Alpine Hydrogeology: The Critical Role of Groundwater in Sourcing the Headwaters of the World

2018 Darcy Lecture
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Mountains – the Water Towers of the World

Relative water yield (R Wy) = \[ \frac{\text{Mountain runoff (mm/y)}}{\text{Lowland runoff (mm/y)}} \]


~40% of world’s population relies on mountain rivers.
(D. Viviroli, pers. comm.)
Mountains as a Water Tower
Bow River at Banff (2200 km$^2$, unregulated)

Data: Water Survey of Canada

Groundwater sustains year-around stream flow.

www.nps.gov

Seti River, Nepal

Tianshan Wildlife Park, China
Climate Warming and Mountain Hydrology


Glacier melt ‘provides’ 10% of the Rheine River flow at Basel in August (Huss et al., 2011, *WRR*, 47).

Glacier melt? Summer flow contribution

**Big question: The role of groundwater in buffering the effects of climate change.**
The lake has more outflow than inflow.

\[
Q_{GW} = \text{groundwater inflow} - \text{outflow}
\]

30-70 % of water input is by groundwater.

Lake O’Hara Hydrological Observatory (14 km²)
Elevation: 2,000-3,500 m

Images from Google Earth

Hydrogeological Response Units

Opabin Lake
Quartzite Bedrock
Talus
Proglacial Moraine
Meadow
Source spring
Opabin Creek
Snowmelt

Source Spring Flow Rate: 2006


Spring flow (m³ s⁻¹)

Lake WL (m above datum)

Opabin Lake water level

Opabin Plateau

Opabin Creek
Opabin Lake
Source spring
Opabin Glacier

500 m

seismic refraction
electrical resistivity
Seismic Refraction

Electrical Resistivity


Nuclear Magnetic Resonance Imaging

Blue colour indicates water molecules

Conceptual Model of Groundwater Processes


Hydrogeological Response Unit: Alpine Meadow

Conceptual Model of Talus-Meadow Complex


Talus-meadow complex in Bolivia (Caballero et al., 2002, *Catena*, 47:101)


Talus-bottom spring in Swiss Alps (Volze, 2015, PhD Thesis, ETH)

Photo: Jeff Mackenzie

Photo: Nina Volze
Groundwater Discharge from Talus Springs

Flux (m³ s⁻¹)

Gauging Station

Talus
Bedrock
Gauging Stn.

Groundwater Discharge from Talus Springs

Flux (m³ s⁻¹)

Gauging Station

Talus
Bedrock
Gauging Stn.

Δt

Discharge
Snowmelt
Hillslope Flow in Unconfined Aquifers
Brutsaert (2005) Approximation: Kinematic Wave

\[ Q = K h \left( -\frac{dh}{dx} + \sin \theta \right) \approx K h \sin \theta \]

\( Q \): Flow per unit width (m\(^2\) s\(^{-1}\))
\( K \): Hydraulic conductivity (m s\(^{-1}\))

Pulse of water table travels like a wave.
\[ c = K \sin \theta / S_y \]
\( c \): Velocity of wave propagation (m s\(^{-1}\))
\( S_y \): Drainable porosity (or specific yield)


Estimation of Talus Hydraulic Conductivity

Theoretical \( K - S_y \) relation
Time lag (\( \Delta t \)) = 3 to 7 hrs

Helen Creek Watershed – Banff NP
Size: 2.5 km², Elevation: 2300-2900 m

Bow Lake
Helen Creek
Helen Lake
Rock glacier
Spring
Talus
Rock glacier
Hydrogeological Conceptual Model


Discharge from the Spring and Helen Creek

Models for Two-Step Drainage


Rock Glacier Hydrology in Other Continents

Active rock glacier in China
(Han et al., 2018, *Vadose Zone J.*

Relict rock glacier in Austria
(Winkler et al., 2016, *Hydrogeol. J.*)
Water Input and Output in the Opabin Watershed

Water inputs

<table>
<thead>
<tr>
<th>Flux (m³/day)</th>
<th>Snow melt</th>
<th>Rain</th>
<th>Glacier melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (month)</td>
<td></td>
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</table>

Basin discharge

<table>
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<tr>
<th>Flux (m³/day)</th>
<th>Basin discharge</th>
</tr>
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<tbody>
<tr>
<td>time (month)</td>
<td></td>
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</table>

Groundwater provides temporary storage.

Snow Water Equivalent (SWE) in Late April

<table>
<thead>
<tr>
<th>SWE (mm)</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
</tr>
</thead>
</table>

Snowmelt model
- Utah Energy Balance
- Hourly time step
- 25 m grid cells

Shortwave radiation
June 21, 13:00

1 km
Groundwater reservoir fills up every summer

In alpine headwaters, groundwater has:
• Minimal effects on summer peak flow.
• Essential for sustaining winter flow.

How does this translate to larger river basins?
Analysis of Winter Flow

18 River Basins
- Unregulated
- < 3900 km²
- 25+ yr of data

Hydrological year: November 1 - October 31
Normalized flow = Discharge / Basin Area

Hydrograph Example – N. Saskatchewan River

Average Winter Flow (January and February)

No long-term trend
Inter-annual variation

High winter flow after wet year?

No correlation!

Long-Term Mean Flow of 18 Rivers

Summary

Annapurna, Nepal