Catchment Hydrology of Permafrost Basins

or more accurately.....

Soil and runoff processes and parameterization research in Wolf Creek (mostly)

IP3 Team (those were the days….)

Sean K. Carey[1], Yinsuo Zhang, Celina Ziegler,
Michael Treberg, Jessica Boucher

Dept. Geography & Environmental Studies
Carleton University, Ottawa

[1] Now at School of Geography & Earth Sciences, McMaster University

With considerable contributions from:

William Quinton, John Pomeroy, Ric Janowicz

And there were quite a few others!!!

IP3 Research

Process Research

- Runoff and soil hydrological processes in a discontinuous permafrost catchment (Jessica Boucher, Celina Zeilger, Dr. Michael Treberg)

Parameterization Research

- Soil freezing and infiltration/redistribution algorithms (Dr. Yinsuo Zhang)

The Wolf Creek Research Basin

Location:
60^o31 N, 135^o 31' W

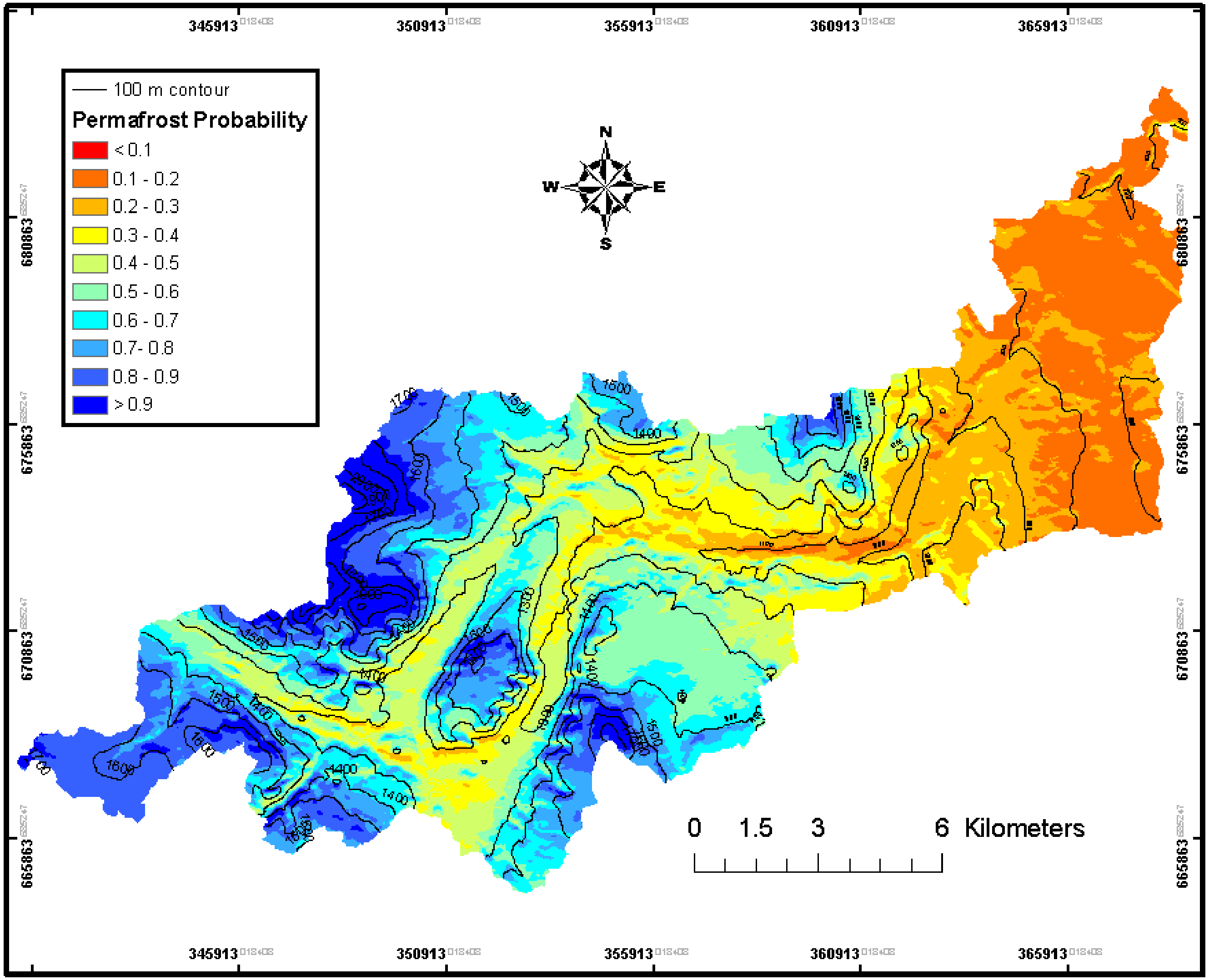
Area:
Approx. 200 km^2

Elevation Range:
800 to 2250 m a.s.l.
(3 ecozones)

Mean Annual Precipitation:
300 to 400 mm (40% snow)

Mean Annual Temperature:
-3 ^oC

Permafrost Distribution within Wolf Creek



Map Courtesy Antoni Lewkowicz, U. of Ottawa

Granger sub-basin

- 8 km^2
- largely above tree-line
- >75% underlain with permafrost

The big (and old...) questions

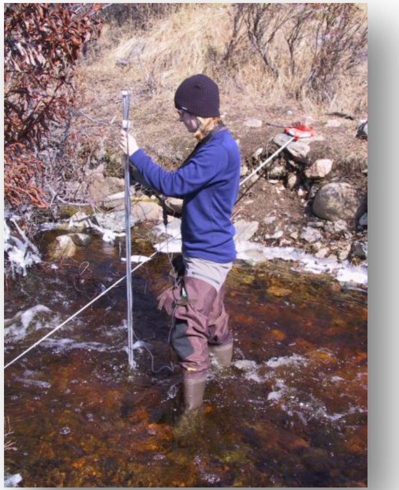
- Where does the water come from?
- How does it get to the stream?

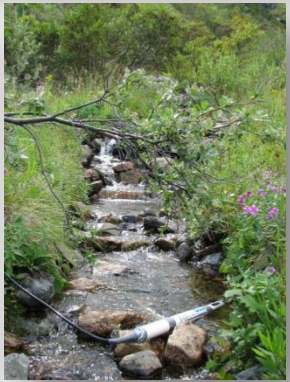
- What are we missing here?

