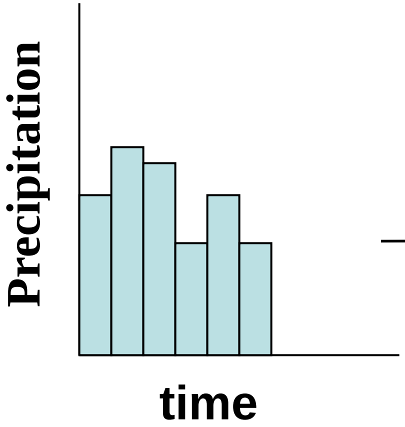
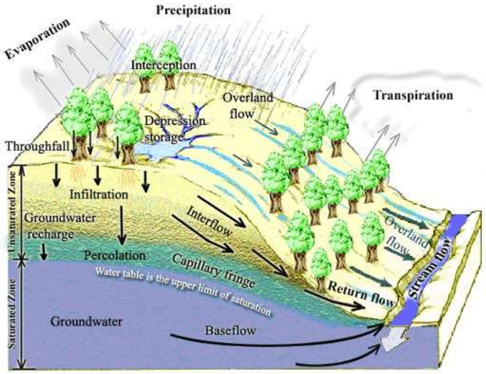
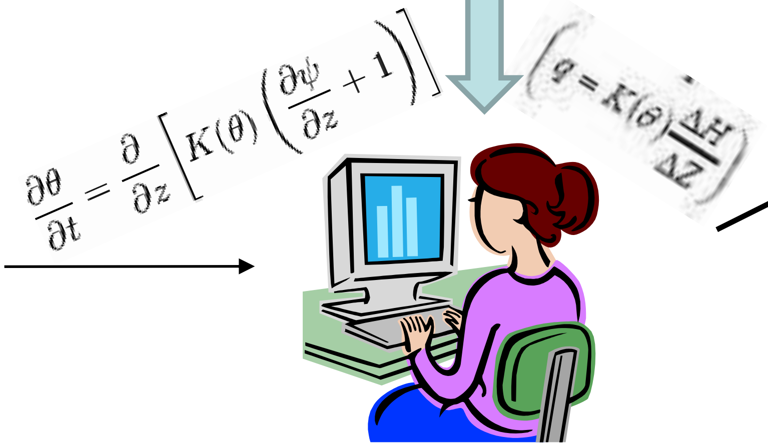
How to Apply Process Information to Improve Prediction

Jim McNamara
Boise State University
Idaho, USA

- Improved prediction and improved process understanding are mutually reliant

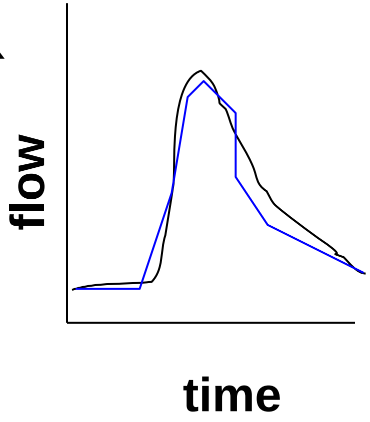






$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial\psi}{\partial z} + 1\right)\right]$$

