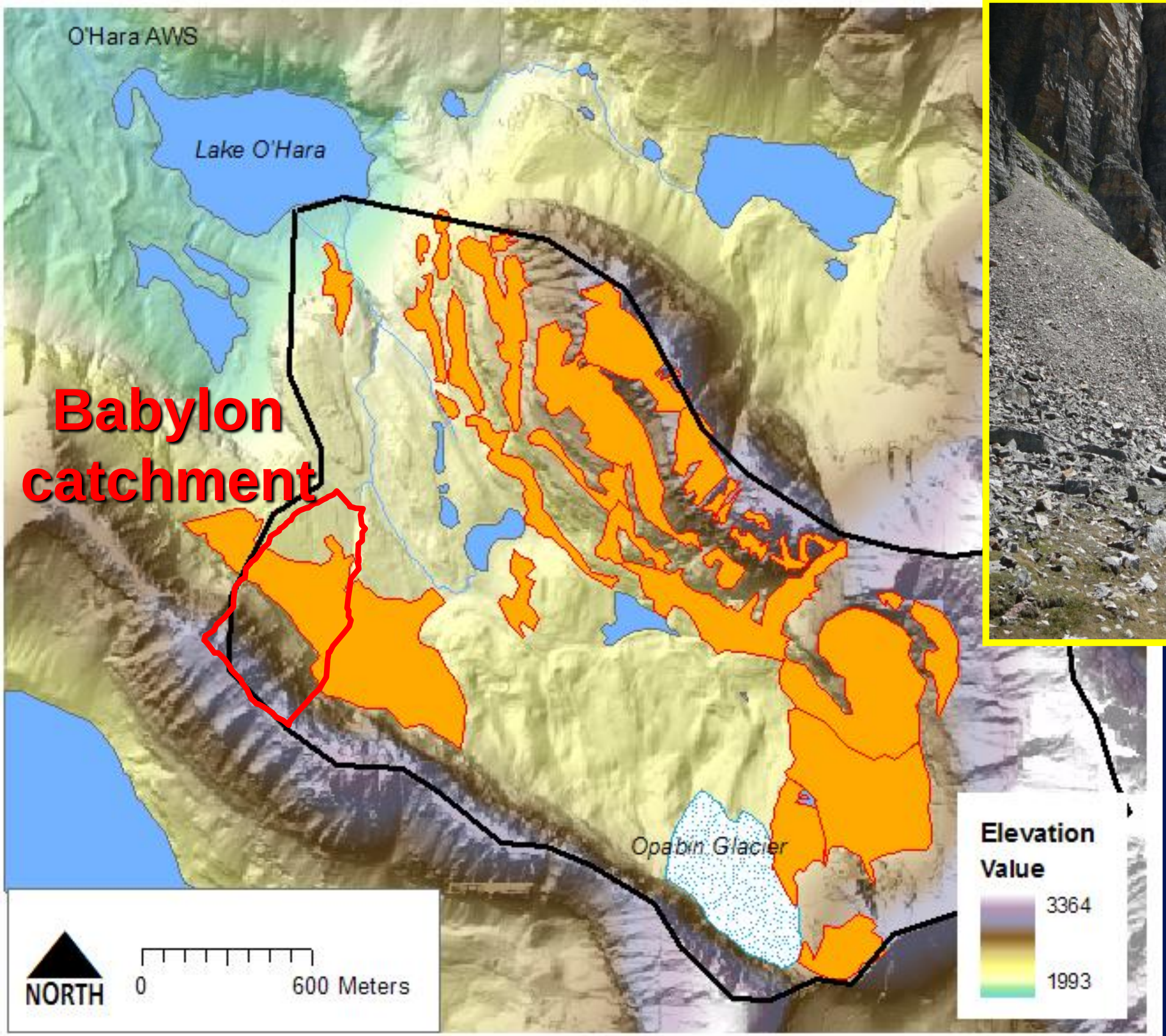
Langston et al. (2013, *Water Resour. Res*. 49: 5411)

Groundwater outflow from the tarn



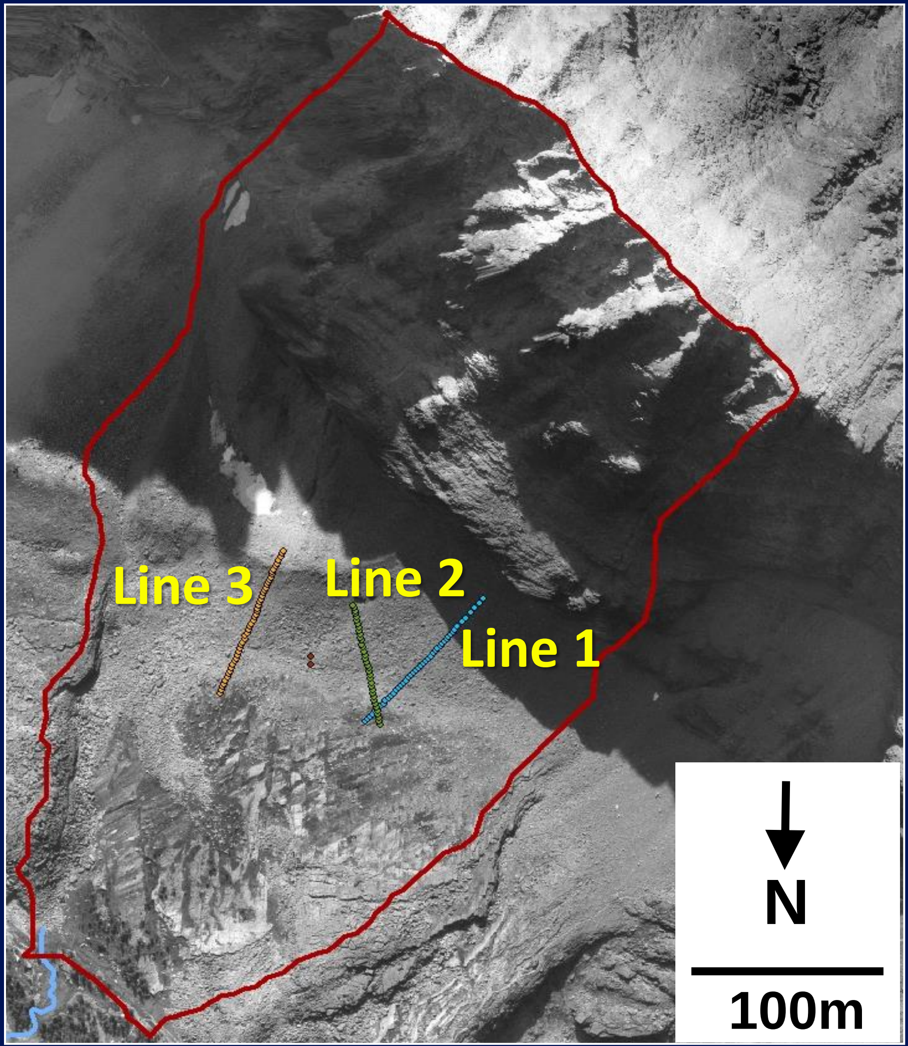
Langston et al. (2013, *Water Resour. Res*. 49: 5411)