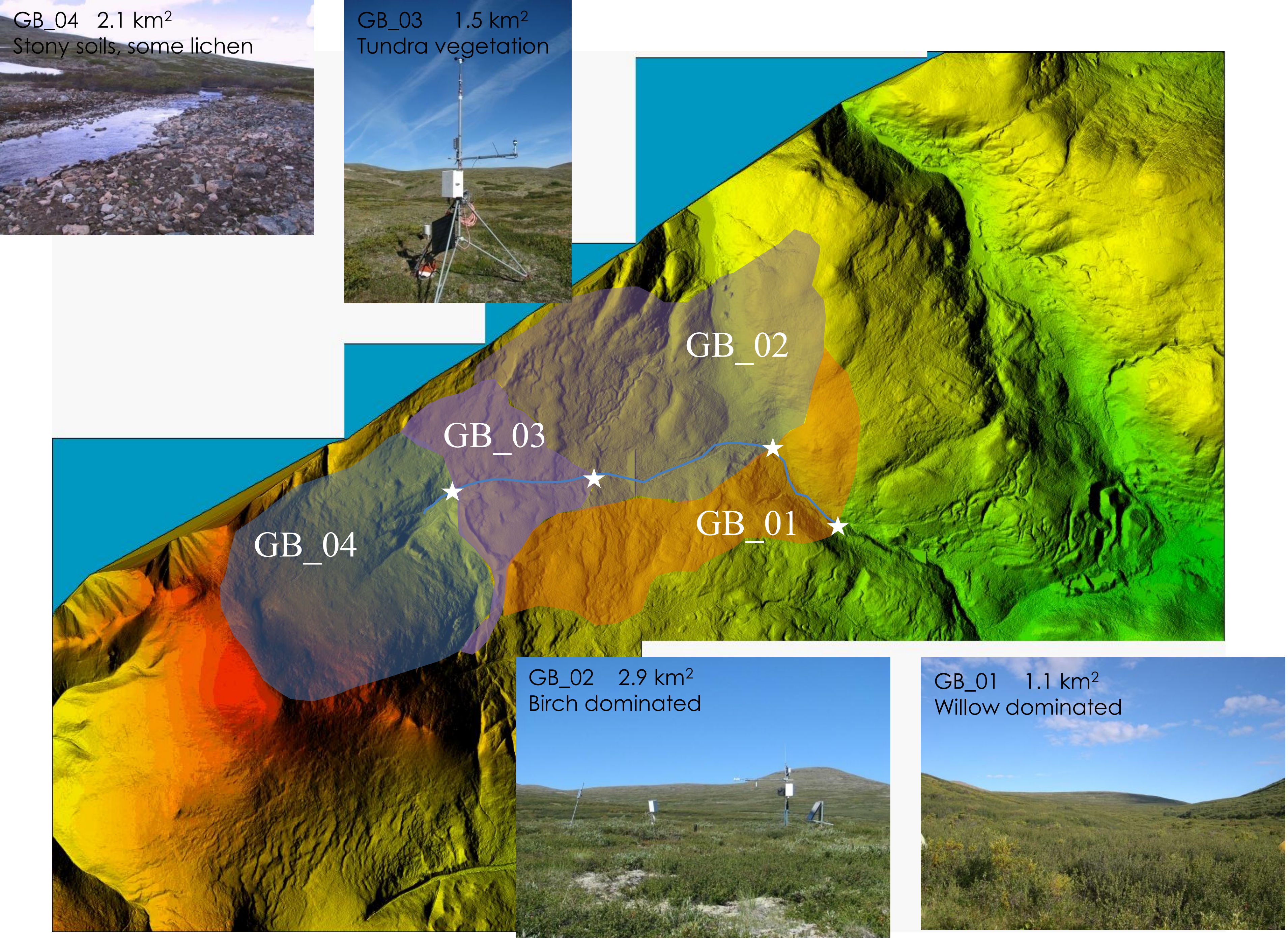
Process Hits and Misses

Techniques

- High-frequency Sampling
- Synoptic Sampling
- Hydrometric
- Hydrochemical





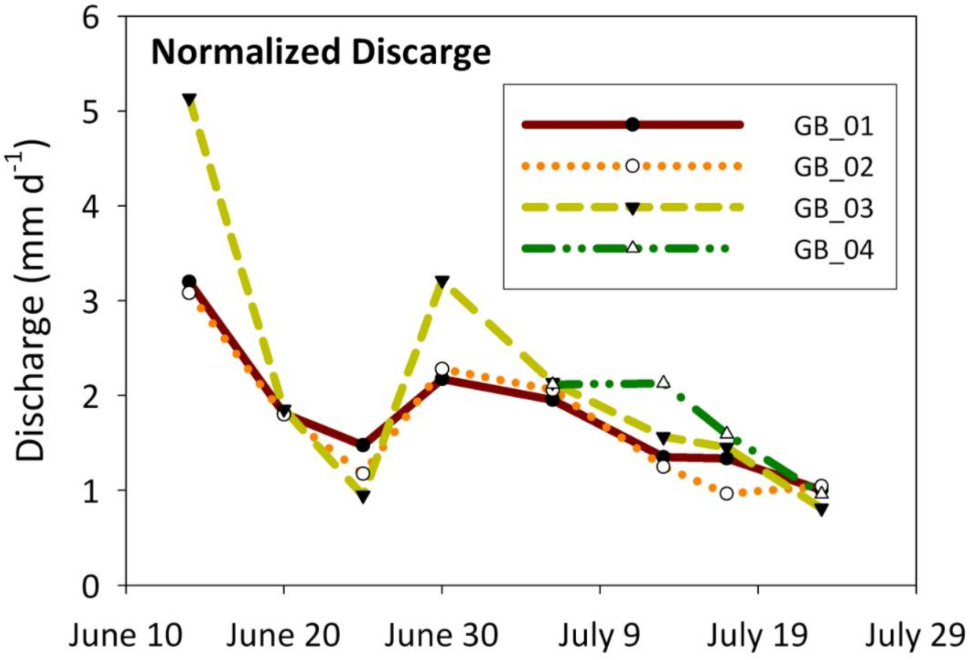


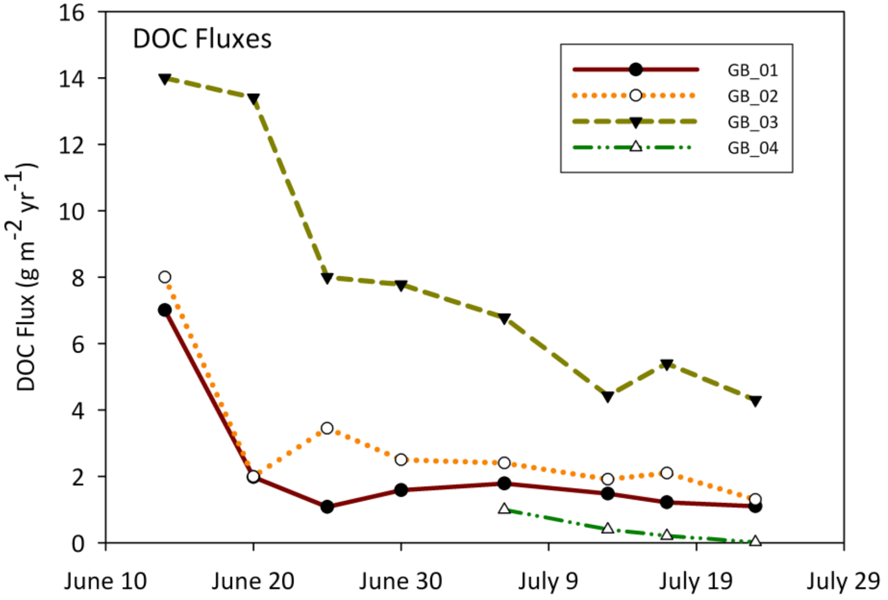
GB_04 2.1 km^2
Stony soils, some lichen

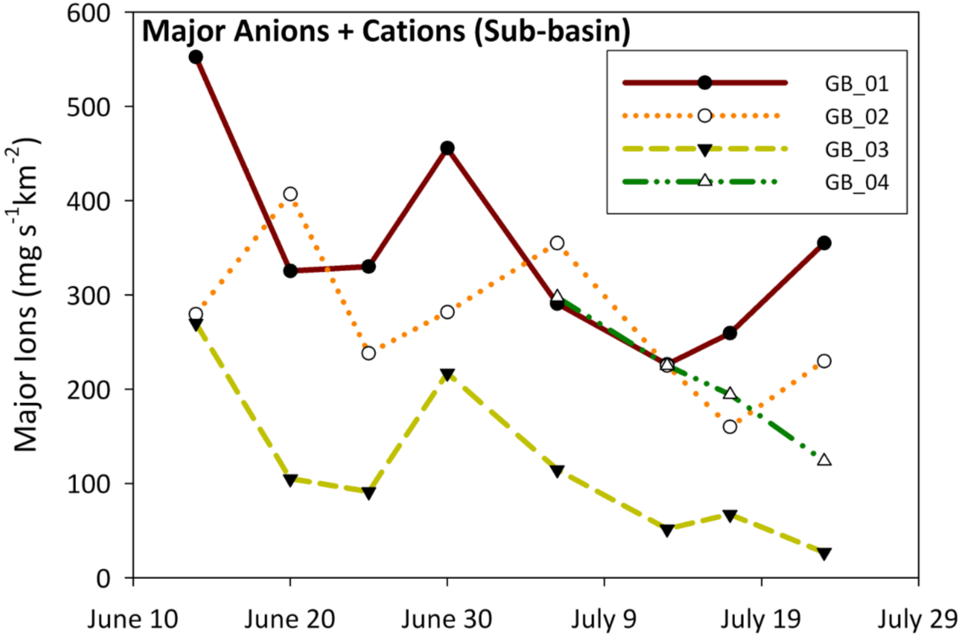
GB_03 1.5 km^2
Tundra vegetation

GB_02 2.9 km^2
Birch dominated

GB_01 1.1 km^2
Willow dominated



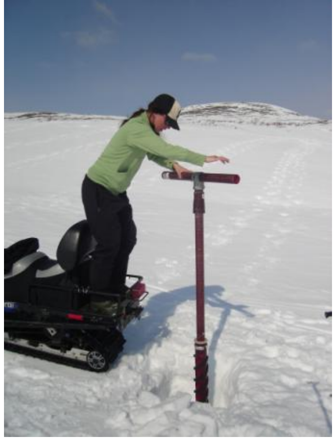


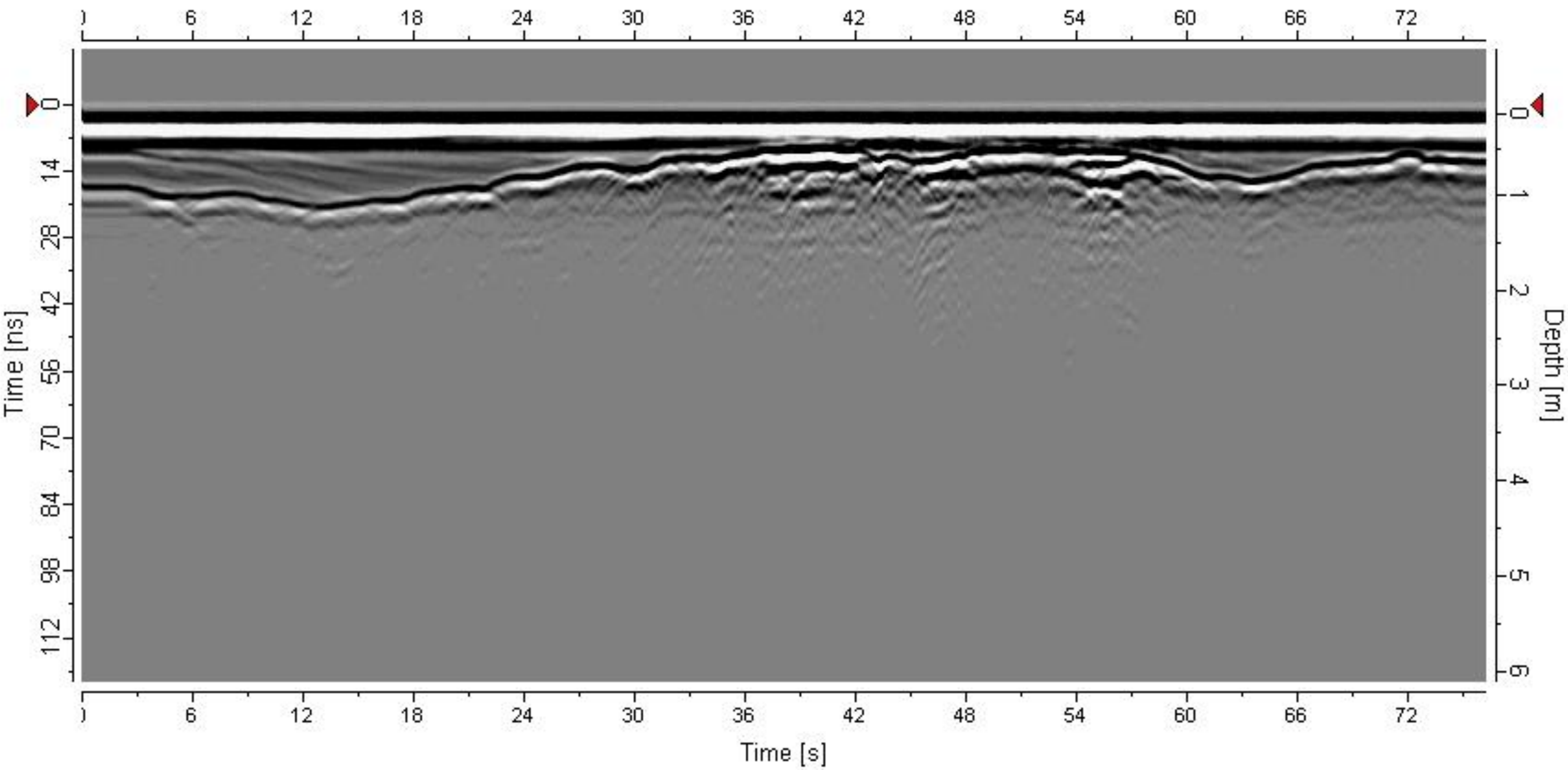


- All HRUs contribute water to the stream in approximately equal volume.
- Much greater deep groundwater flow than previously reported or anticipated.
- Role of channel ice/snow to be investigated

How can we get a handle on channel processes?

Adventures in GPR




0
6
12
18
24
30
36
42
48
54
60
66
72
Time [ns]
0
14
28
42
56
70
84
98
112
Depth [m]
0
1
2
3
4
5
6
Time [s]

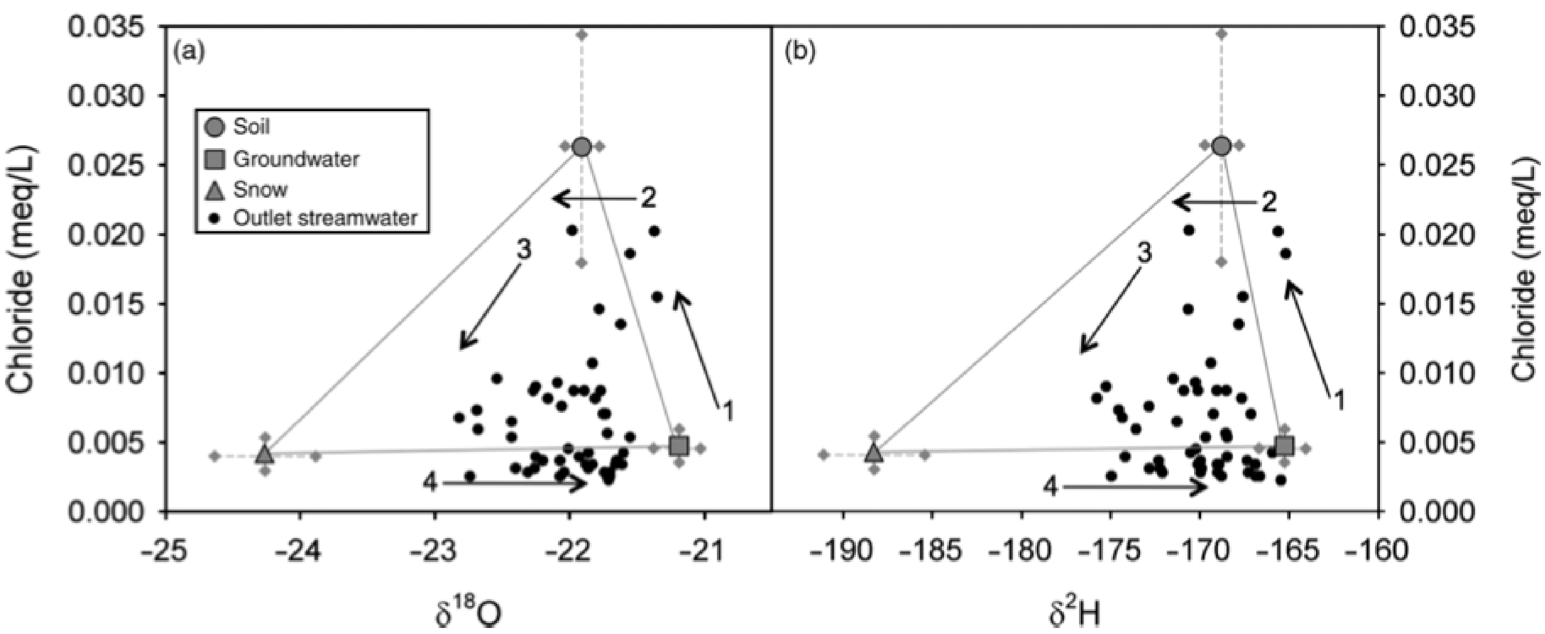


Table 3 | Granger Basin water balance components, melt period air temperature and event-water contributions using $\delta^{18}O$ for four years. Period is 20 April–1 July

Year	2002	2003	2006	2008
Runoff (mm)	112	62	118	147
SWE (mm)	213	190	160	152
Precipitation (mm)	24	27	76	68
SWE + precipitation (mm)	237	217	236	220
Runoff ratio	0.47	0.29	0.50	0.67
Previous August–October Rainfall (mm)	69	74	80.3	109
April–June air temp (°C)	4.9	6.2	6.6	6.4
Event-water contribution	22	10	26	32
Maximum event water contribution	0.47	0.29	0.50	0.55

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Exploring runoff processes using chemical, isotopic and hydrometric data in a discontinuous permafrost catchment