$$q = K(\theta)\frac{\Delta H}{\Delta Z}$$

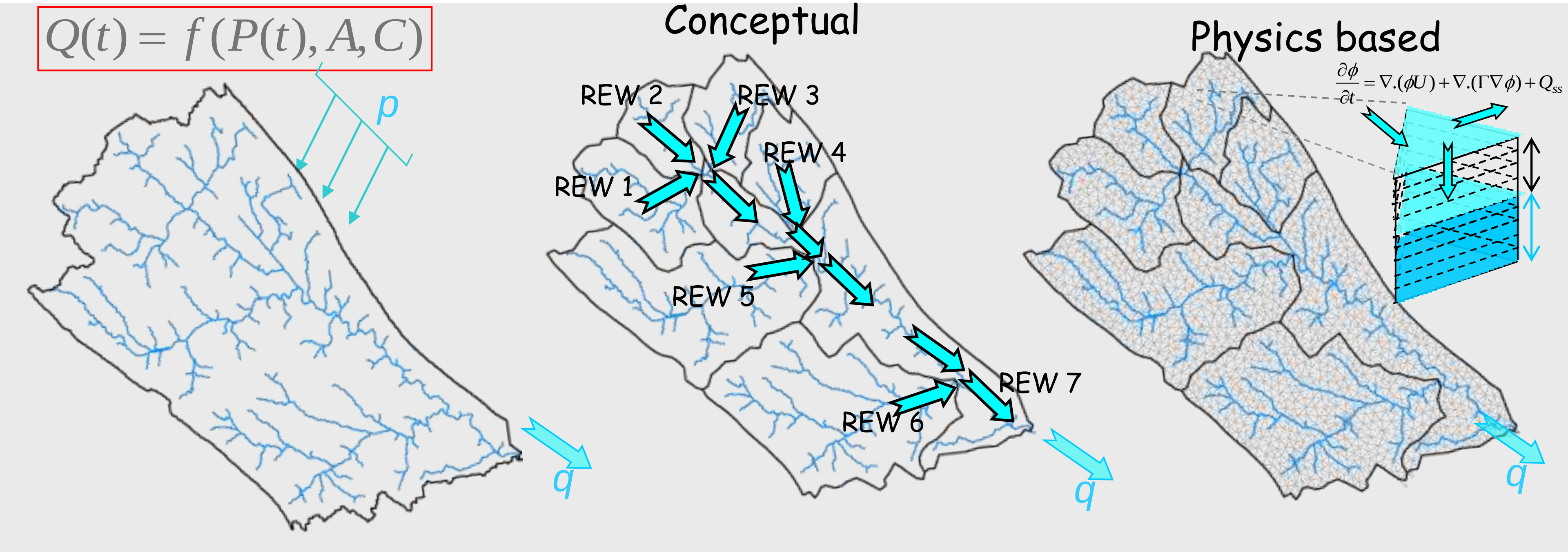


Modified from Mukesh Kumar

Lumped Model

Semi-Distributed Model, Conceptual

Distributed Model, Physics based



Process Representation: Parametric → Physics-Based

Predicted States Resolution: Coarser → Fine

Data Requirement:
Computational Requirement: } Small → Large

Perceived Intellectual Value: Small → Large

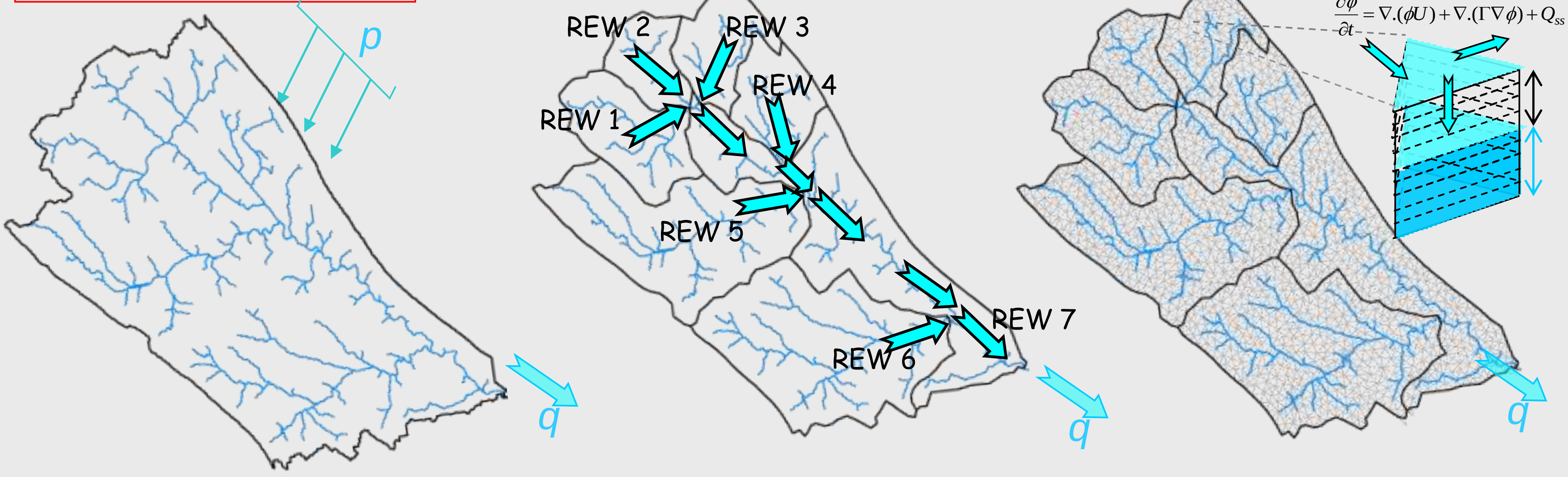
Modified from Mukesh Kumar

Lumped Model

$$Q(t) = f(P(t), A, C)$$

Semi-Distributed Model, Conceptual

Distributed Model, Physics based