Hydrogeological Response Unit: Talus

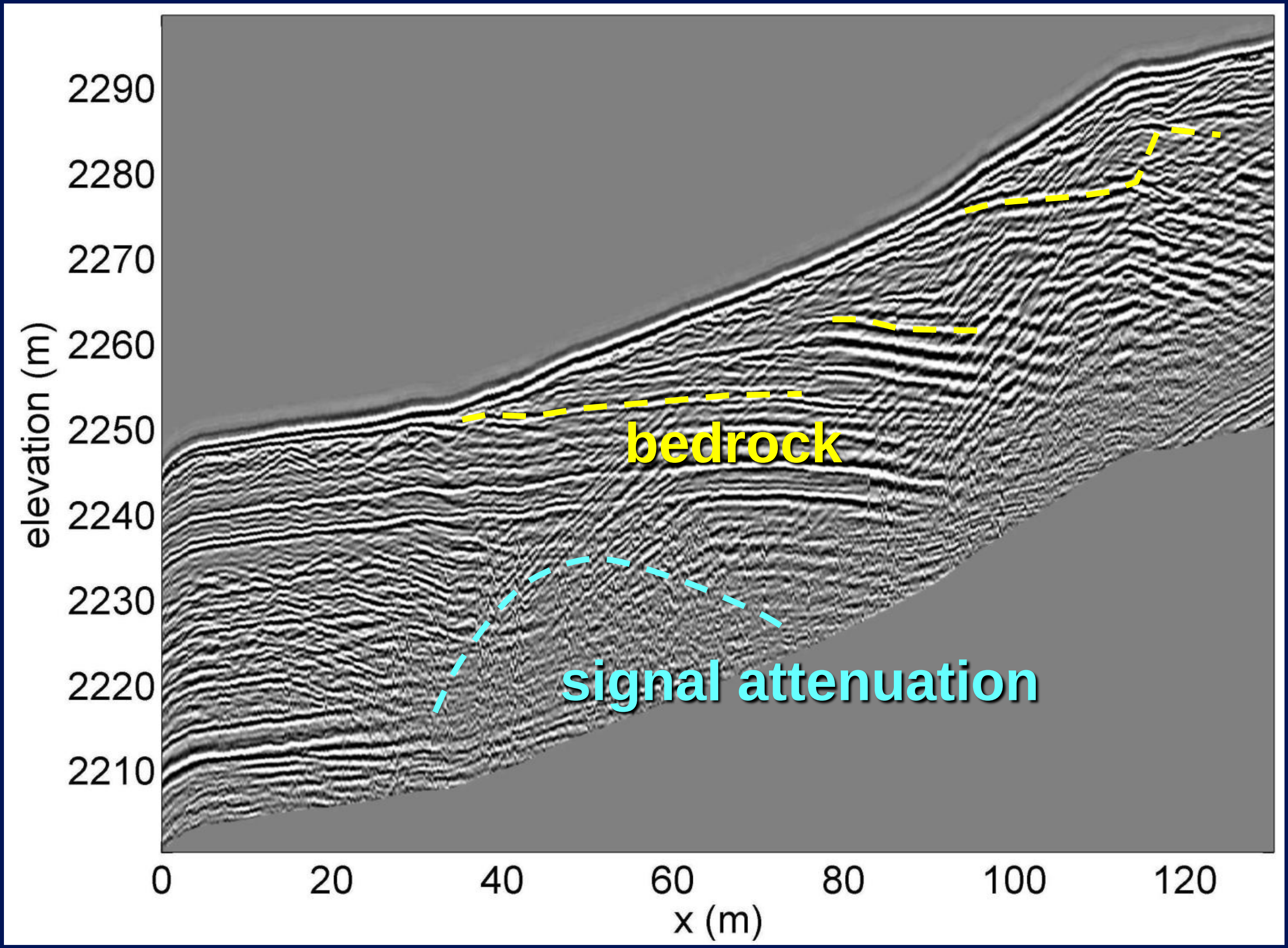


Geophysical Survey of Talus

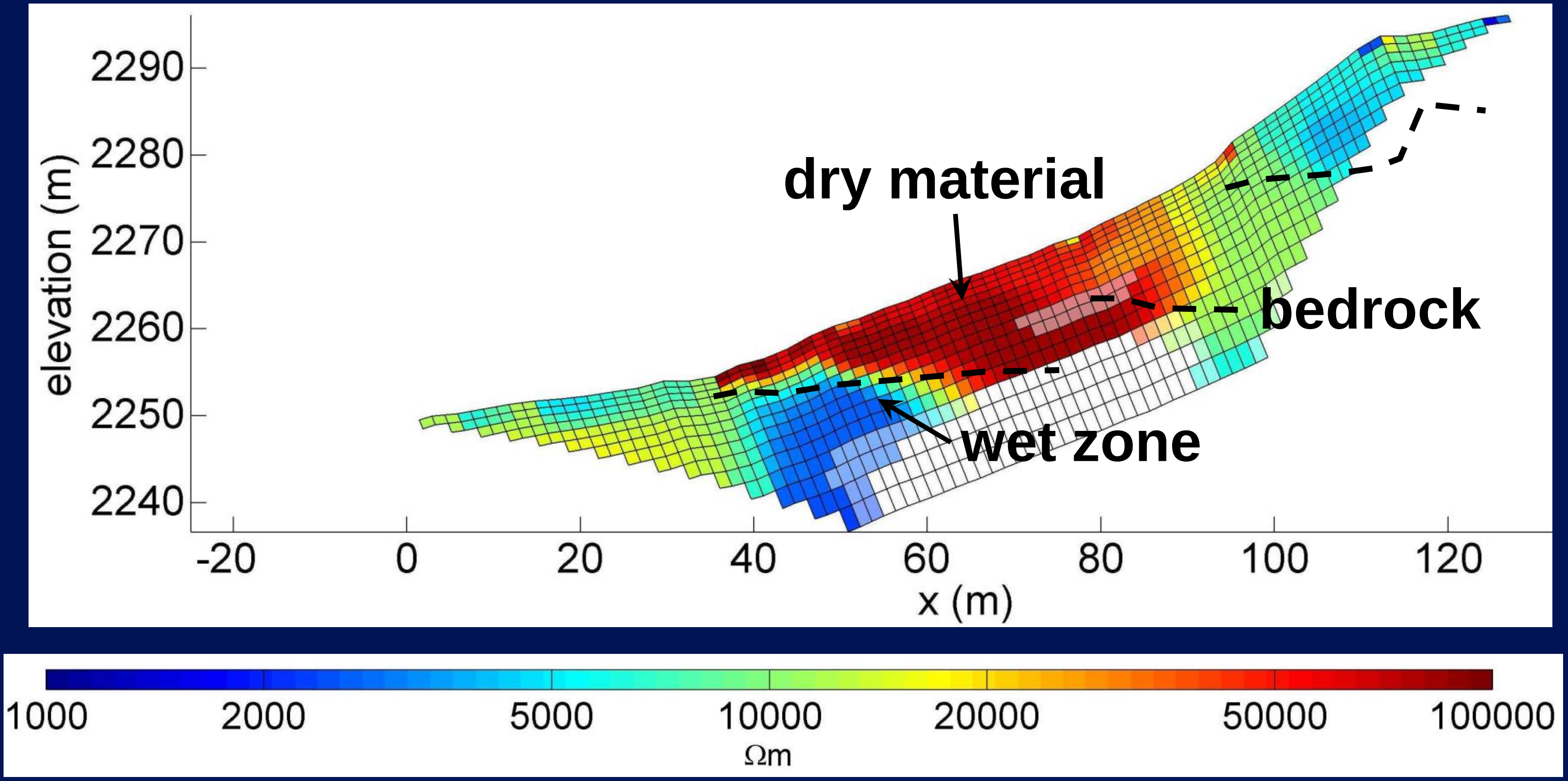
Resistivity Imaging and Ground Penetrating Radar (GPR)