Jessica L. Boucher and Sean K. Carey

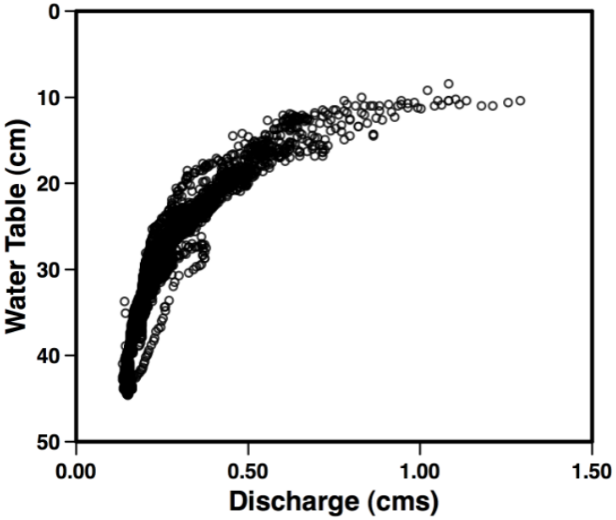
ABSTRACT

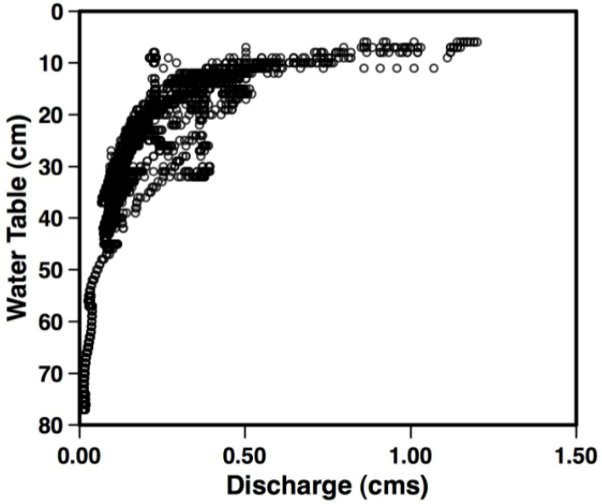
Hydrometric, isotopic and hydrochemical data were used to investigate runoff generation in a discontinuous permafrost headwater catchment. Research was undertaken between 10 April and 8 July 2008 within Granger Basin, a 7.6 km^2 sub-catchment of the Wolf Creek Research Basin, Yukon Territory, Canada. The objectives of this research were to utilize hydrometric, stable isotope and hydrochemical methods to: (i) establish water balance components and (ii) couple water balance information with stable isotope and hydrochemical information to provide an

Jessica L. Boucher
Sean K. Carey (corresponding author)
Department of Geography and Environmental Studies,
Carleton University,
Ottawa, Ontario,
Canada K1S 5B6
Tel.: +1 613 520 2600
Fax: +1 613 520 4301
E-mail: *sean_carey@carleton.ca*