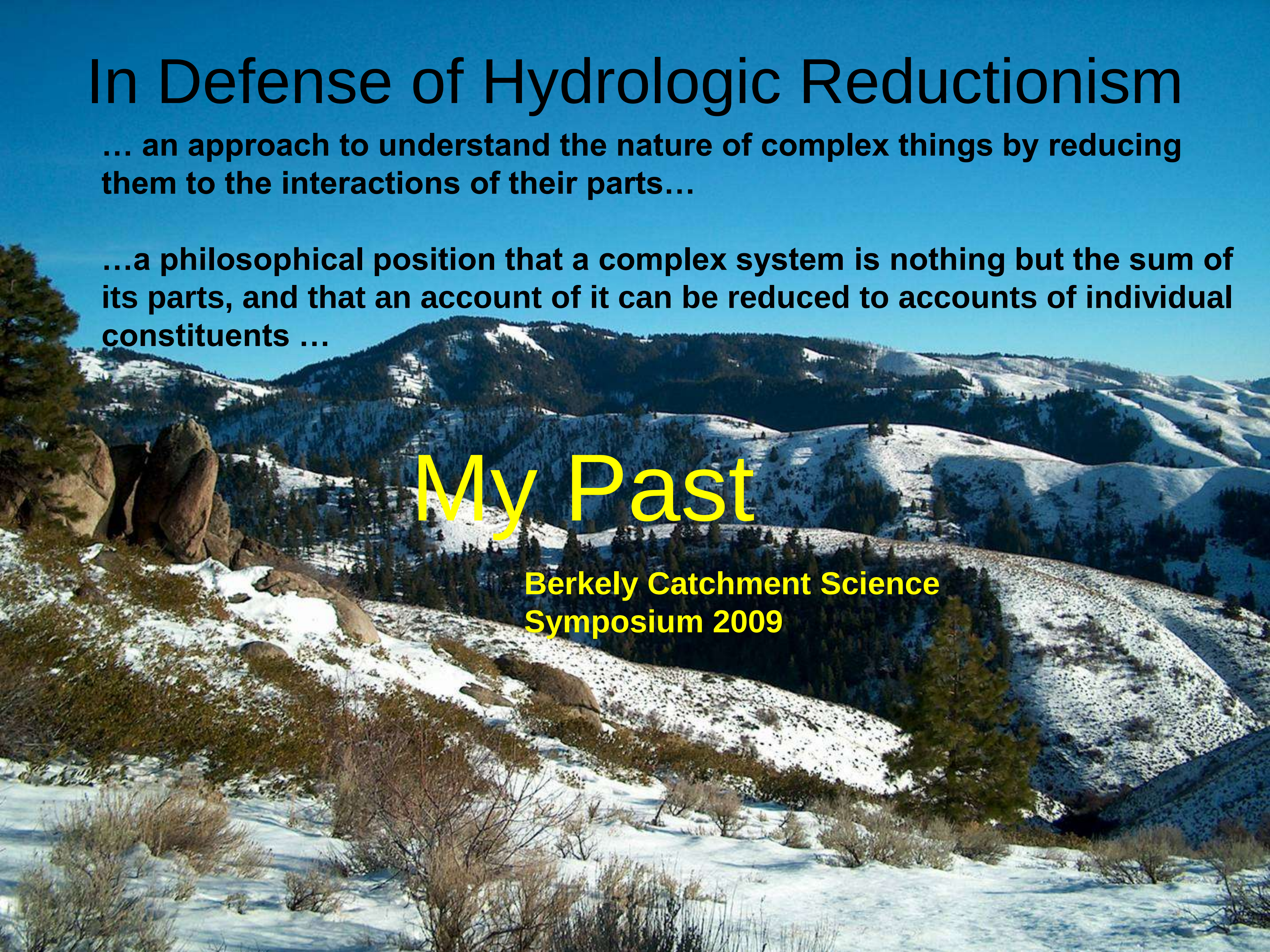


$$\frac{\partial \phi}{\partial t} = \nabla.(\phi U) + \nabla.(\Gamma \nabla \phi) + Q_{ss}$$

Outcome: Right for Wrong Reasons → Wrong for Right Reasons

History: Mathematical Lumping → Process Understanding

Future: ? ← Process Understanding



In Defense of Hydrologic Reductionism

… an approach to understand the nature of complex things by reducing them to the interactions of their parts…

…a philosophical position that a complex system is nothing but the sum of its parts, and that an account of it can be reduced to accounts of individual constituents …