Line 3: Ground Penetrating Radar

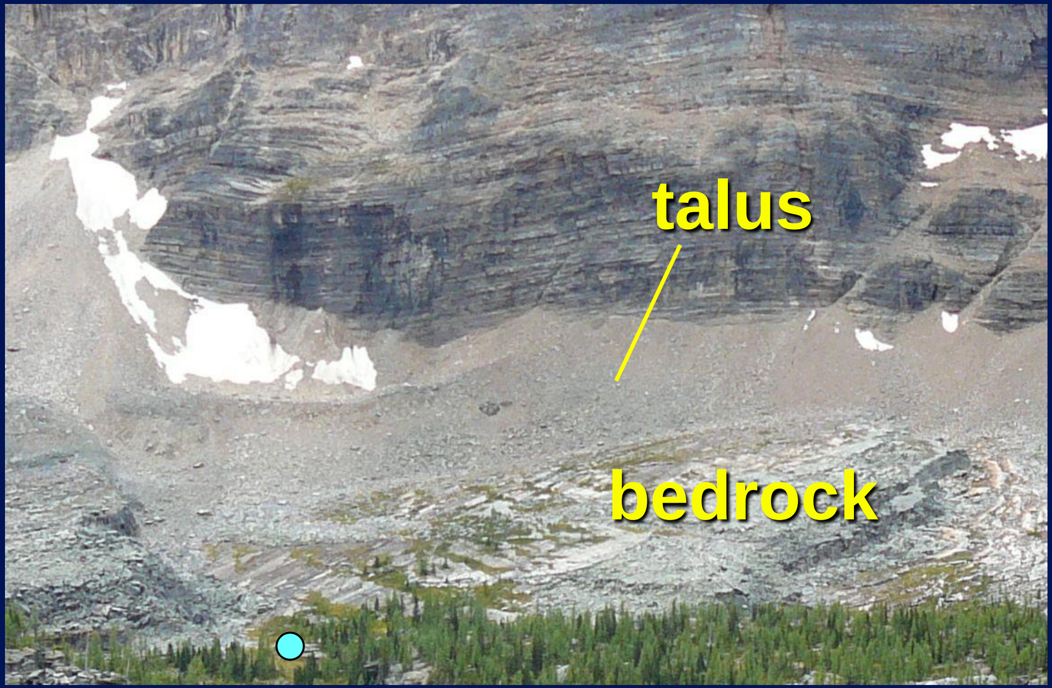


Line 3: Electrical Resistivity

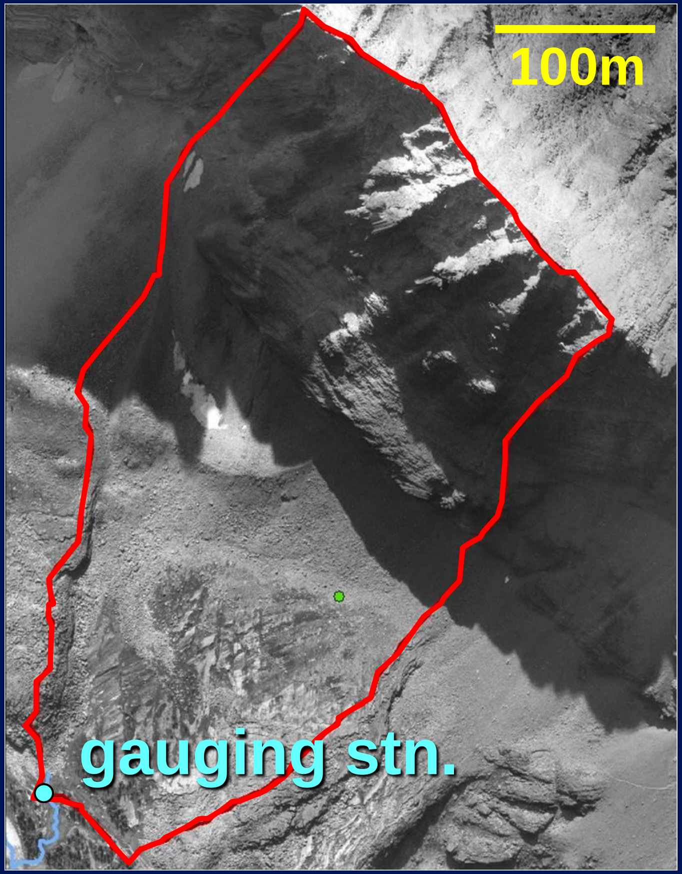


Thickness of low resistivity zone below high resistivity cannot be determined (Hilbich et al., 2009).