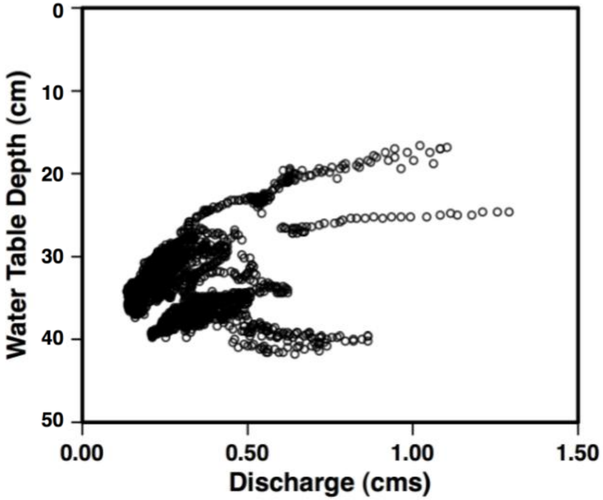
Water table – discharge patterns

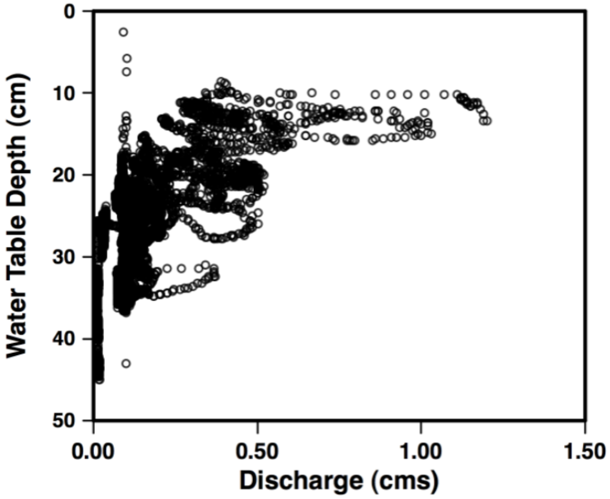
Near-stream



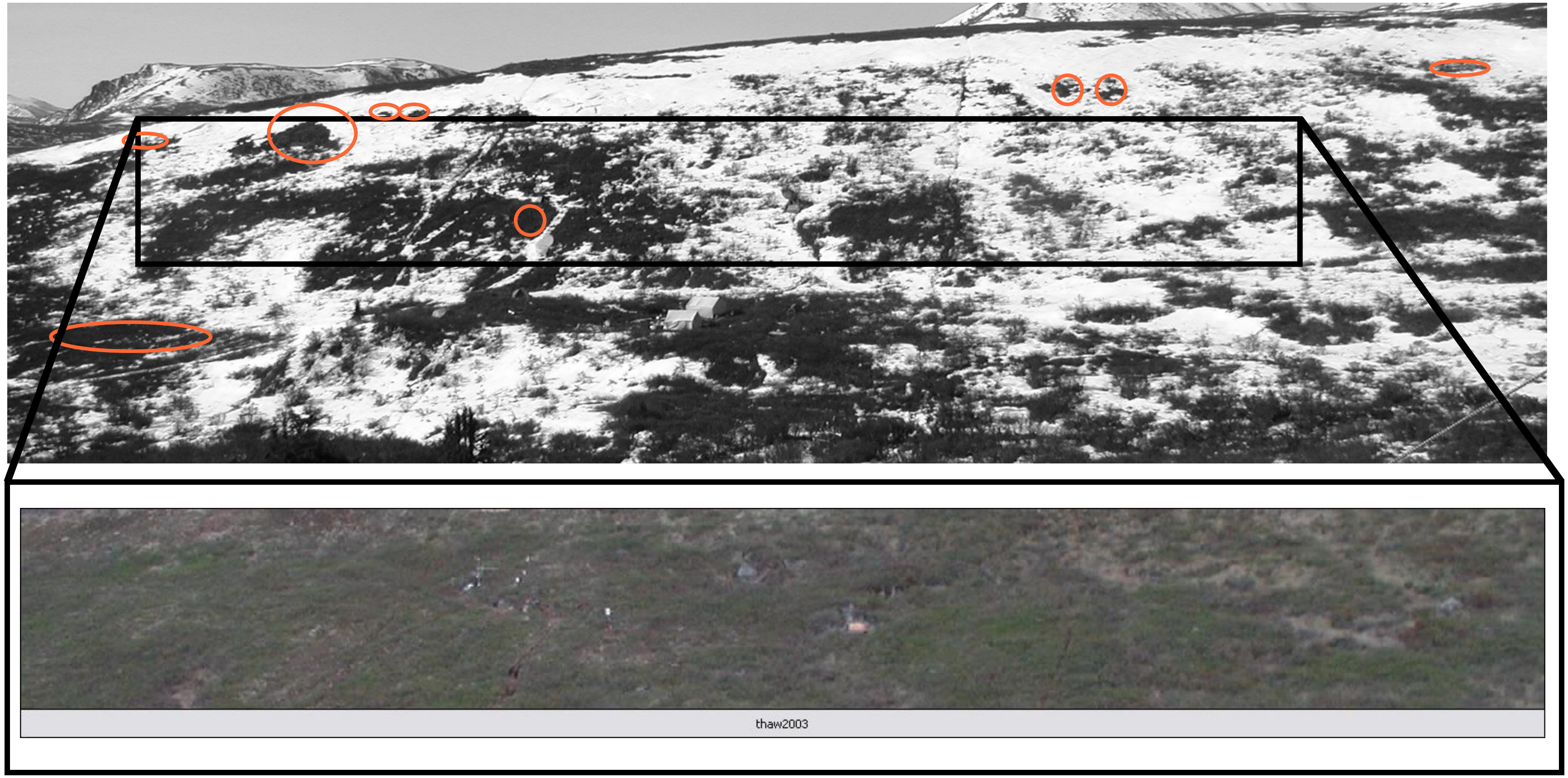


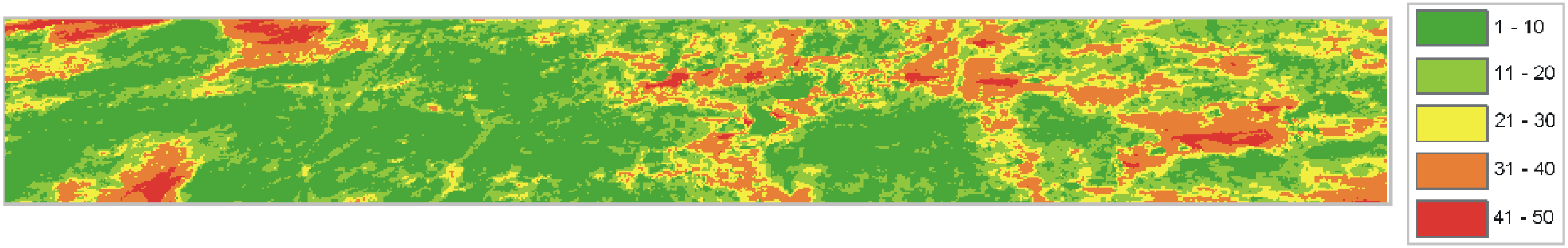
Away from stream



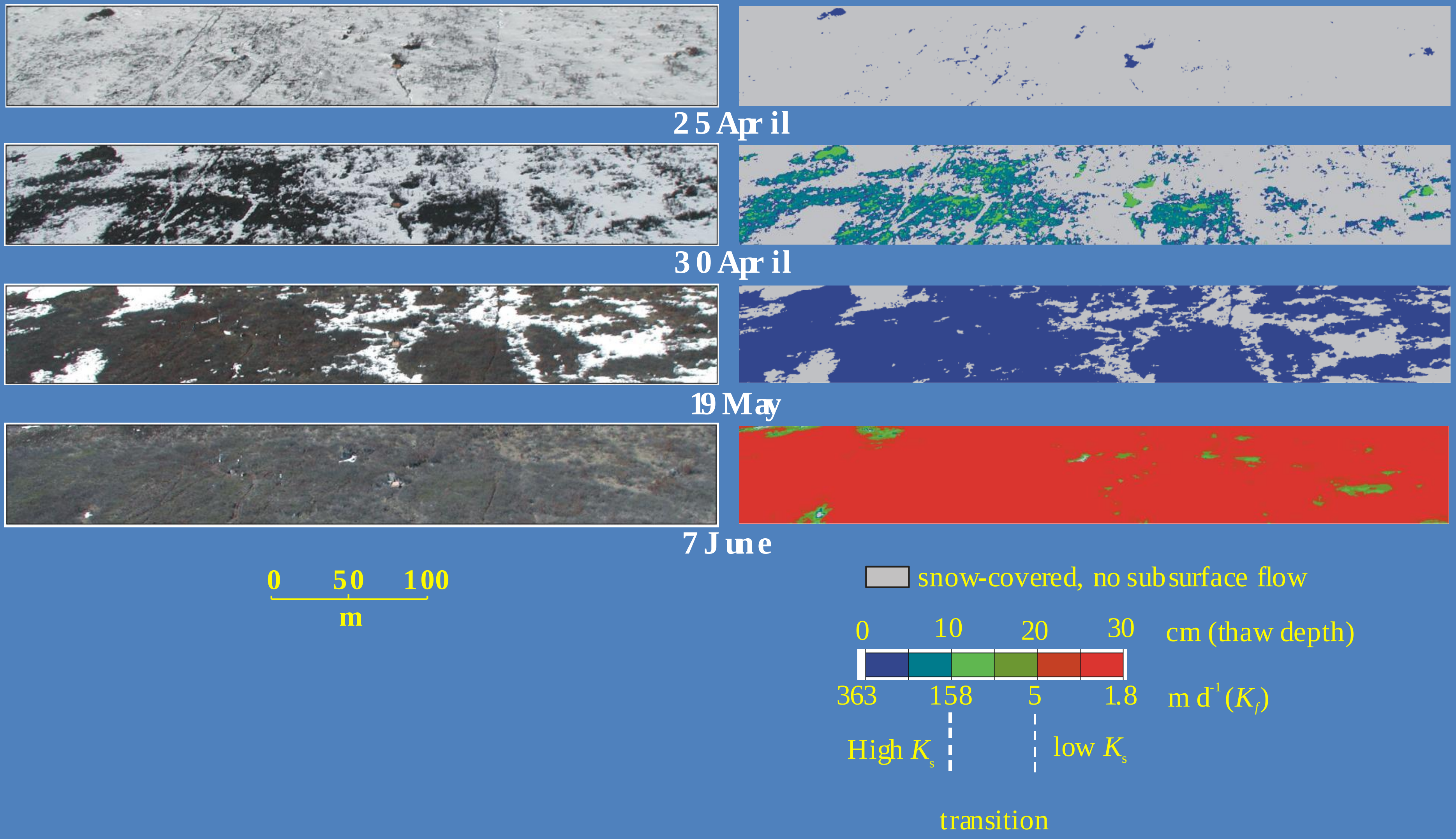


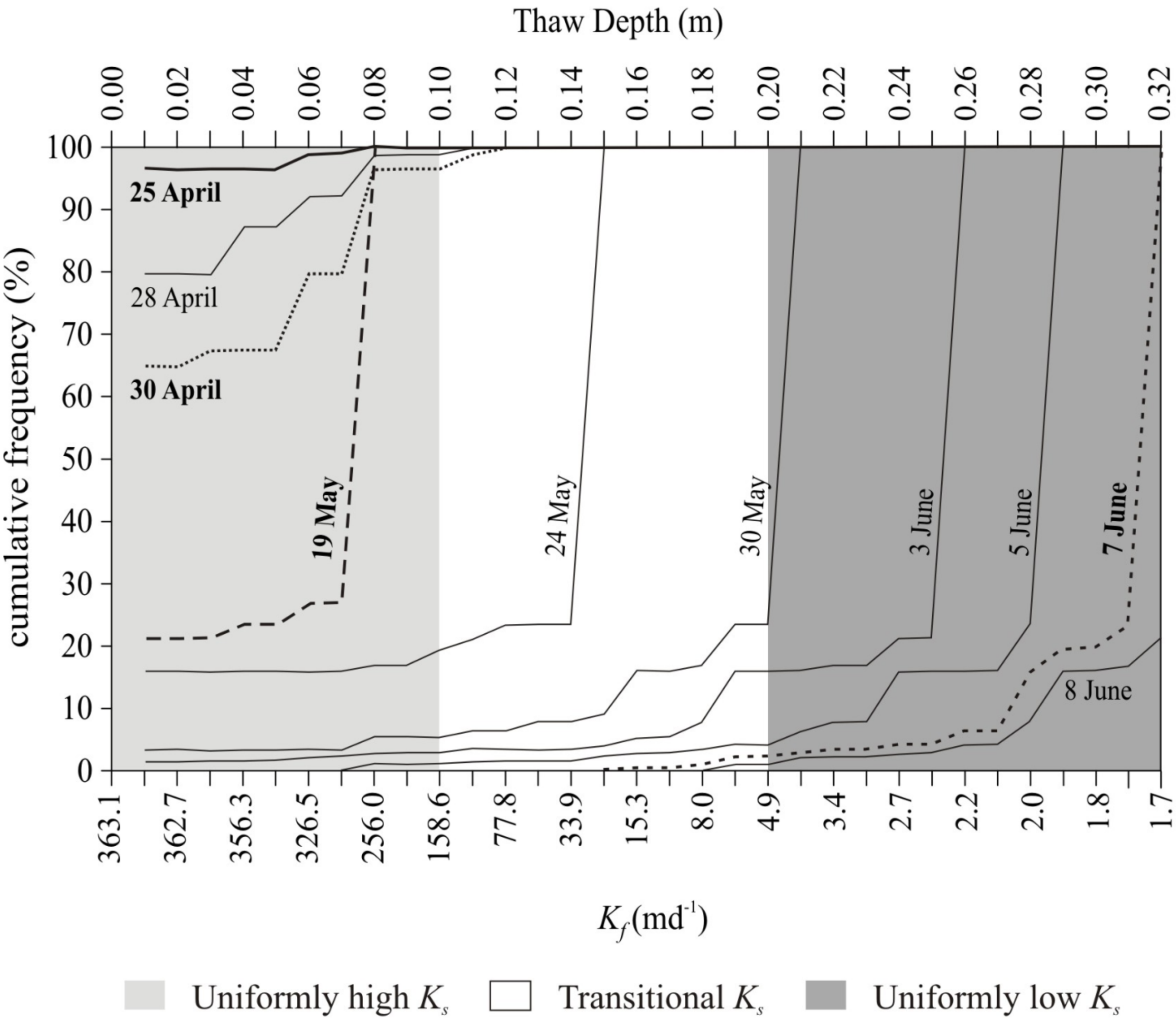
Thermal energy controls on active layer development

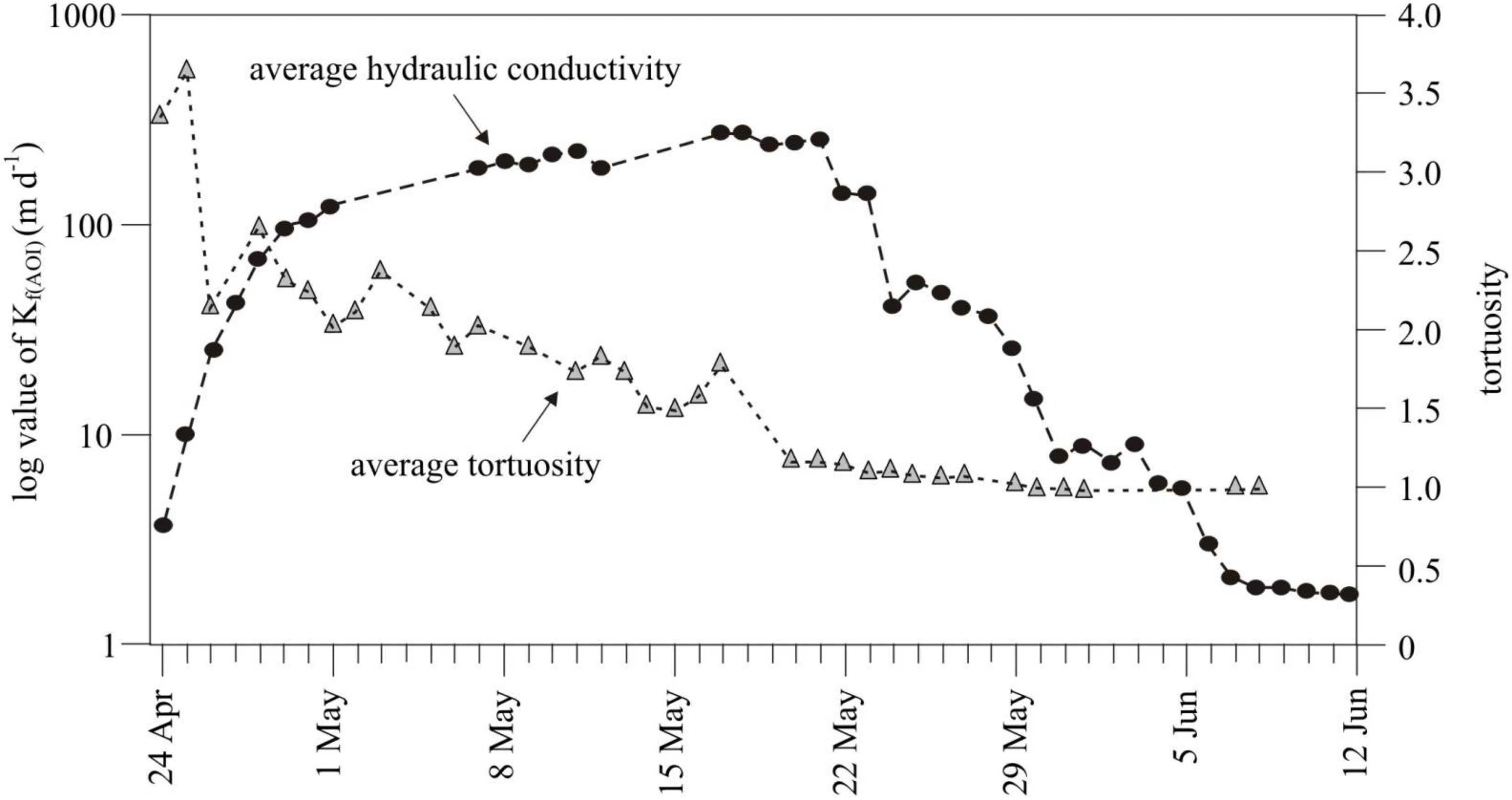




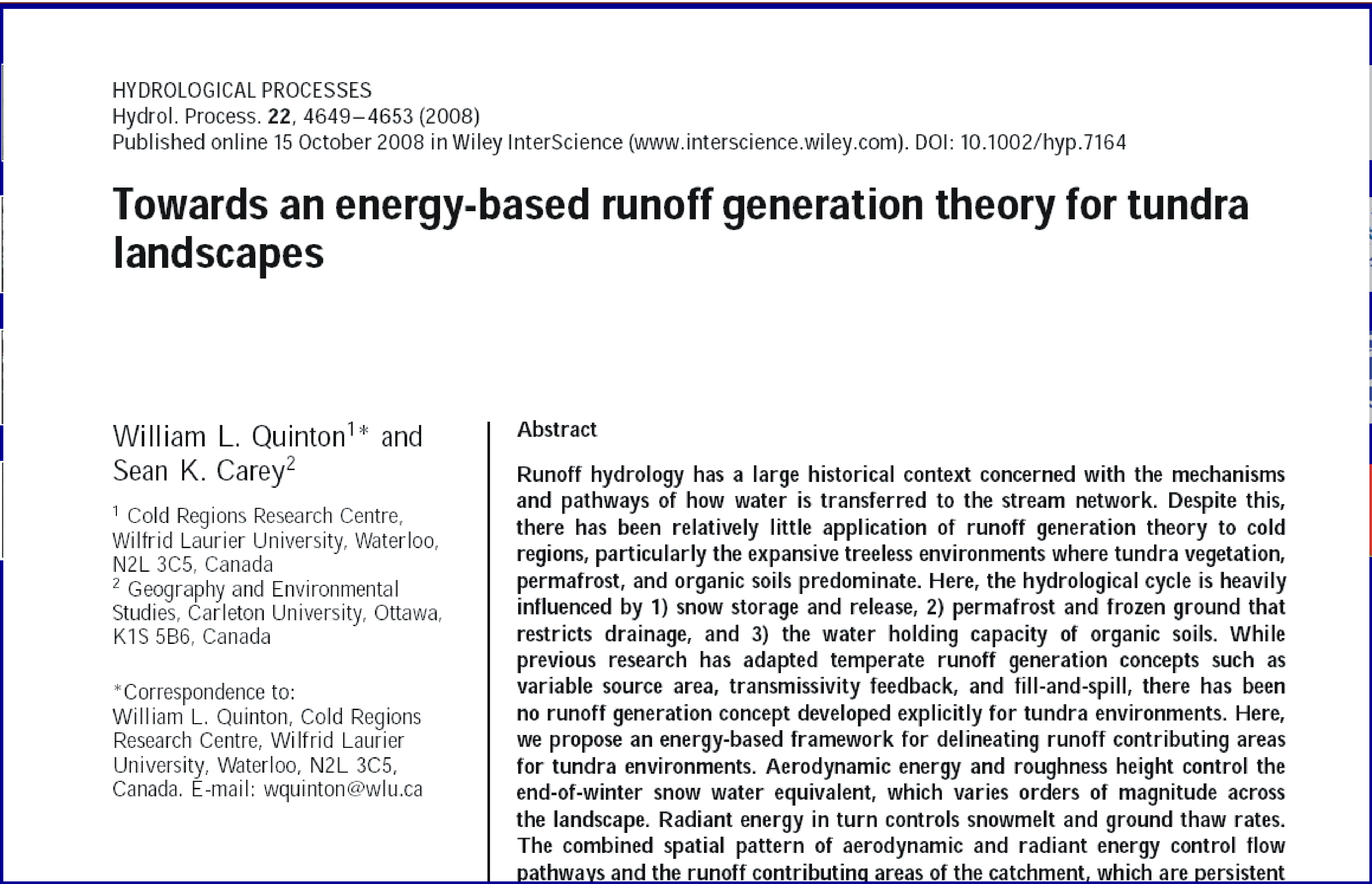
Hillslope-scale hydraulic conductivity determined via frost table topography




Thaw Depth (m)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
cumulative frequency (%)
100
90
80
70
60
50
40
30
20
10
0
25 April
28 April
30 April
19 May
24 May
30 May
3 June
5 June
7 June
8 June
363.1
362.7
356.3
326.5
256.0
158.6
77.8
33.9
15.3
8.0
4.9
3.4
2.7
2.2
2.0
1.8
1.7
K_f(md^{-1})
Uniformly high K_s
Transitional K_s
Uniformly low K_s


1000
100
10
1
log value of $K_{f(AOI)}$ (m d^{-1})
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
tortuosity
average hydraulic conductivity
average tortuosity
24 Apr
1 May
8 May
15 May
22 May
29 May
5 Jun
12 Jun

How has IP3 influenced catchment hydrological thinking?