My Past

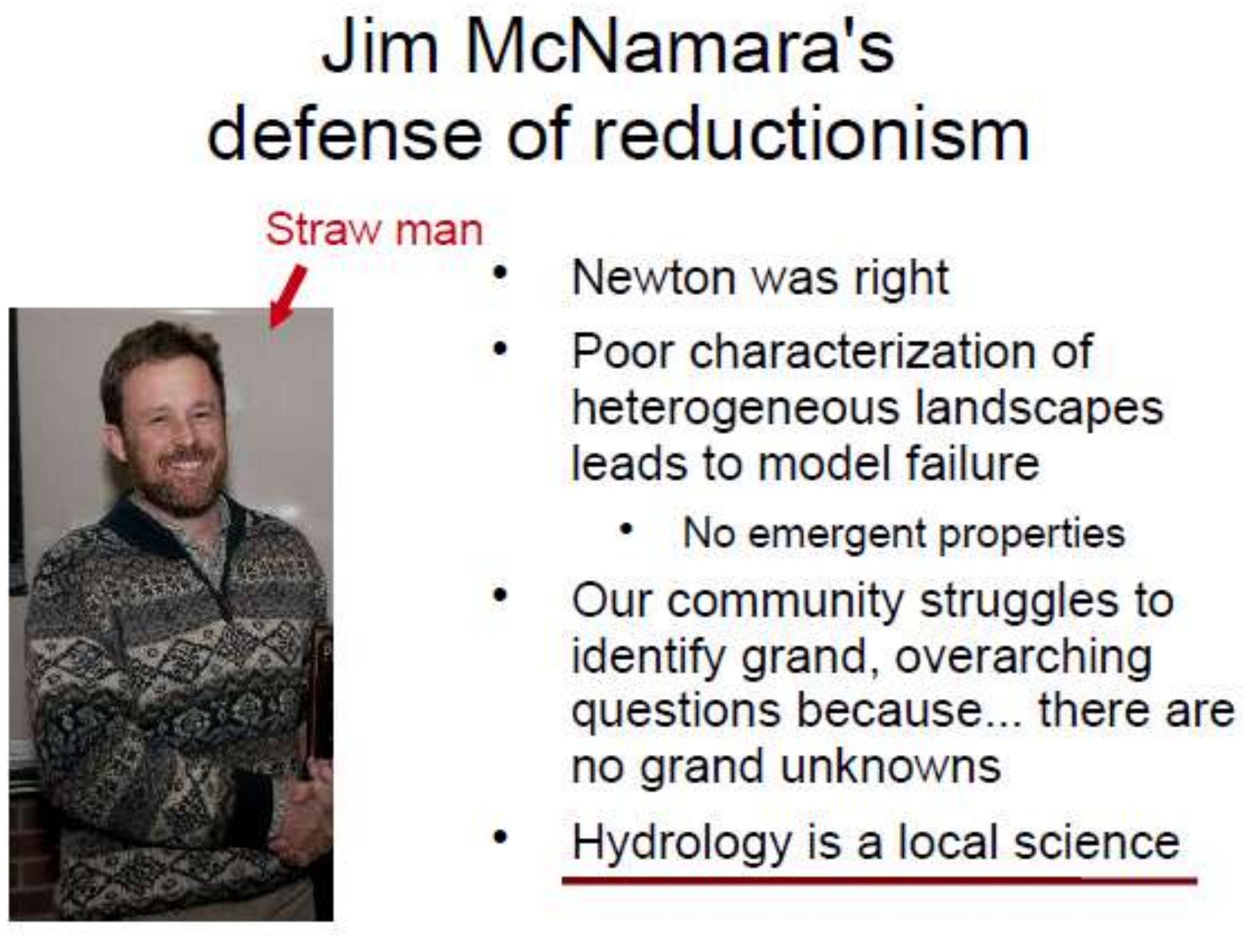
Berkely Catchment Science
Symposium 2009

My Past:
In Defense of Reductionism

- Newton was right
- Model failures result from poor characterization of heterogeneous landscapes leads to
  - No emergent properties
- Our community struggles to identify grand, overarching questions because…there are no grand unknowns
- Hydrology is a local science