Measurement of Talus Discharge



Babylon Creek

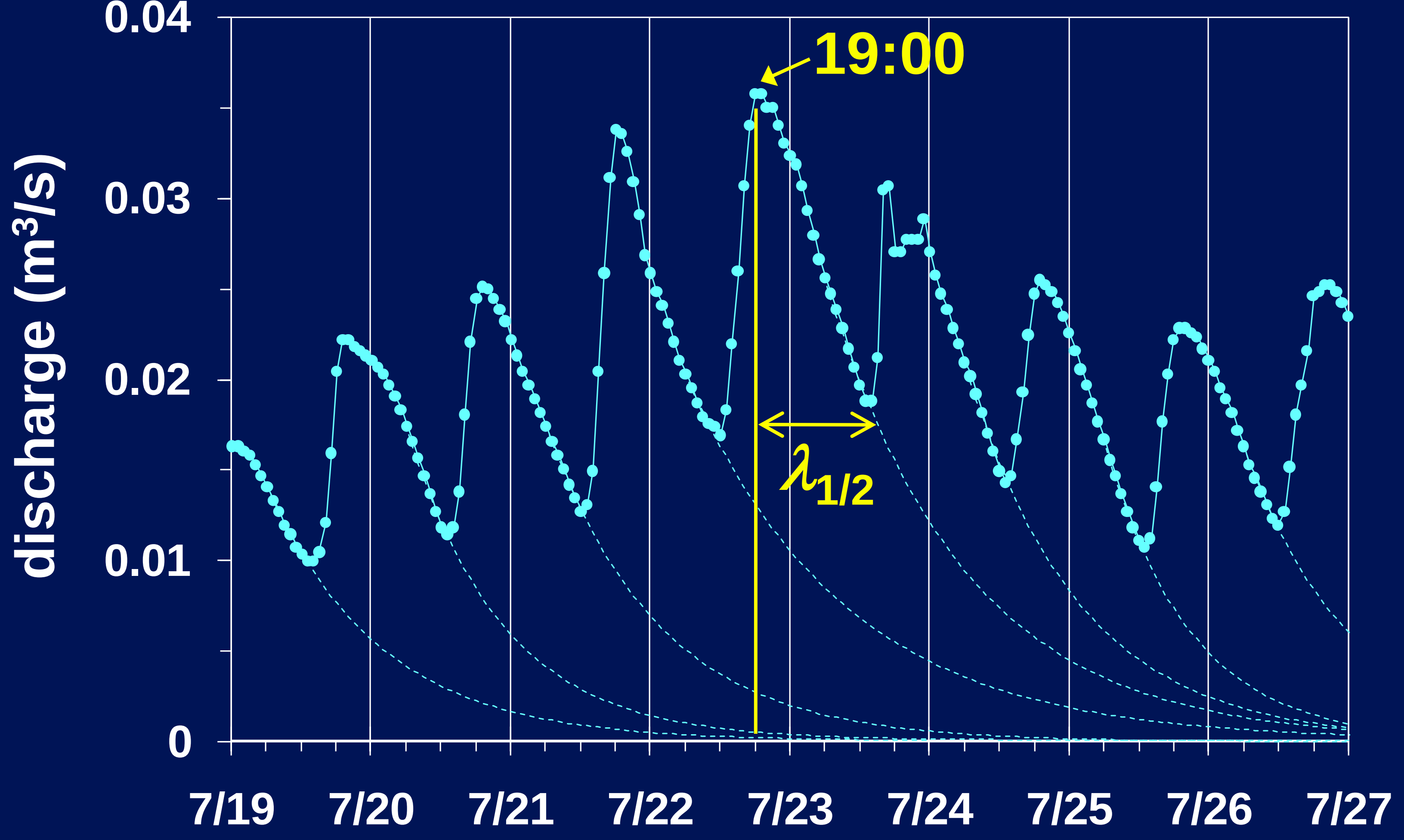


Gauging Station

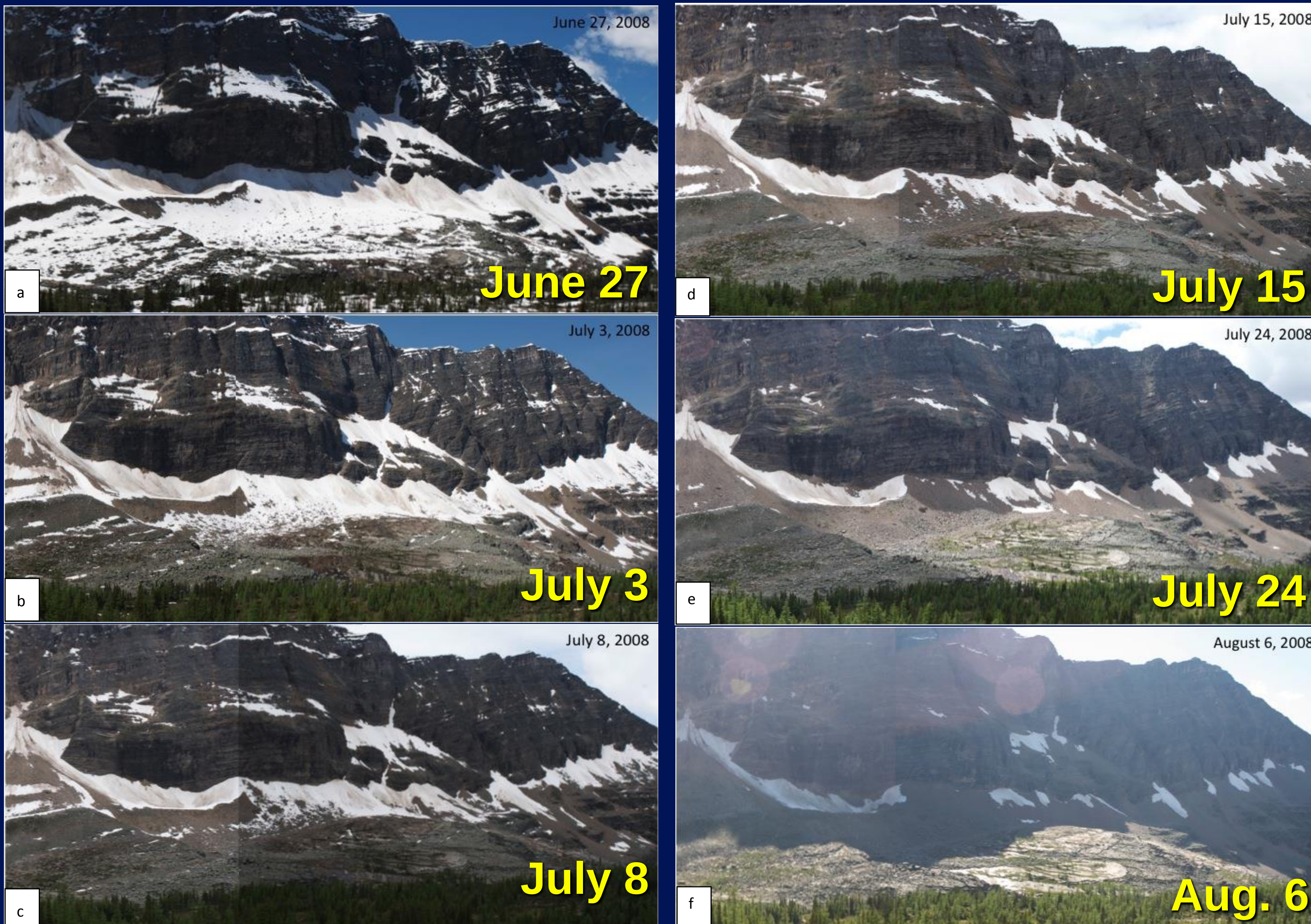
Babylon Creek Discharge, 2008

Diurnal fluctuations, peaking in early evening.

Half life ($\lambda_{1/2}$) of exponential decay < 1 day.

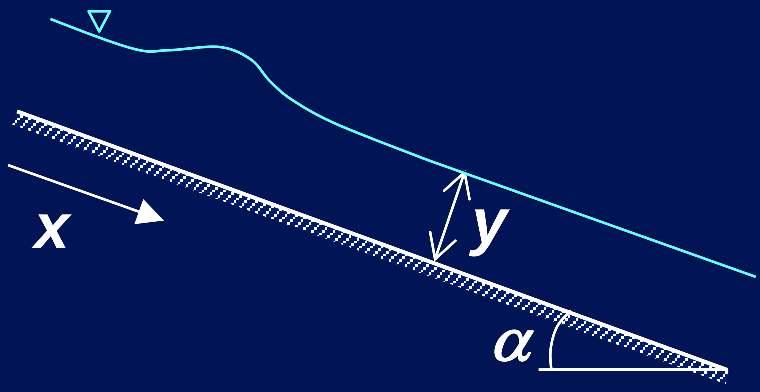


Sequential Photographs, 2008



Hillslope Flow in Unconfined Aquifers

Brutsaert (2005) Approximation: Kinematic Wave



$$Q = Ky\left(-\frac{dy}{dx} + \sin\alpha\right) \cong Ky\sin\alpha$$

Q: flow per unit width (m^2/s)

K: hydraulic conductivity (m/s)

The pulse of water table travels like a wave.