HYDROLOGICAL PROCESSES
Hydrol. Process. **22**, 4649–4653 (2008)
DOI: 10.1002/hyp.7164

Towards an energy-based runoff generation theory for tundra landscapes

William L. Quinton[1]* and
Sean K. Carey[2]

[1] Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, N2L 3C5, Canada
[2] Geography and Environmental Studies, Carleton University, Ottawa, K1S 5B6, Canada

*Correspondence to:
William L. Quinton, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, N2L 3C5, Canada. E-mail: wquinton@wlu.ca

Abstract

Runoff hydrology has a large historical context concerned with the mechanisms and pathways of how water is transferred to the stream network. Despite this, there has been relatively little application of runoff generation theory to cold regions, particularly the expansive treeless environments where tundra vegetation, permafrost, and organic soils predominate. Here, the hydrological cycle is heavily influenced by 1) snow storage and release, 2) permafrost and frozen ground that restricts drainage, and 3) the water holding capacity of organic soils. While previous research has adapted temperate runoff generation concepts such as variable source area, transmissivity feedback, and fill-and-spill, there has been no runoff generation concept developed explicitly for tundra environments. Here, we propose an energy-based framework for delineating runoff contributing areas for tundra environments. Aerodynamic energy and roughness height control the end-of-winter snow water equivalent, which varies orders of magnitude across the landscape. Radiant energy in turn controls snowmelt and ground thaw rates. The combined spatial pattern of aerodynamic and radiant energy control flow pathways and the runoff contributing areas of the catchment, which are persistent

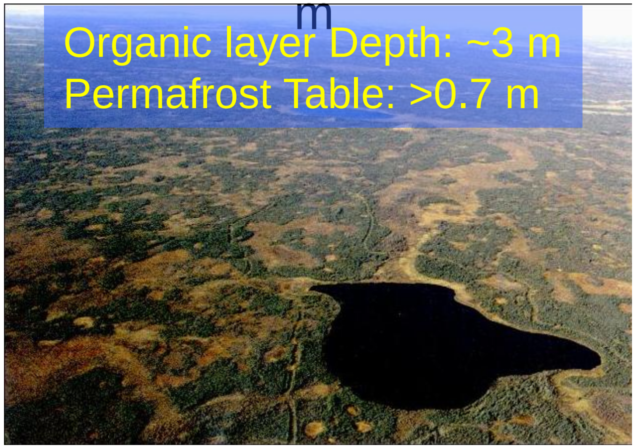
Parameterization!

Soil Freezing and Infiltration: Two Key Cold Processes

- Frozen ground status exerts a dominant control on infiltration, subsurface redistribution and runoff
- Most land-surface and hydrological models have not been evaluated against field data in cold regions
- What are the right choices and why?

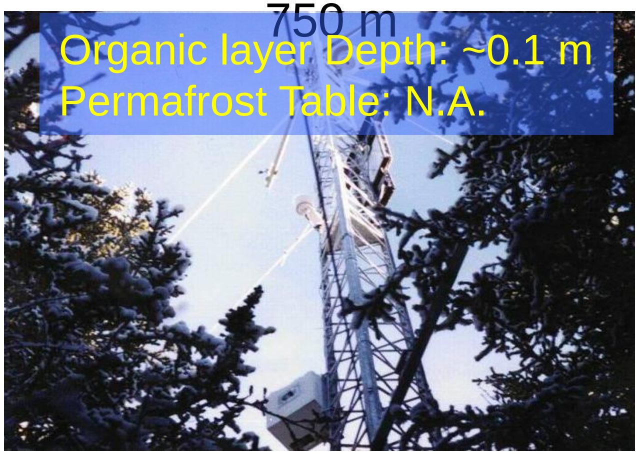
Sites

Scotty Creek Peat Plateau
61°18’N, 121° 18’W, 280 m



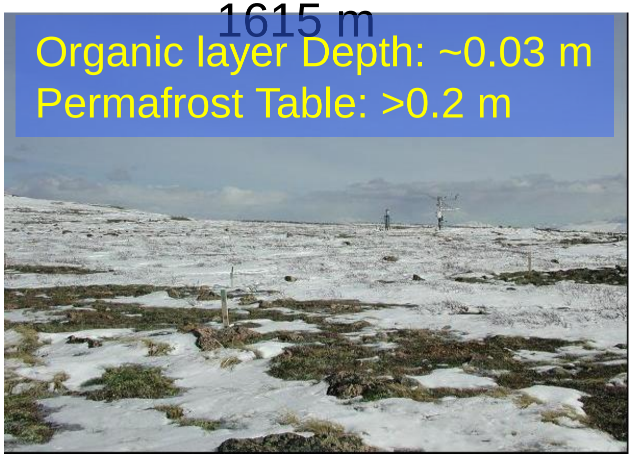
Organic layer Depth: ~3 m
Permafrost Table: >0.7 m

Wolf Creek Forest Site
60° 36’ N; 134° 57’ W, 750 m



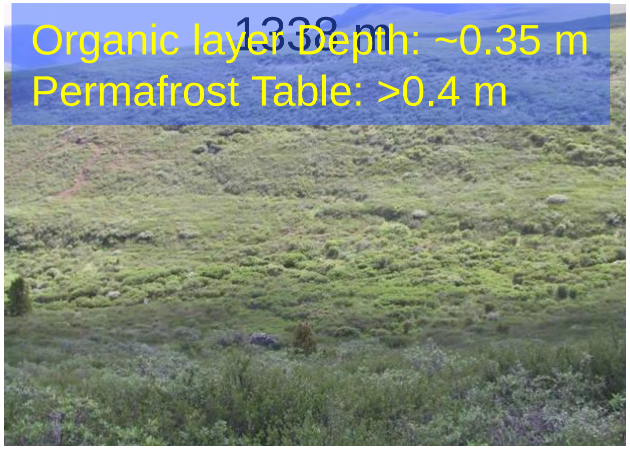
Organic layer Depth: ~0.1 m
Permafrost Table: N.A.

Wolf Creek Alpine Site
60° 34’ N; 134° 09’ W, 1615 m



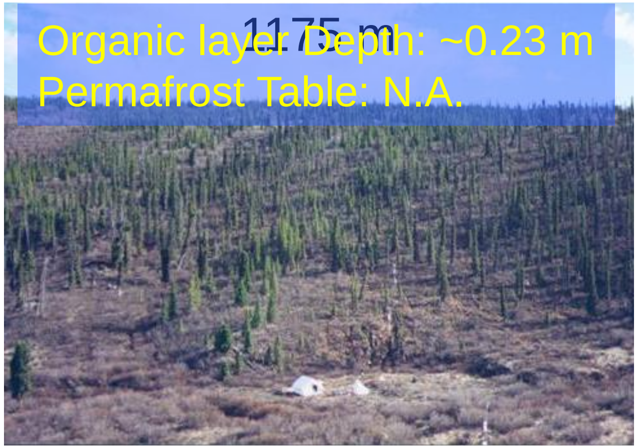
Organic layer Depth: ~0.03 m
Permafrost Table: >0.2 m

Granger Creek North Facing Slope
60° 33’ N, 135° 11’ W, 1338 m



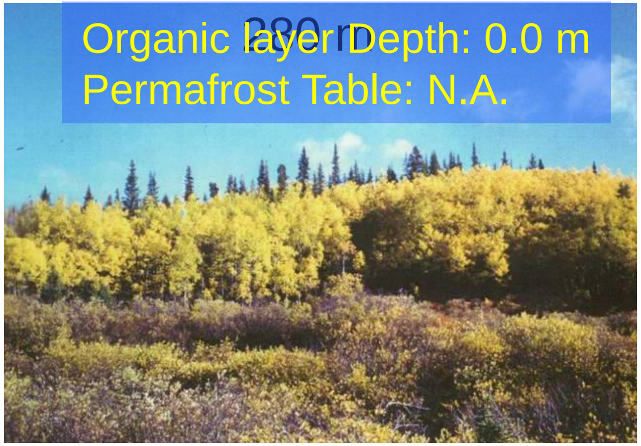
Organic layer Depth: ~0.35 m
Permafrost Table: >0.4 m

Wolf Creek North Facing Slope
61° 31’ N, 135° 31’ W, 1175 m



Organic layer Depth: ~0.23 m
Permafrost Table: N.A.

Wolf Creek South Facing Slope
61° 18’ N, 121° 18’ W, 280 m



Organic layer Depth: 0.0 m
Permafrost Table: N.A.

Soil Freezing and Infiltration: Two Key Cold Processes

Thaw/Freeze

- ATIA
- TDSA
- HMSA
- FD-DECP
- FD-AHCP

Infiltration

- GA-SHAW
- ML-CLASS
- IT-TOPO
- GRAY-IN
- ZHAO-IN

Abbreviations

ATIA	Accumulated Thermal Index Algorithm
TDSA	Two Directional Stefan Algorithm
HMSA	Hayashi’s Modified Stefan Algorithm
FD-DECP	Finite difference numerical scheme with the Decoupled Energy Conservation Parameterization
FD-AHCP	Finite difference numerical scheme with the Apparent Heat Capacity Parameterization
GA-SHAW	Modified Green and Ampt algorithm for non-uniform soils
ML-CLASS	Modified Mein and Larson algorithm for non-uniform soils
IT-TOPO	Instantaneous infiltration algorithm in Topoflow
GRAY-IN	Gray’s empirical infiltration algorithm
ZHAO-IN	Zhao and Gray’s parametric infiltration algorithm

Soil Parameterizations Examined

Soil thermal conductivity

- Complete-Johansen
- Common-Johansen
- De Vries's Method

Soil hydraulic conductivity and retention curves

- Clapp and Hornberger (CH-Para)
- Brooks and Corey (BC-Para)
- van Genuchten (VG-Para)

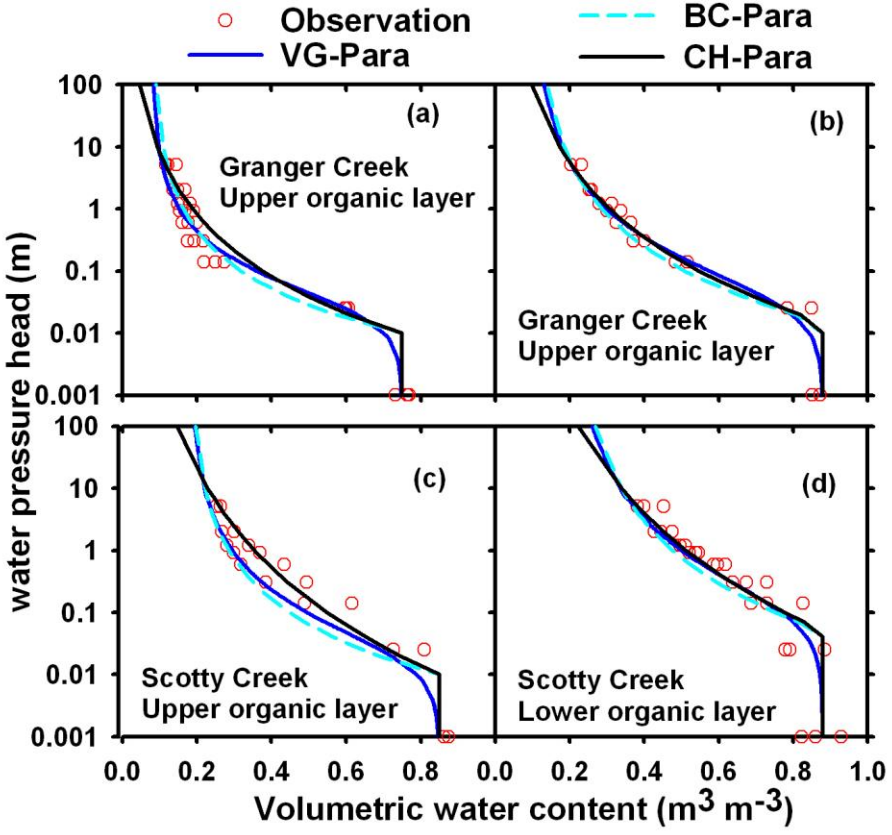
Unfrozen water content

- Power function (UFW-PF)
- Segmented linear function (UFW-SL)
- Water potential-freezing point depression function (UFW-WP)

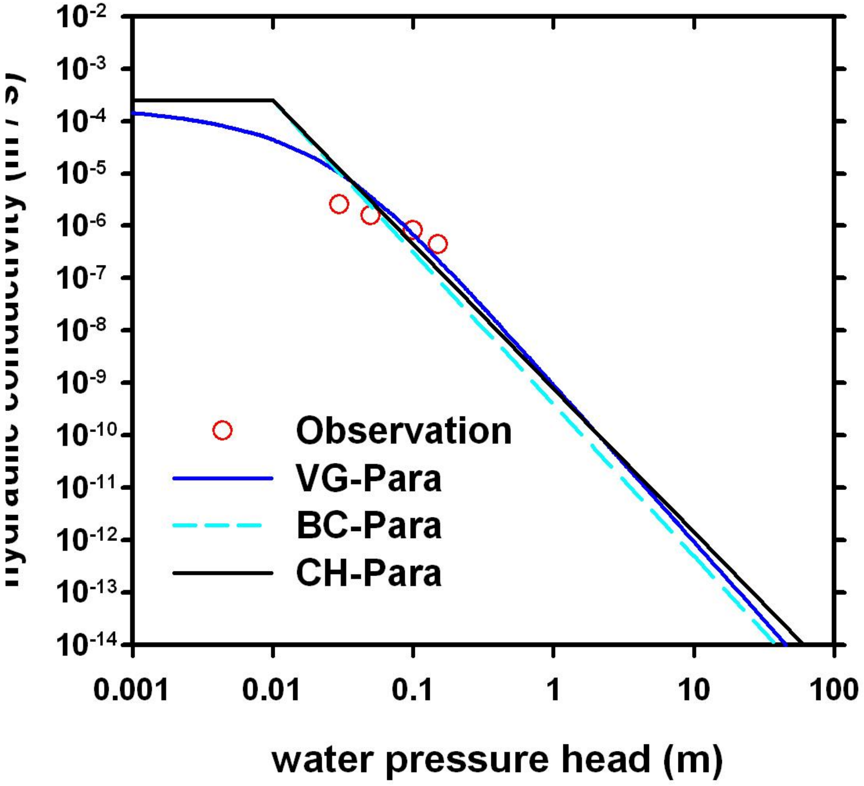
Ice impedance factors

- Exponential function (EP-Ice)
- Squared function (SQ-Ice)
- Linear function (LN-Ice)
- None