The Response

Ciaran Harman, Catchment Science Symposium, EGU 2011



Jim McNamara's defense of reductionism

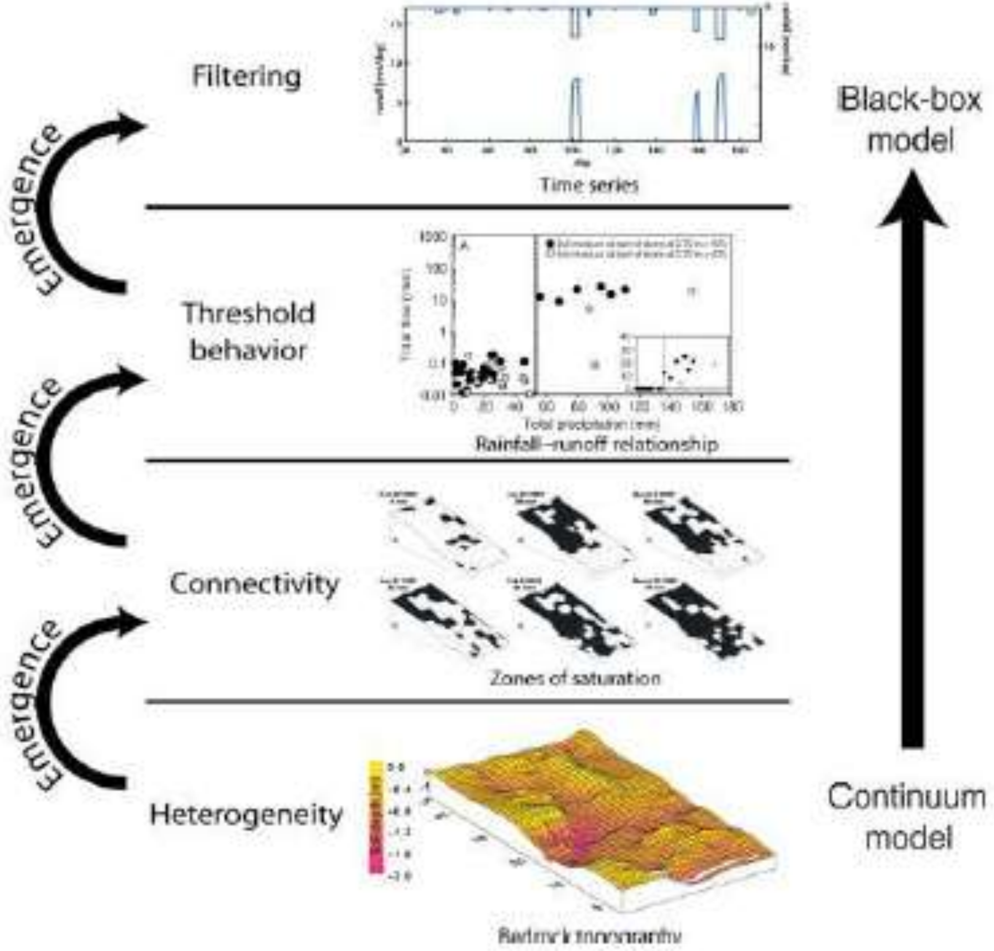
Straw man

- Newton was right
- Poor characterization of heterogeneous landscapes leads to model failure
  - No emergent properties
- Our community struggles to identify grand, overarching questions because... there are no grand unknowns
- Hydrology is a local science

The Response

Ciaran Harman, Catchment Science Symposium, EGU 2011

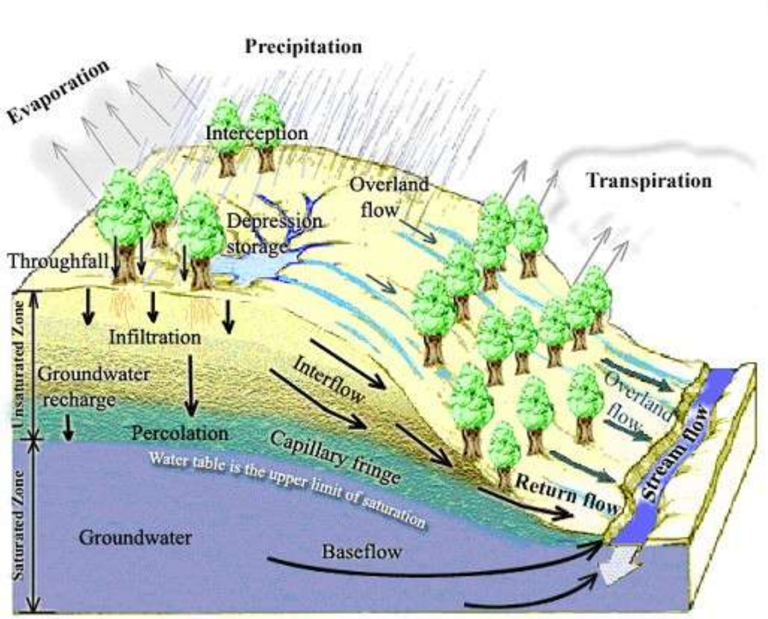
1. Mechanistic understanding of processes across scales