$c = K \sin\alpha / n_e$

c: velocity of wave propagation (m/s)

n_e: drainable porosity

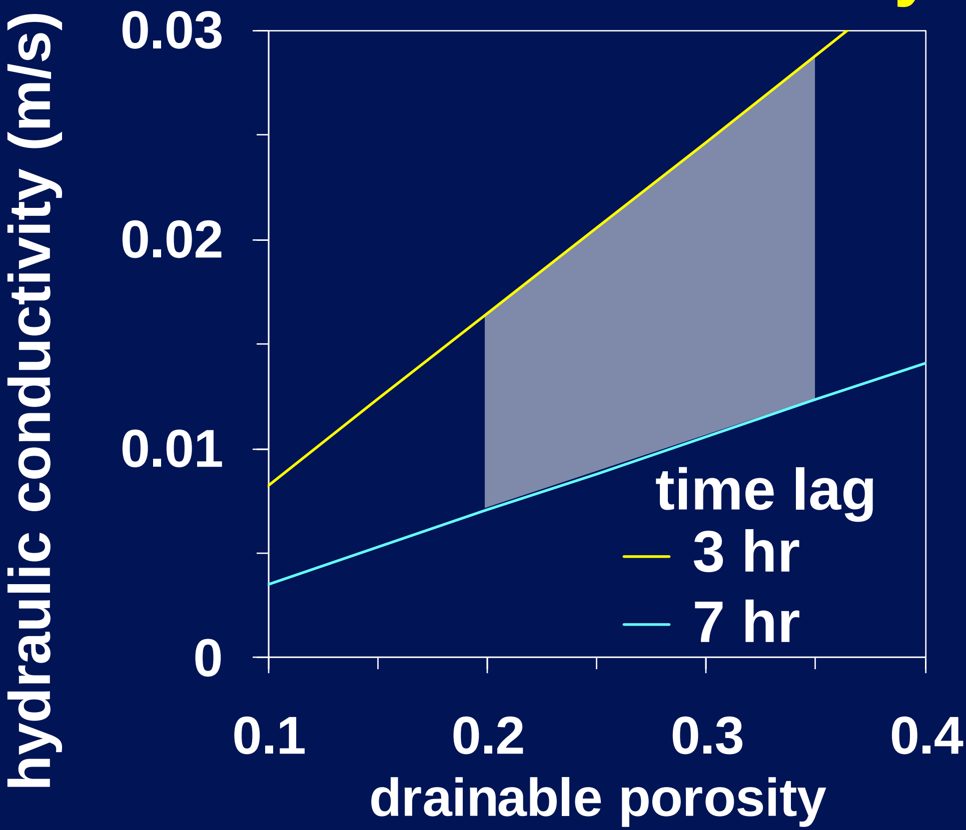
Muir et al. (2011, *Hydrol. Process*., 25: 2954)

Analysis of Babylon Hydrograph

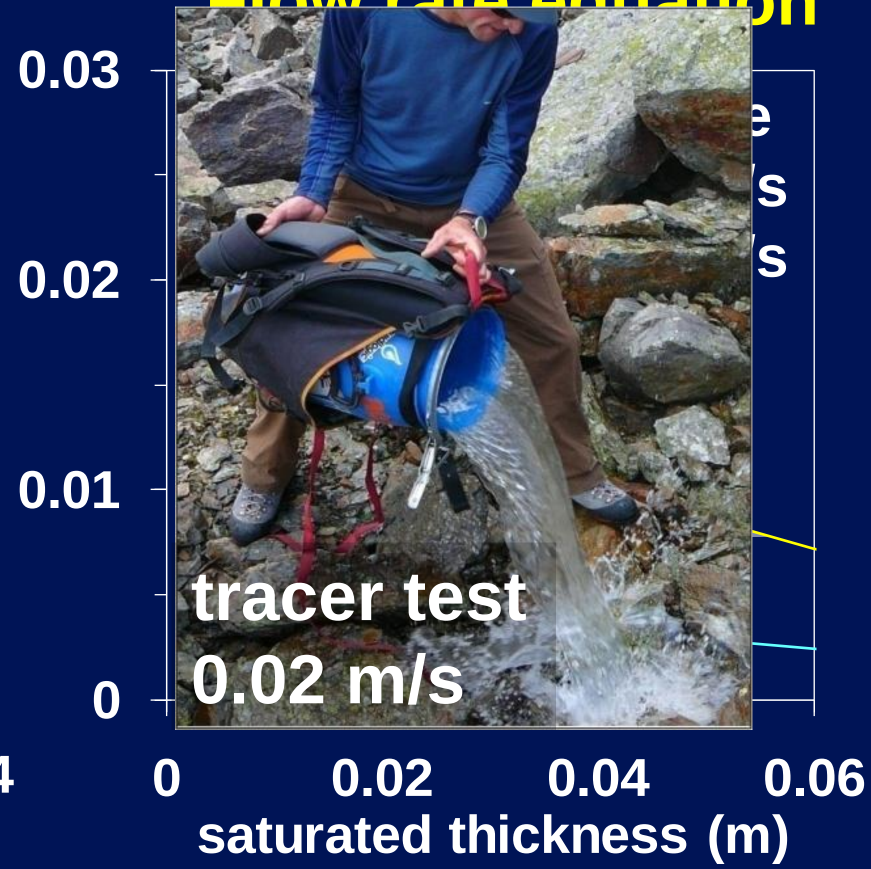
Peak discharge – peak snowmelt = 3 to 7 hrs

Flow rate ranged between 0.01 and 0.03 m^3/s

From wave velocity



Flow rate equation

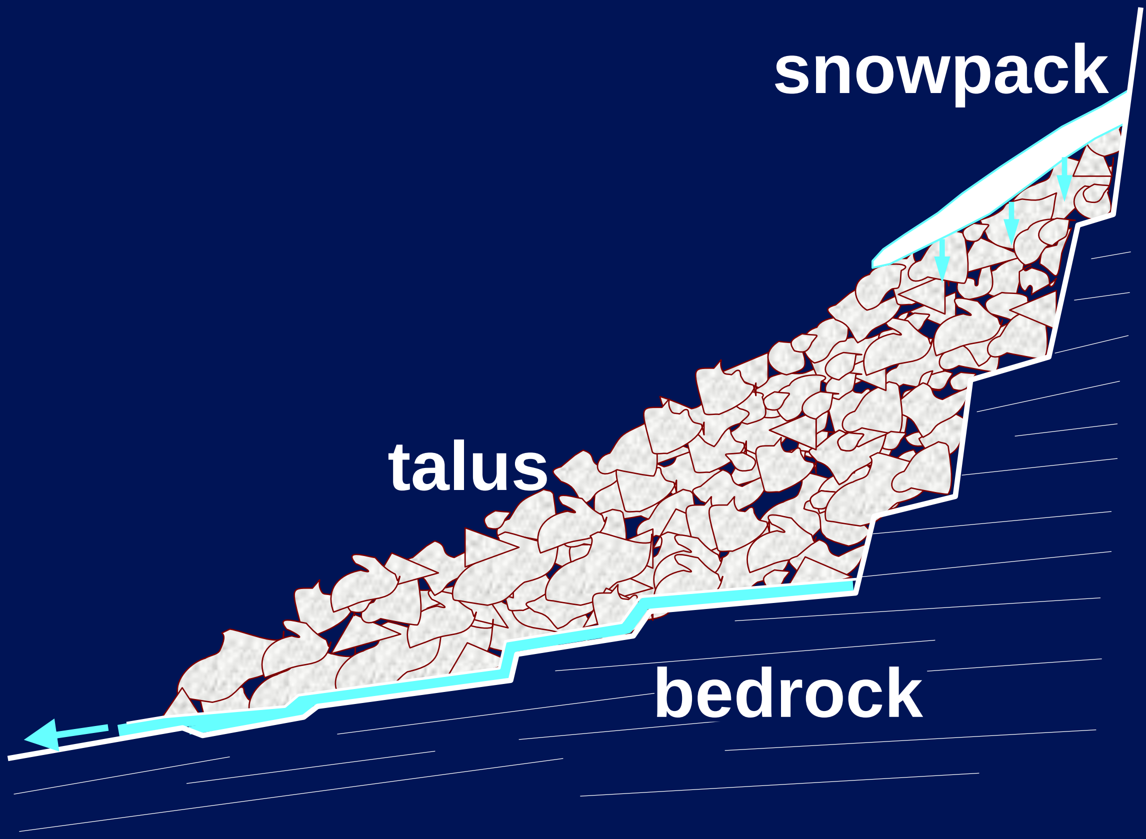


Muir et al. (2011, *Hydrol. Process*., 25: 2954)

Conceptual Model of Talus Groundwater

Fast hydraulic response time (< 2-3 days).