Results-soil hydraulic property parameterization



Comparison of three parameterisations for soil water retention curves

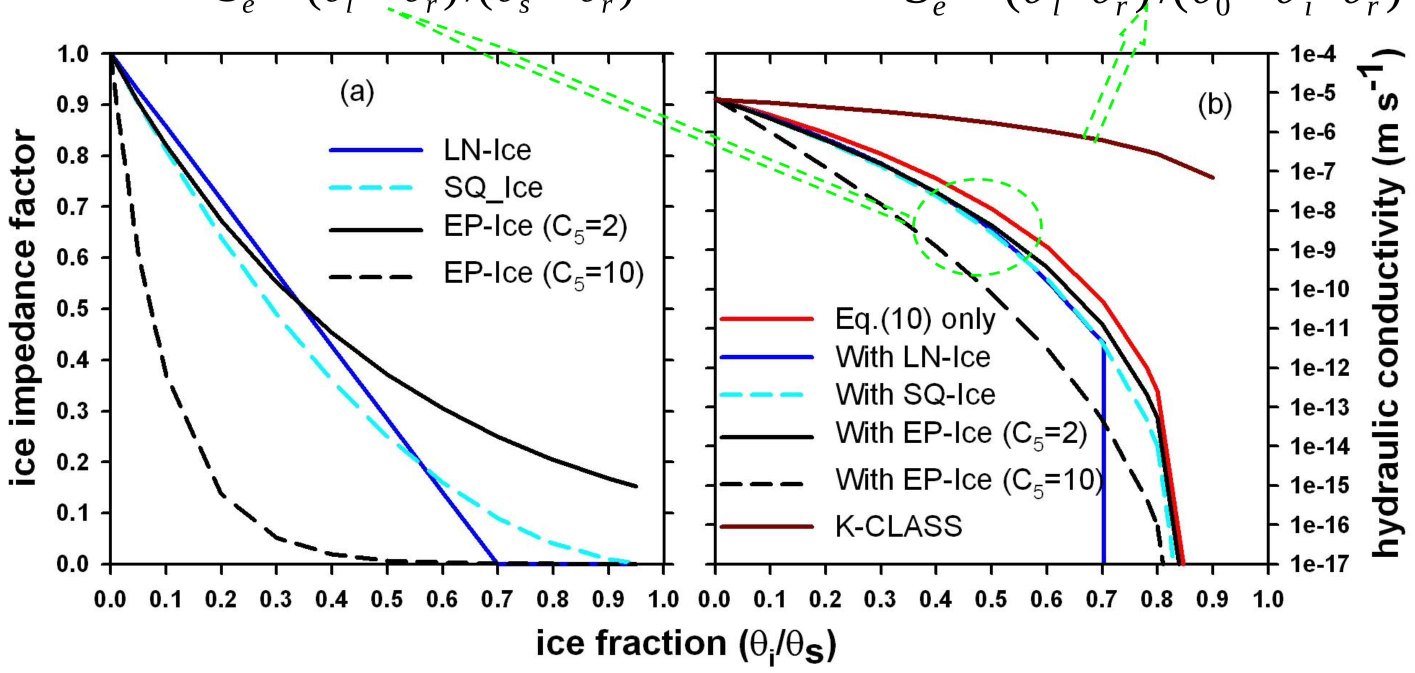


Comparison of three parameterisations for soil hydraulic conductivity

Results-ice impedance to hydraulic conductivity

$$S_e = (\theta_l - \theta_r)/(\theta_s - \theta_r)$$

$$S_e = (\theta_l - \theta_r)/(\theta_0 - \theta_i - \theta_r)$$



Fine sand

0°C

-0.3°C

Reported frozen soil K reduction (Burt and Williams, 1976)

Equations and Applications

K-ψ relation (Eq. 10)	$K = K_s S_e^{2/\lambda+3} = K_s(\psi/\psi_0)^{-(2+3\lambda)}$	CLASS;SHAW
EP-Ice	$f_{imp,1} = 10^{-C_5\theta_i}$	CHRM
SQ-Ice	$f_{imp,2} = (1.0 - \theta_i/\theta_s)^2$	CLASS
LN-Ice	$f_{imp,3} = \begin{cases} (\theta_0 - \theta_i - 0.13)/(\theta_0 - 0.13) & \theta_0 - \theta_i > 0.13 \\ 0 & \theta_0 - \theta_i \le 0.13 \end{cases}$	SHAW

Thermal Modelling

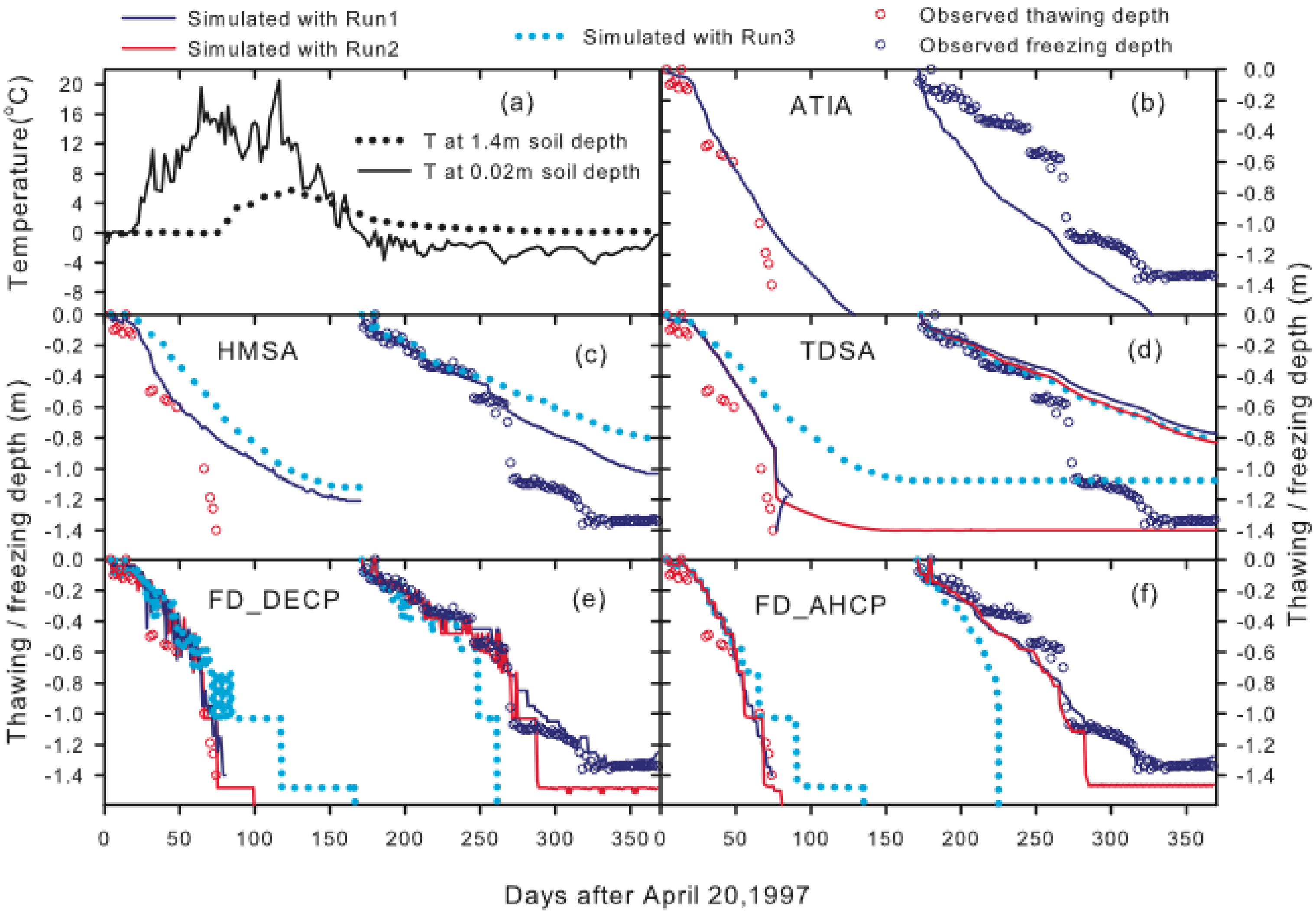


Figure 6. (a) Observed surface and bottom temperatures during the evaluation period. (b)–(f) Comparisons of observed and simulated thawing and freezing depths at a north-facing slope in Wolf Creek with five algorithms and three sets of model runs.