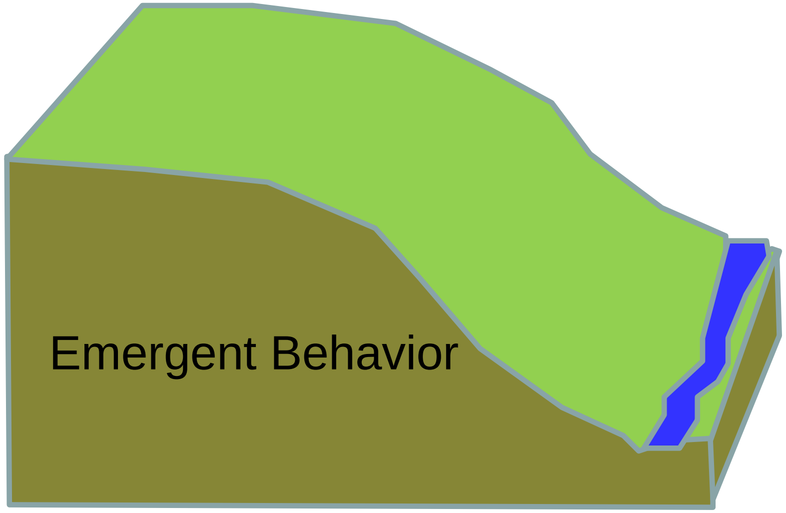


Not simple averaging

Emergent behavior dependent on smaller-scale structure

Catchments Lump Processes





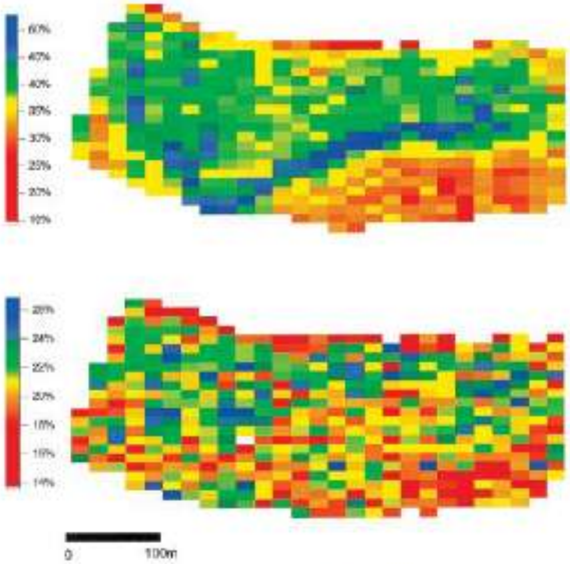
Decades of case studies have documented the many ways that water moves downhill

Recent work has identified many **Physically Lumped Properties** that are manifestations of the **system** of states and fluxes

-A physical basis for lumped parameter modeling

Physically Lumped Properties (emergent behavior)

- **Connectivity**
- Thresholds
- Residence Time



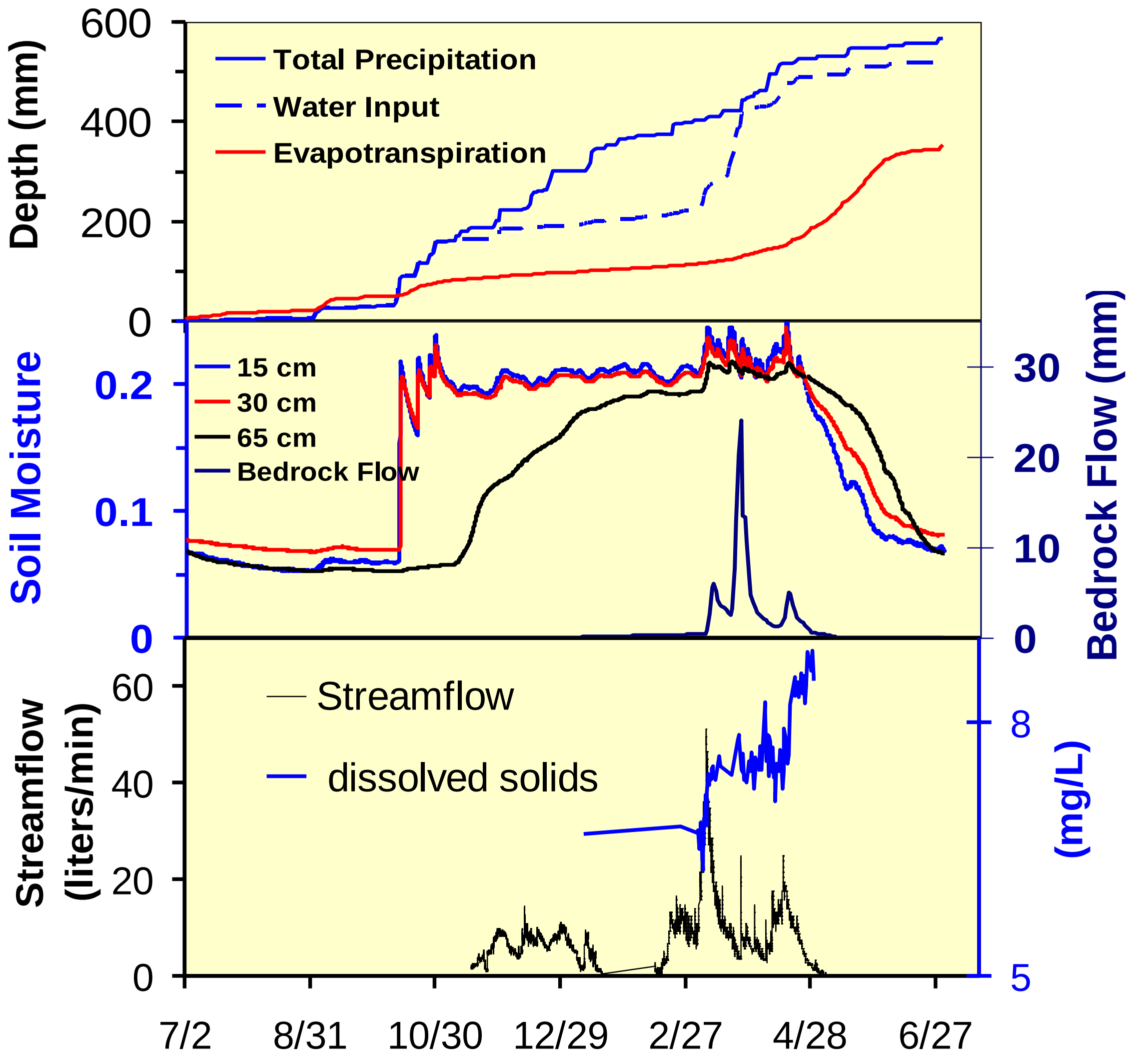
Wet conditions
Topography
controls soil moisture