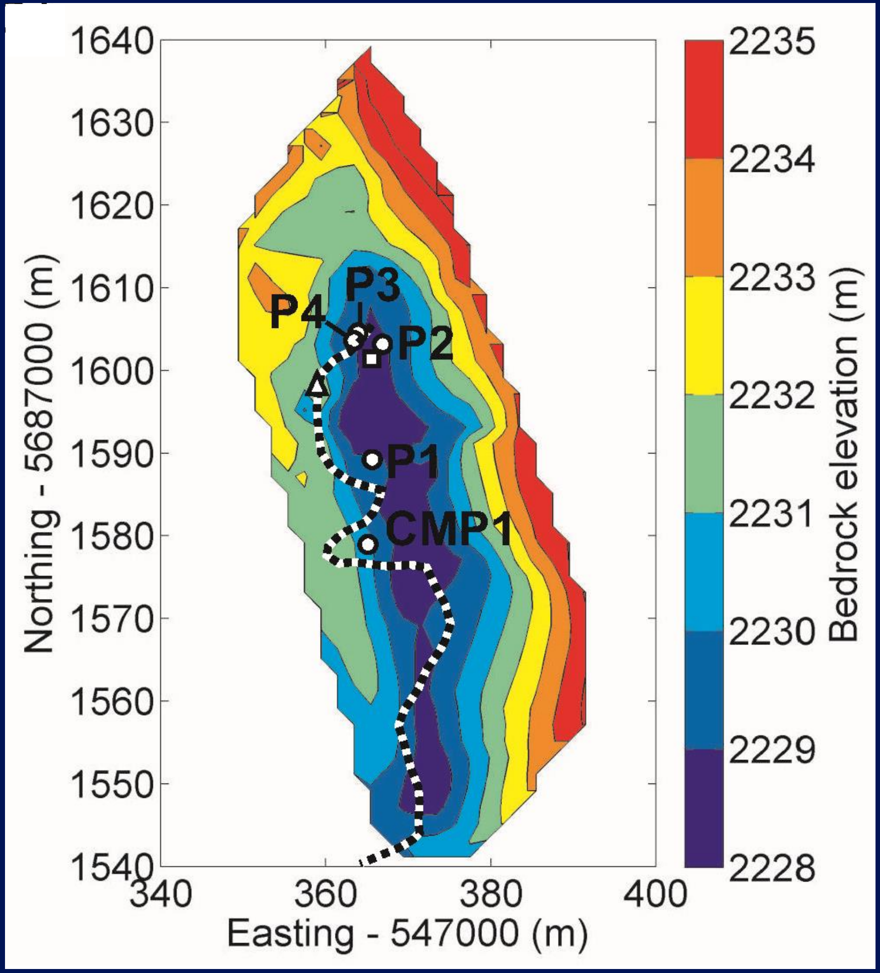
Flow through a thin (< 0.1 m) saturated layer.



Muir et al. (2011, *Hydrol. Process*., 25: 2954)

Hydrogeological Response Unit: Alpine Meadow

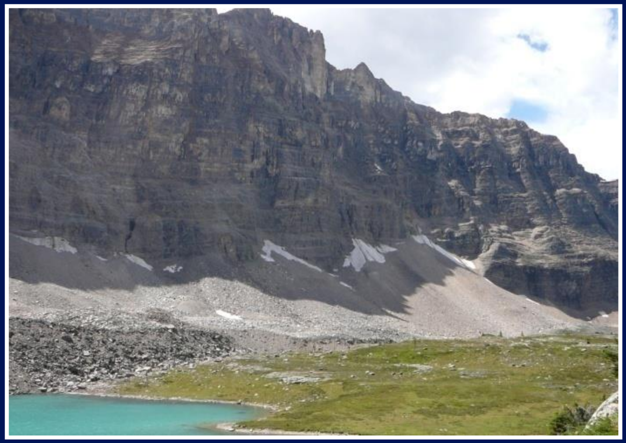
Water table is controlled by fill-spill of bedrock basin.



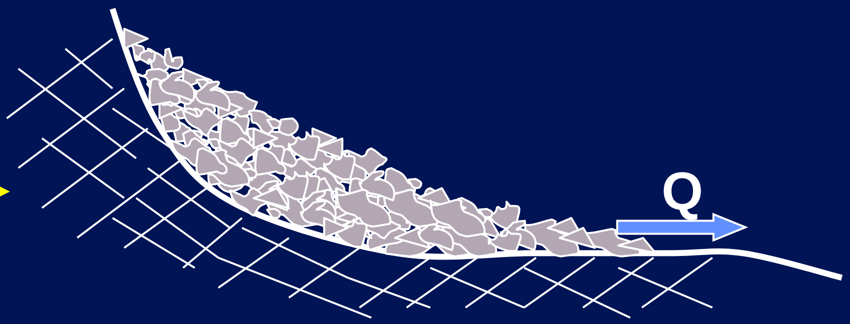
McClymont et al. (2010, *Hydrol. Earth System Sci*., 14: 849)