Infiltration/Percolation Modelling

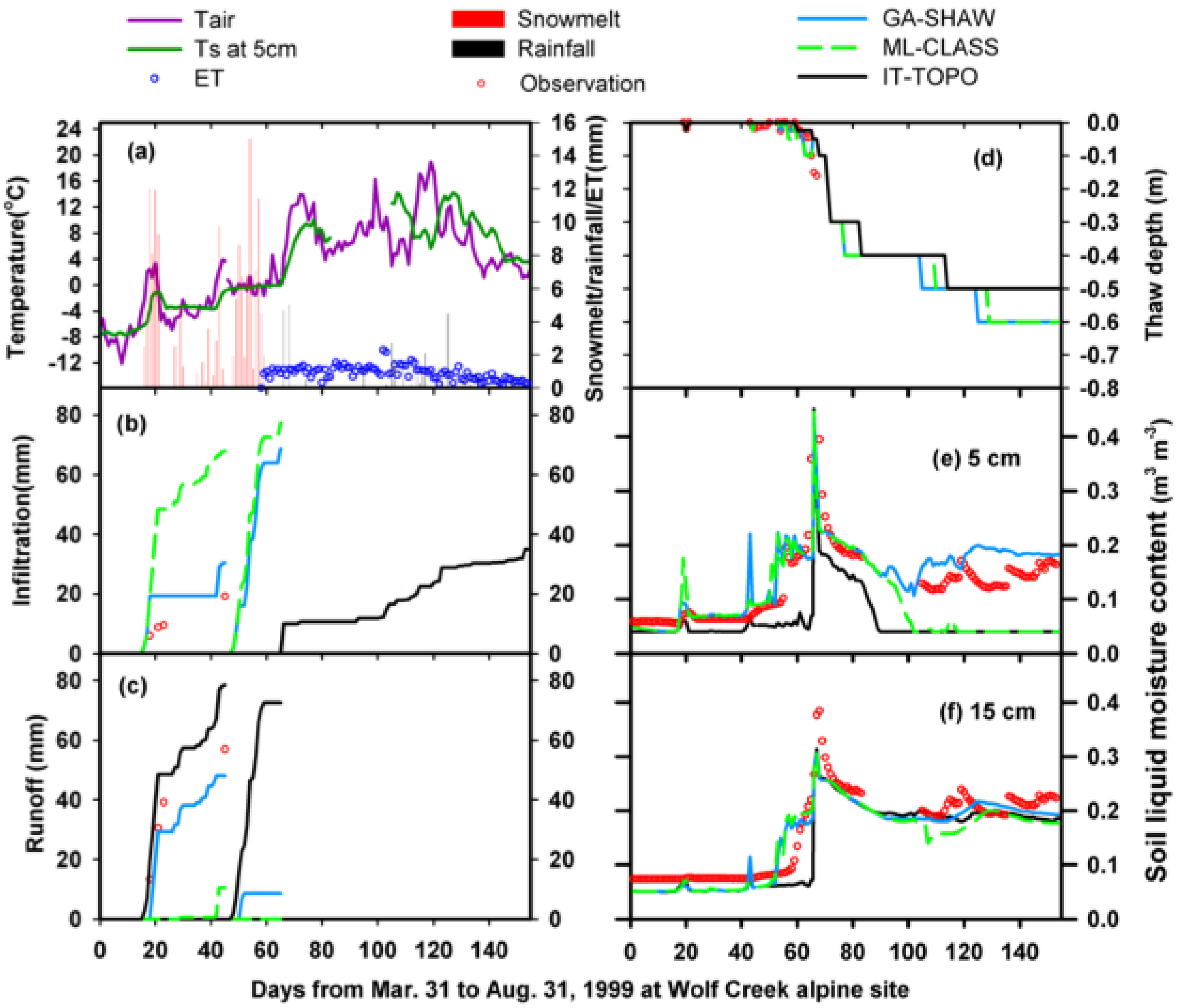
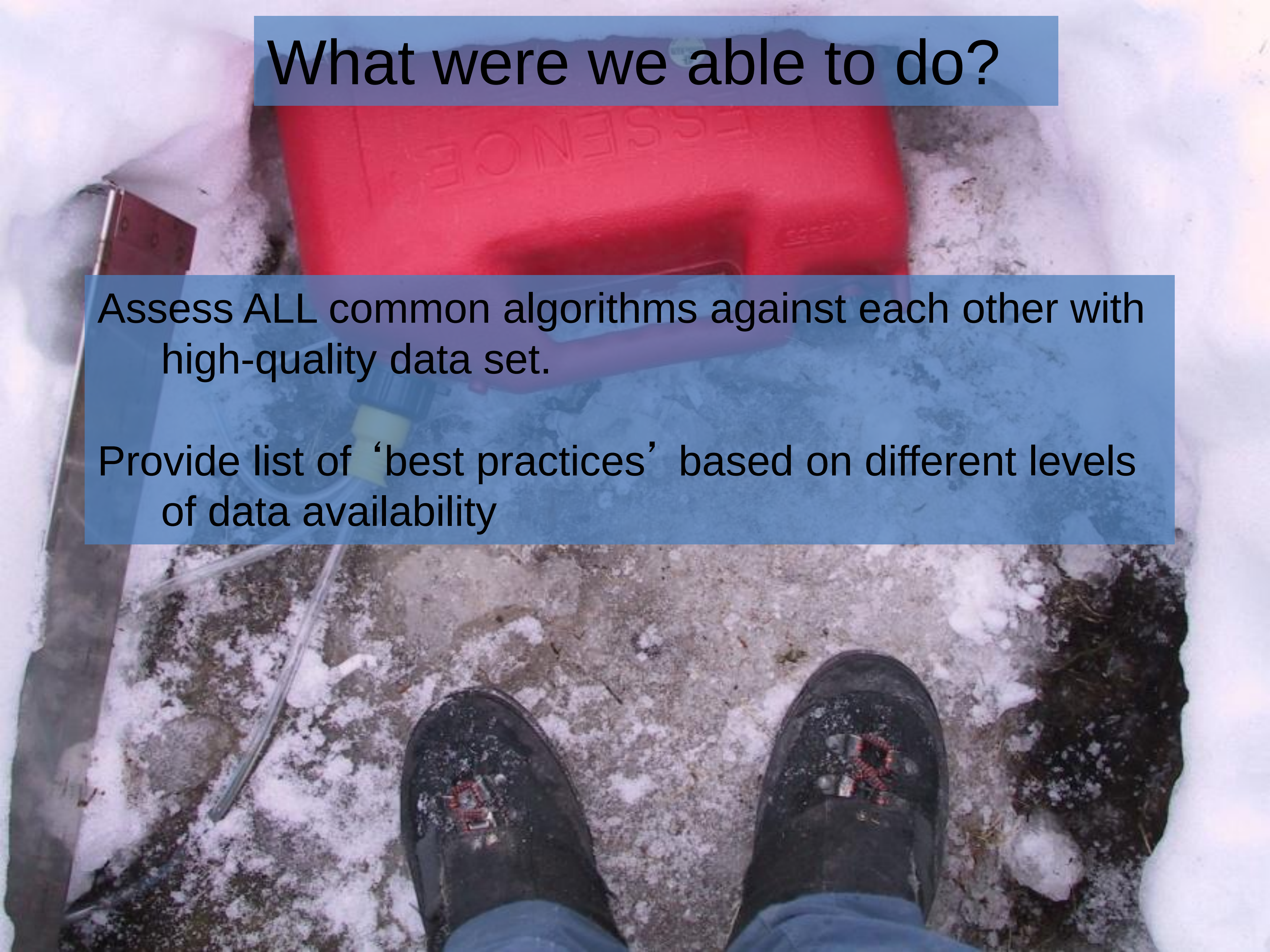


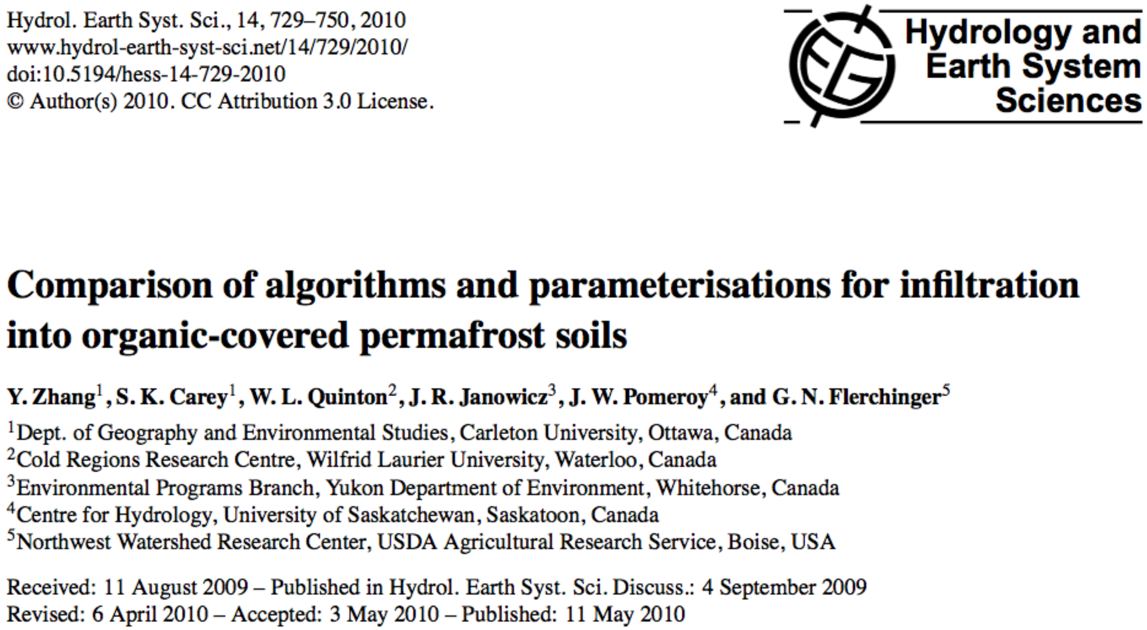
Fig. 7. Surface forcing variables **(a)**, observed and simulated cumulative infiltration **(b)** and runoff **(c)** at three thawing stages, ground thaw depths **(d)**, and liquid soil water content at the monitoring depths (**e** and **f**) at Wolf Creek alpine site.

What were we able to do?



Assess ALL common algorithms against each other with high-quality data set.

Provide list of ‘best practices’ based on different levels of data availability



Hydrol. Earth Syst. Sci., 14, 729–750, 2010
www.hydrol-earth-syst-sci.net/14/729/2010/
doi:10.5194/hess-14-729-2010

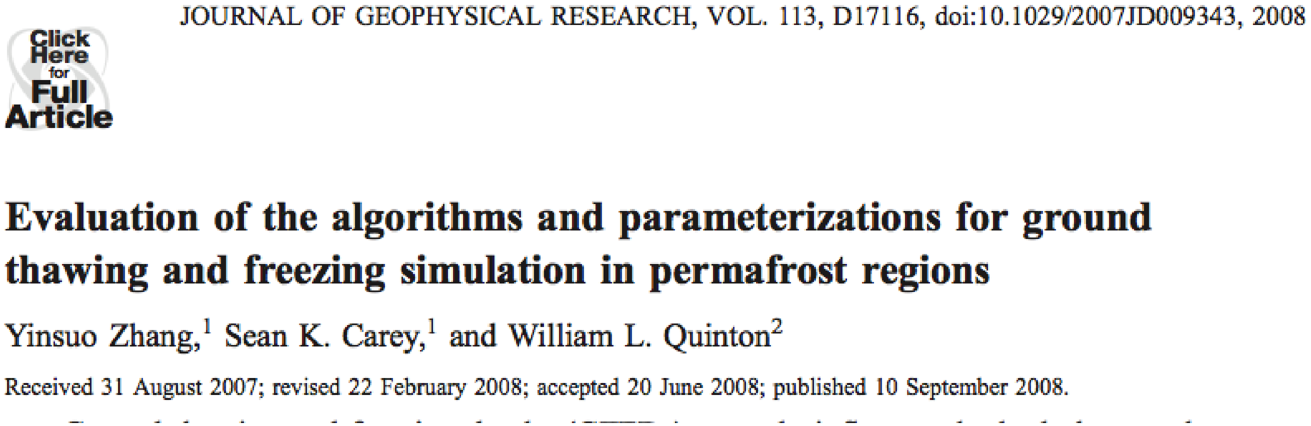
Hydrology and Earth System Sciences

Comparison of algorithms and parameterisations for infiltration into organic-covered permafrost soils

Y. Zhang[1], **S. K. Carey**[1], **W. L. Quinton**[2], **J. R. Janowicz**[3], **J. W. Pomeroy**[4], **and G. N. Flerchinger**[5]

[1]Dept. of Geography and Environmental Studies, Carleton University, Ottawa, Canada
[2]Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, Canada
[3]Environmental Programs Branch, Yukon Department of Environment, Whitehorse, Canada
[4]Centre for Hydrology, University of Saskatchewan, Saskatoon, Canada
[5]Northwest Watershed Research Center, USDA Agricultural Research Service, Boise, USA

Received: 11 August 2009 – Published in Hydrol. Earth Syst. Sci. Discuss.: 4 September 2009
Revised: 6 April 2010 – Accepted: 3 May 2010 – Published: 11 May 2010



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D17116, doi:10.1029/2007JD009343, 2008

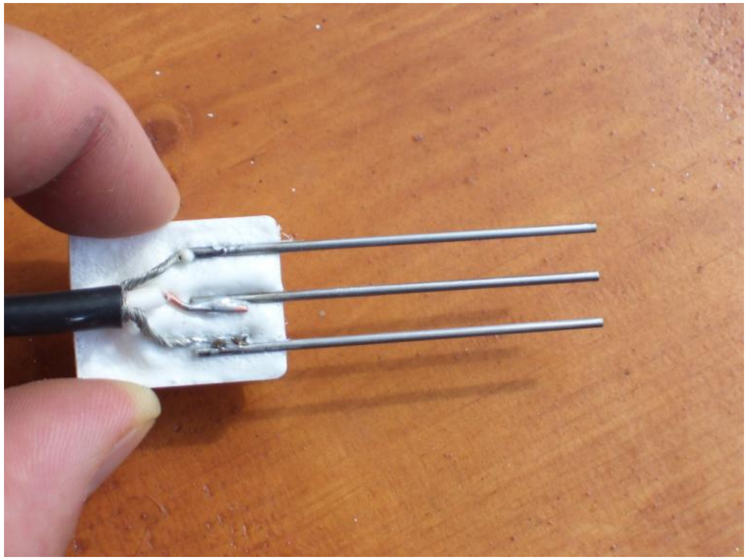
Evaluation of the algorithms and parameterizations for ground thawing and freezing simulation in permafrost regions

Yinsuo Zhang,[1] Sean K. Carey,[1] and William L. Quinton[2]

Received 31 August 2007; revised 22 February 2008; accepted 20 June 2008; published 10 September 2008.

But…. We could never measure all of what we were modelling…… so we needed to build something….