Dry conditions
Soil/Vegetation
controls soil moisture

Spatial distribution in soil moisture
Tarawarra Catchment
Western and Grayson (1998)
Grayson and Bloschl (2000)

Physically Lumped Properties

- Connectivity
- **Thresholds**
- Residence Time



Physically Lumped Properties

- Connectivity
- Thresholds
- **Residence Time**

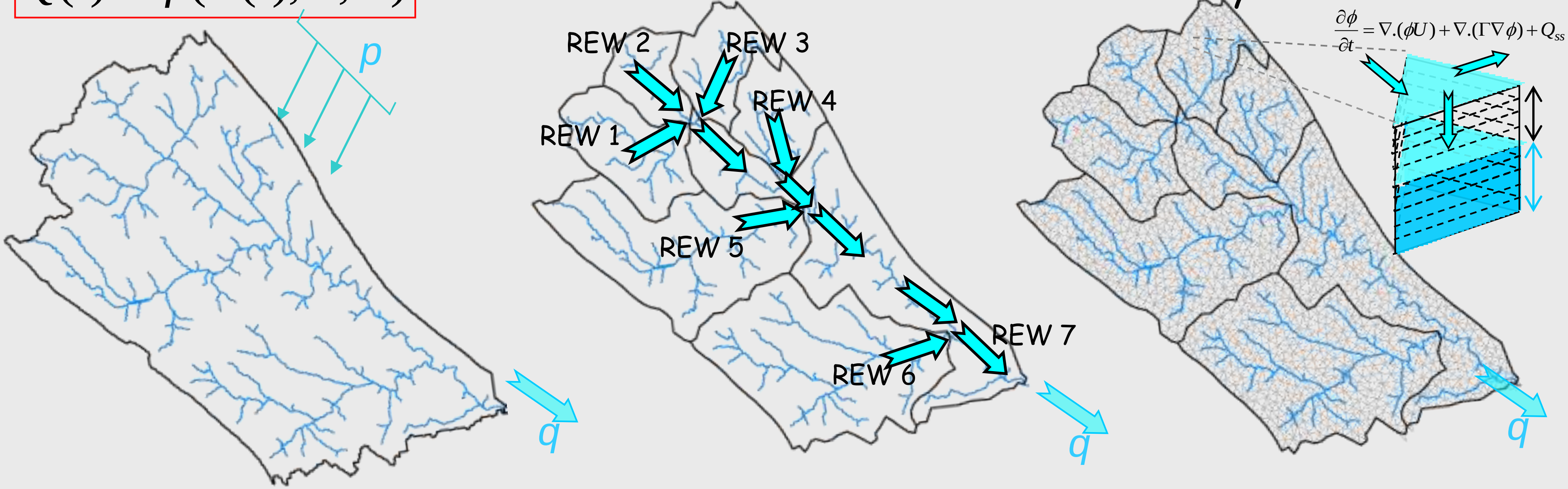
Modified from Mukesh Kumar

Lumped Model

Semi-Distributed Model, Conceptual

Distributed Model, Physics based

$$Q(t) = f(P(t), A, C)$$



$$\frac{\partial \phi}{\partial t} = \nabla.(\phi U) + \nabla.(\Gamma \nabla \phi) + Q_{ss}$$