From Process Observation to Hydrograph

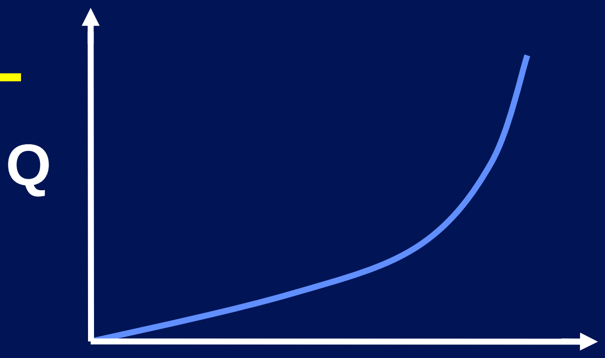
field observation



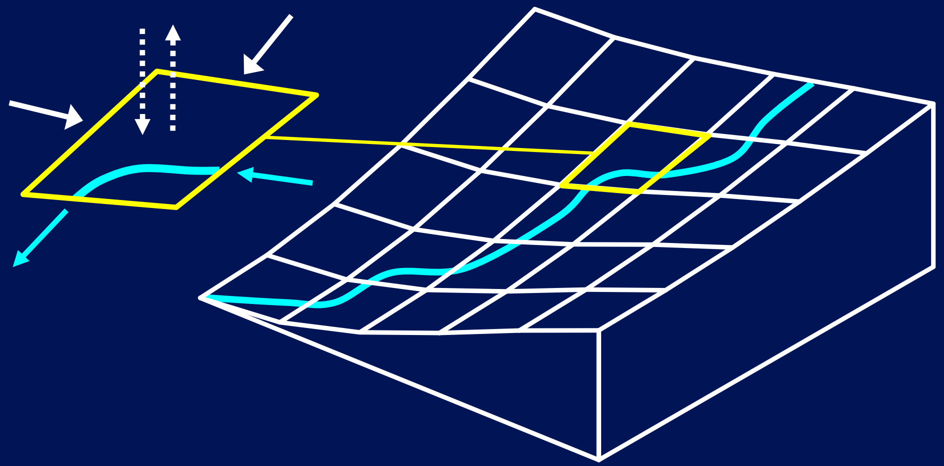
physically-based model



grid-scale function

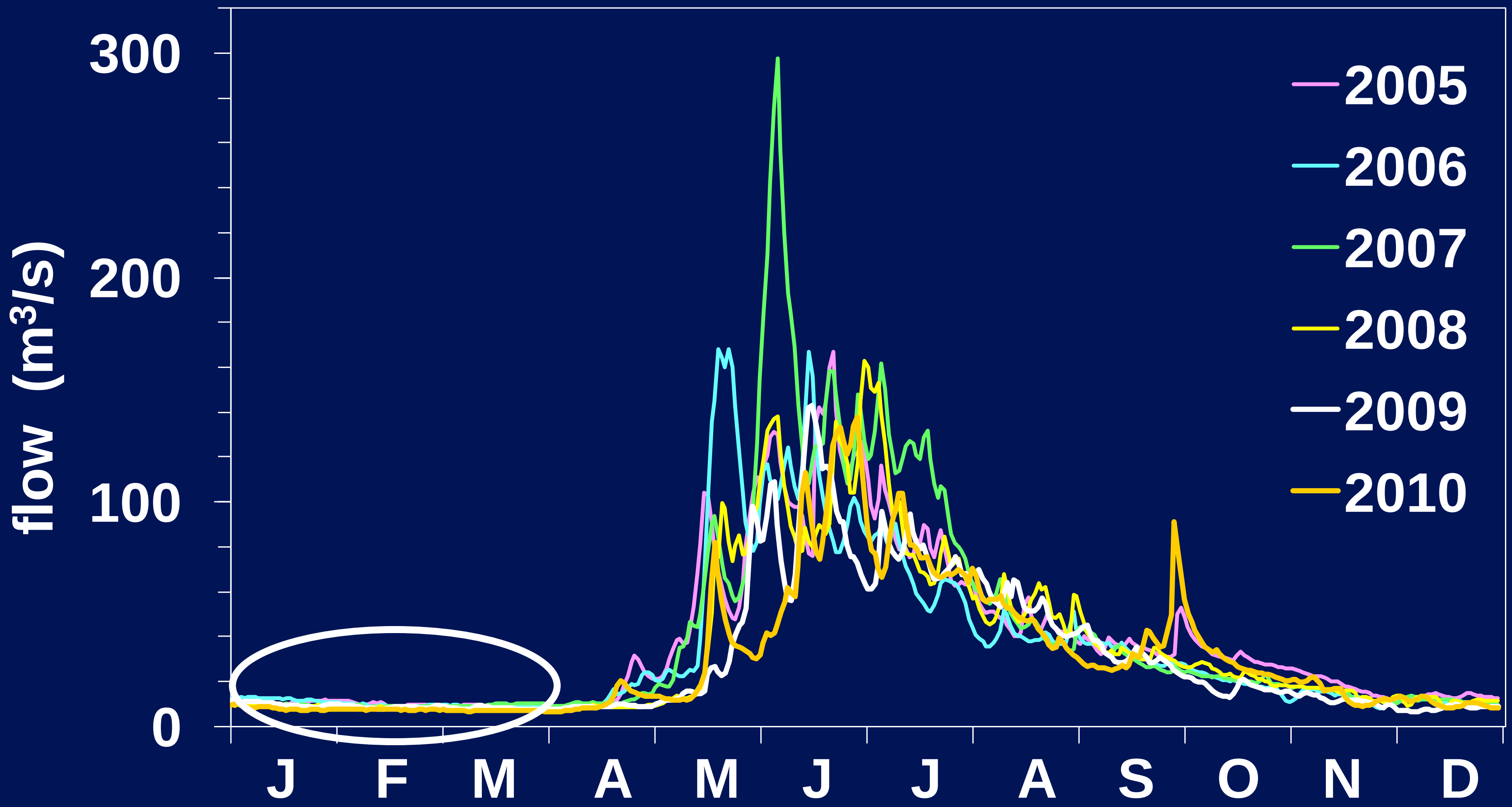


river-basin model



Bow River in the Canadian Rockies

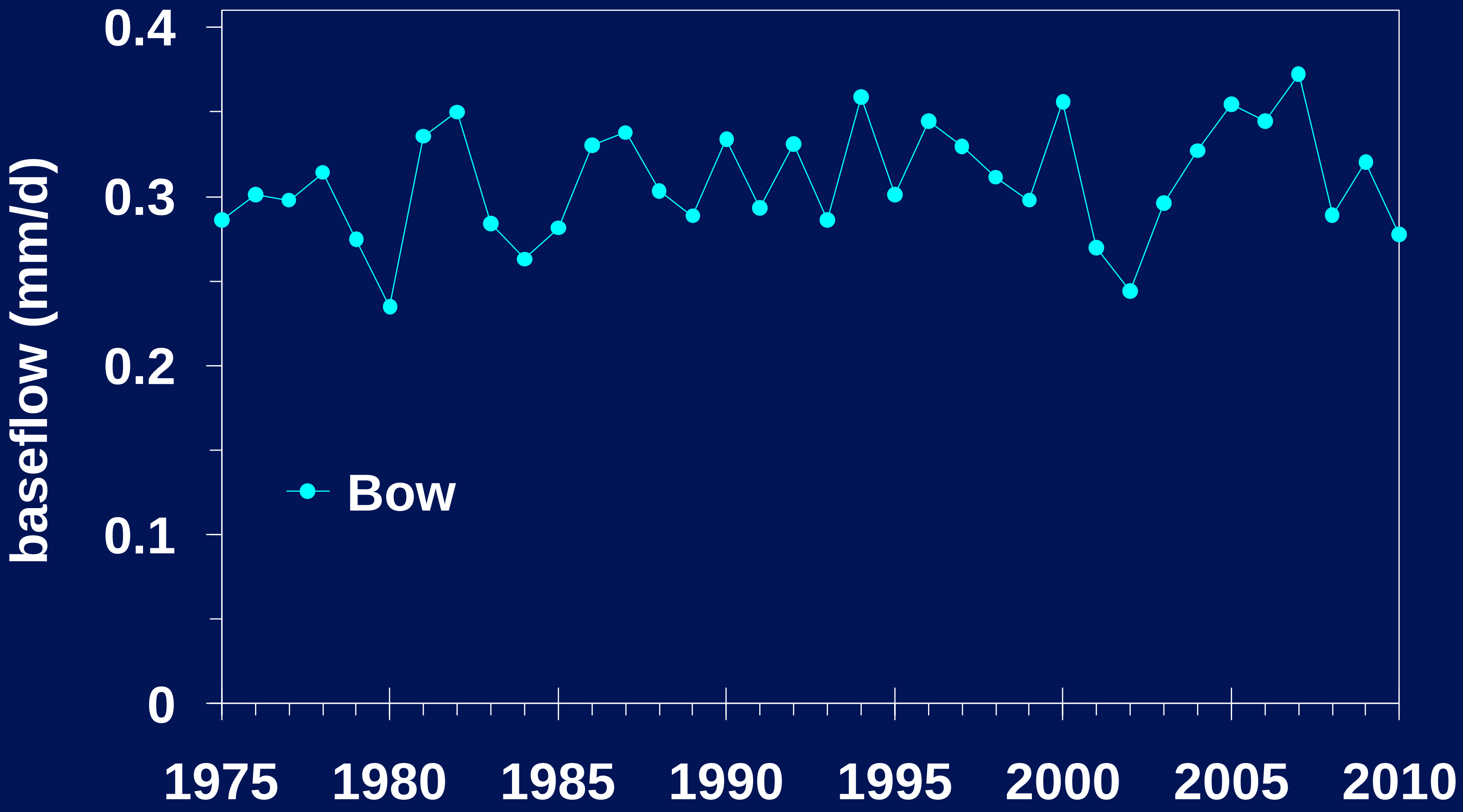
Discharge at Banff (2200 km^2, unregulated)