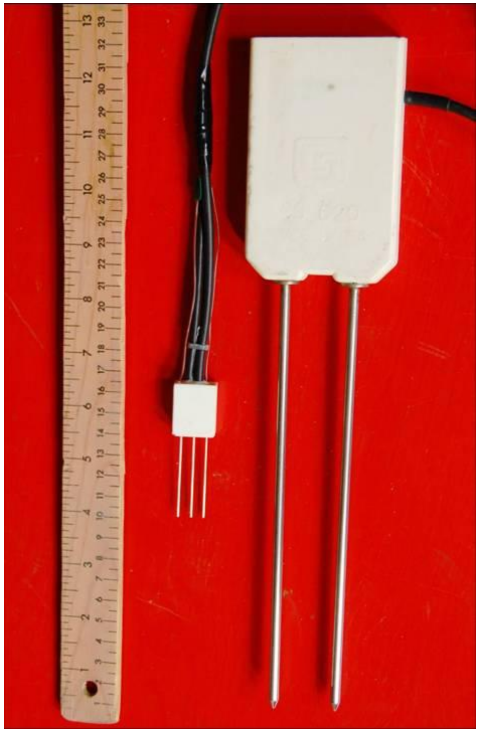
Multi-Function Heat-Pulse Probes (MFHPP)

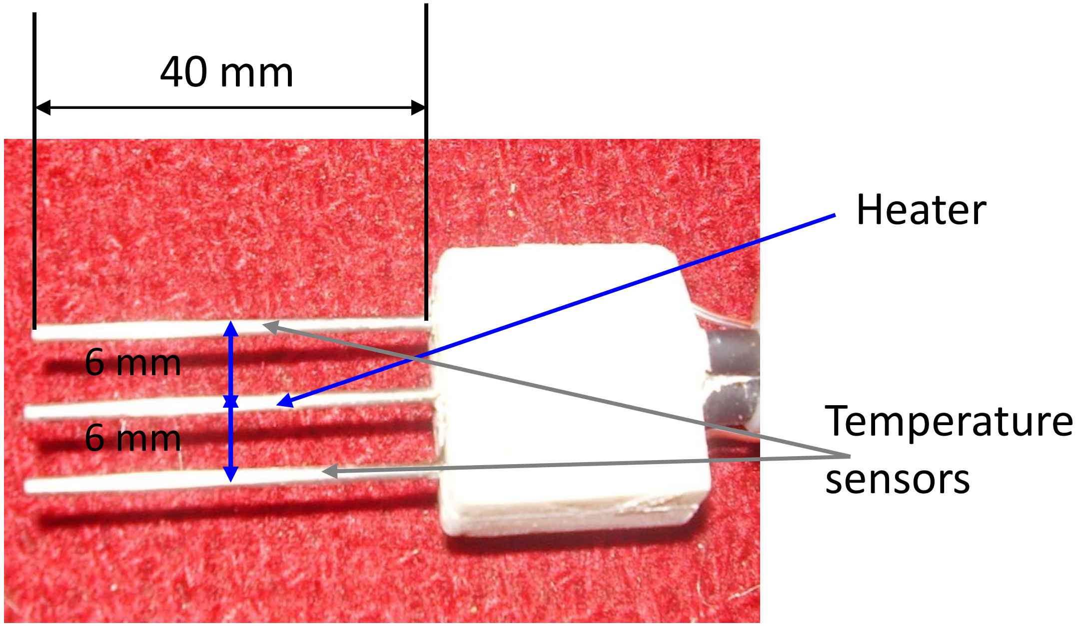


Design a sensor that is able, real time, to measure all water components (solid, liquid) below zero.

Multi-Function Heat-Pulse Probes (MFHPP)

What is Heat Pulse Probe (HPP)





$$\Delta T = f(C, q, t_0, t, r) \longrightarrow$$ Determines C

$$C = \Sigma\,(C_m\theta_m + C_o\theta_o + C_l\theta_l + C_i\theta_i) \longrightarrow$$ Determines θ_l , θ_i

Mathematical solutions…. never meant for freezing conditions

1. Instantaneous Infinite Line Source (IILS)

$$\Delta T(r,t) = \frac{q}{4\pi\lambda t}\exp\left(\frac{-r^2}{4\kappa t}\right)$$

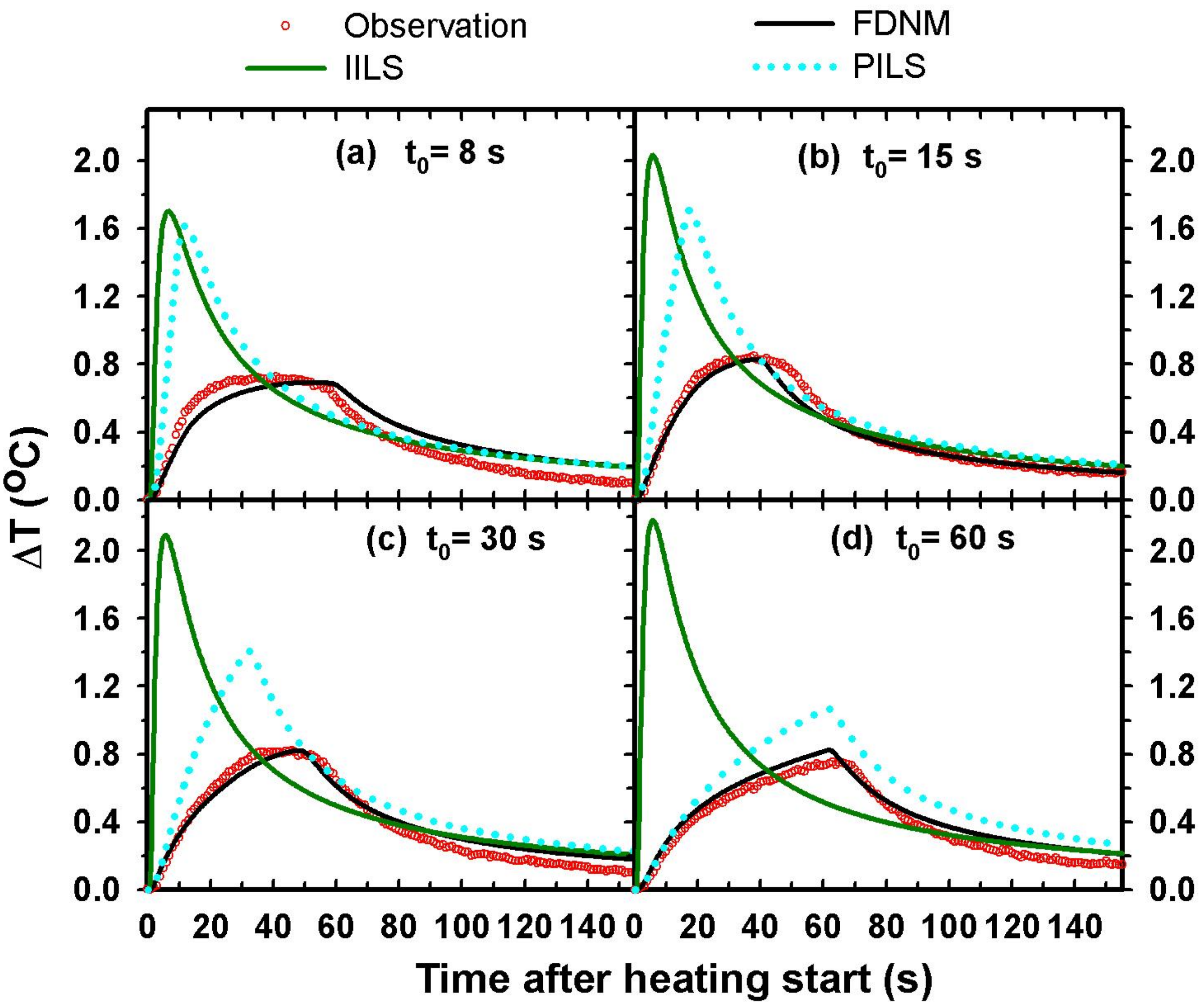
2. Pulsed Infinite Line Source (PILS)

$$\Delta T(r,t) = \begin{cases} \dfrac{-q'}{4\pi\lambda} Ei\left(\dfrac{-r^2}{4\kappa t}\right) & 0 < t \le t_0 \\ \dfrac{q'}{4\pi\lambda}\left\{ Ei\left[\dfrac{-r^2}{4\kappa(t-t_0)}\right] - Ei\left(\dfrac{-r^2}{4\kappa t}\right)\right\} & t > t_0 \end{cases}$$

3. Finite Difference Numerical Model (FDNM)

$$C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right) + q' \qquad C_p = C_v + \rho_i L \frac{d\theta_u}{dT}$$

Bottom line: we (mostly) figured it out!



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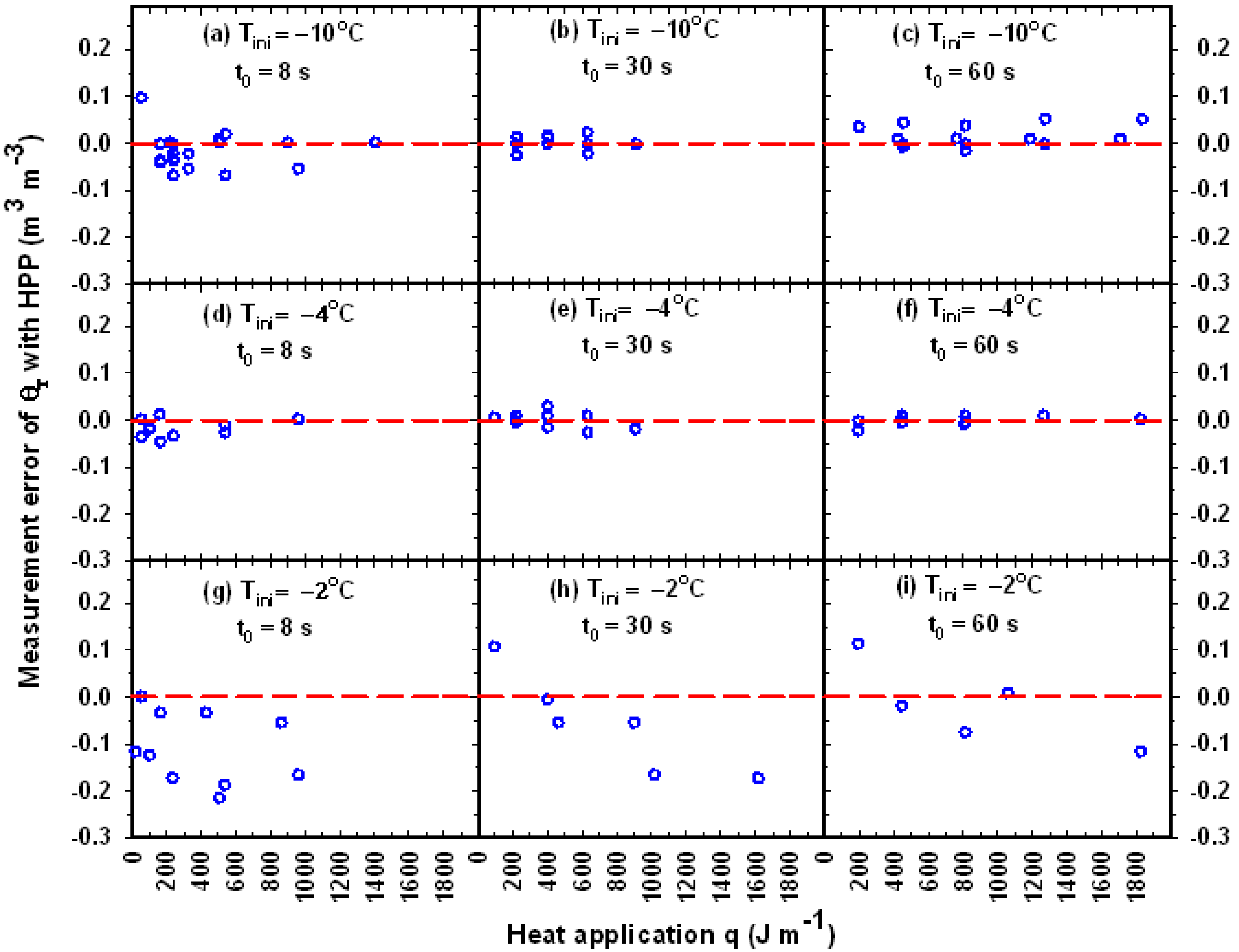

Measurement errors of total moisture content (θ_T) as determined by the HPP using the numerical model FDNM under different initial soil temperature (T_{ini}) and heating pulse durations (t_0).

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Evaluation of the heat pulse probe method for determining frozen soil moisture content

Yinsuo Zhang,[1] Michael Treberg,[1] and Sean K. Carey[1]

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[1] Heat pulse probes (HPP) have been widely utilized to determine soil thermal properties and water content in unfrozen soils; however, their applications in frozen soils are largely restricted by phase change and the presence of unfrozen water. This study explores the possibility of using HPP to determine total water content of frozen soils by (1) establishing the optimum heat applications to limit melting, (2) improving the mathematical representations for frozen conditions, and (3) evaluating the applicability of HPP methods under various temperature and moisture conditions. A custom-built HPP was tested at total moisture levels that varied from full saturation to oven dry and initial soil temperatures from 20°C to −11°C. The applied heat pulse durations varied from 8 to 60 s, with total heat strength varying from 100 to 2000 J m^{-1}. Comparison of mathematical methods involved two analytical solutions and a one-dimensional finite difference numerical model. While both analytical methods assumed no phase change, the numerical model considered ice melting and unfrozen water. Conclusions include the following: (1) the numerical model with phase change is the only appropriate method to represent the temperature change curve once melting occurs; (2) below −4°C, ice melting could be limited, and measurement errors of total moisture content were within ± 0.05 m^3 m^{-3}; (3) application of HPP between −2°C and 0°C is difficult because of the retarded response of probe temperature to changing moisture contents and heat applications; and (4) probe spacing is a sensitive parameter requiring calibration once reinstallation of the probe or the thawing and freezing process occurs.

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And the work goes on…….Thank You CFCAS