Data: Water Survey of Canada

Average Winter Baseflow

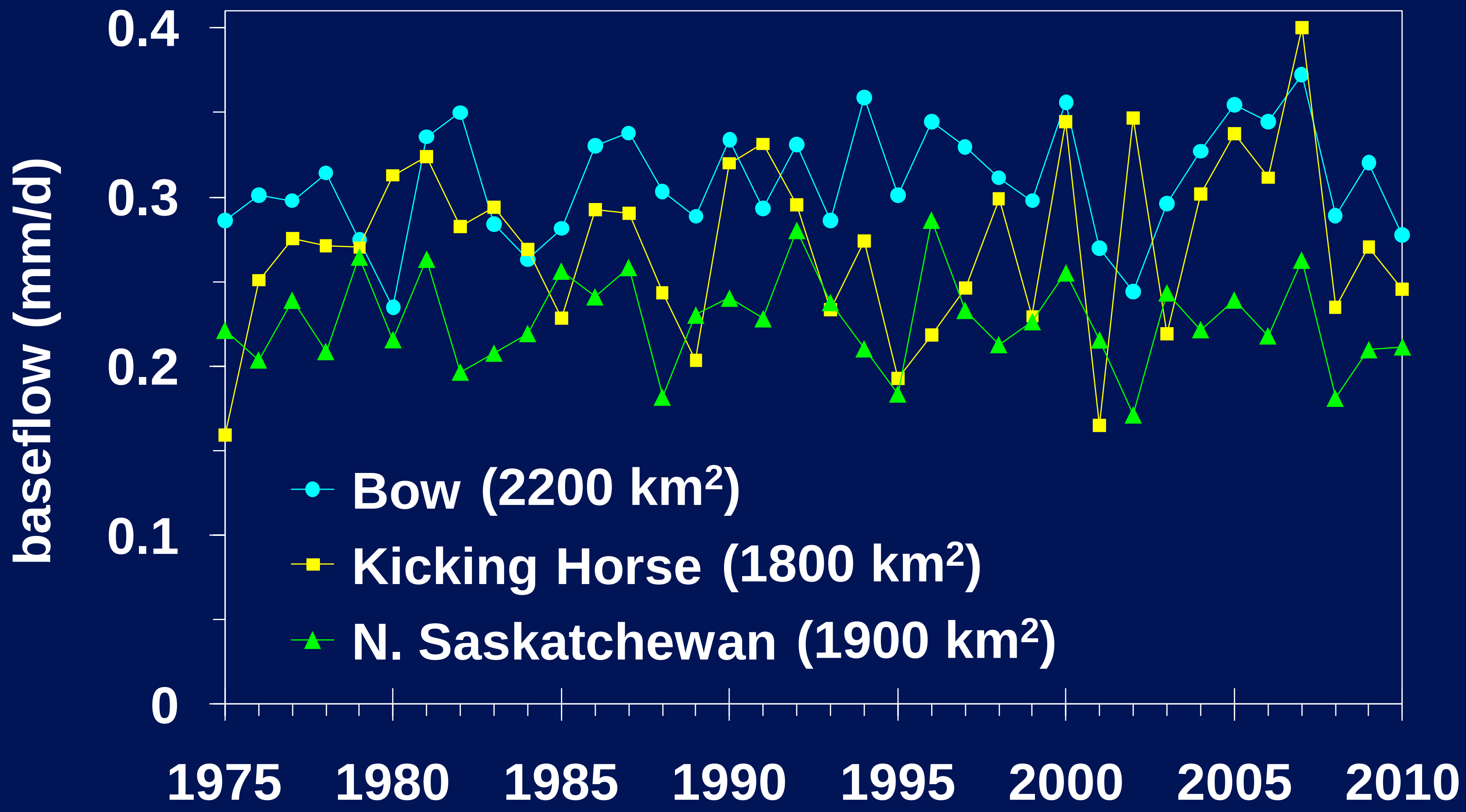
discharge / drainage area



Data: Water Survey of Canada

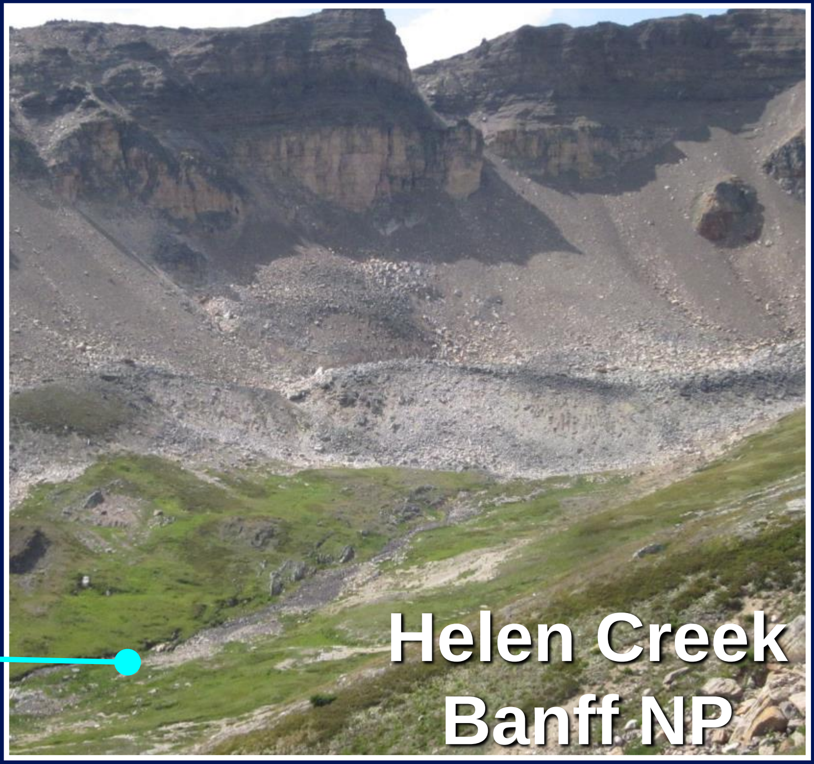
Average Winter Baseflow Runoff

discharge / drainage area



Data: Water Survey of Canada

Groundwater-Dependent Ecosystems



Key Points

1. Groundwater stores snowmelt, glacier-melt, and rain water; and releases them slowly.
2. Storage capacity is smaller than snowmelt volume, but significant for baseflow provision.
3. Bedrock topography controls groundwater flow in alpine hydrogeological response units.
4. Challenge remains in scaling up the field-based understanding to river basin models.

Acknowledgements

Students, Technicians, Post-docs, Colleagues

Greg Langston, Danika Muir, James Roy, Alastair McClymont, Larry Bentley, …..

Funding Support

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