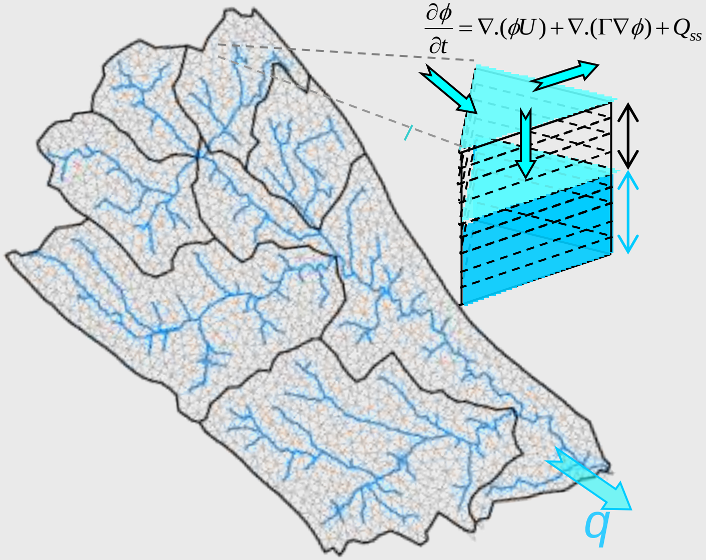
History: Mathematical Lumping → Process Understanding

Future: ? ← Process Understanding

Modified from Mukesh Kumar

Distributed Model,

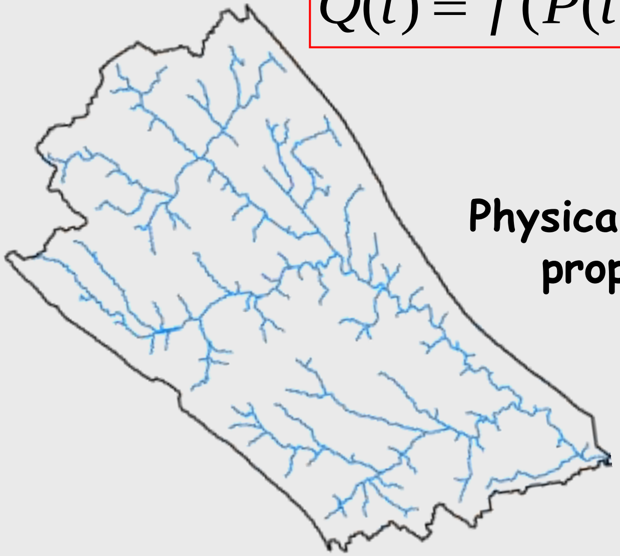
Physics based



$$\frac{\partial \phi}{\partial t} = \nabla.(\phi U) + \nabla.(\Gamma \nabla \phi) + Q_{ss}$$

Physically Lumped Model

$$\boxed{Q(t) = f(P(t), A, C)}$$



Physically lumped properties

History: Mathematical Lumping → Process Understanding

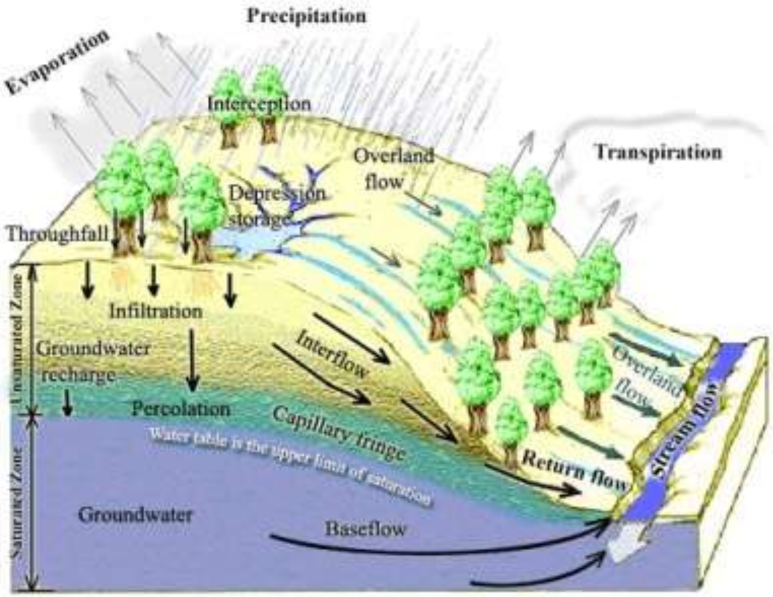
Future: Process Understanding → Physically lumped properties

How to Apply Process Information to Improve Prediction

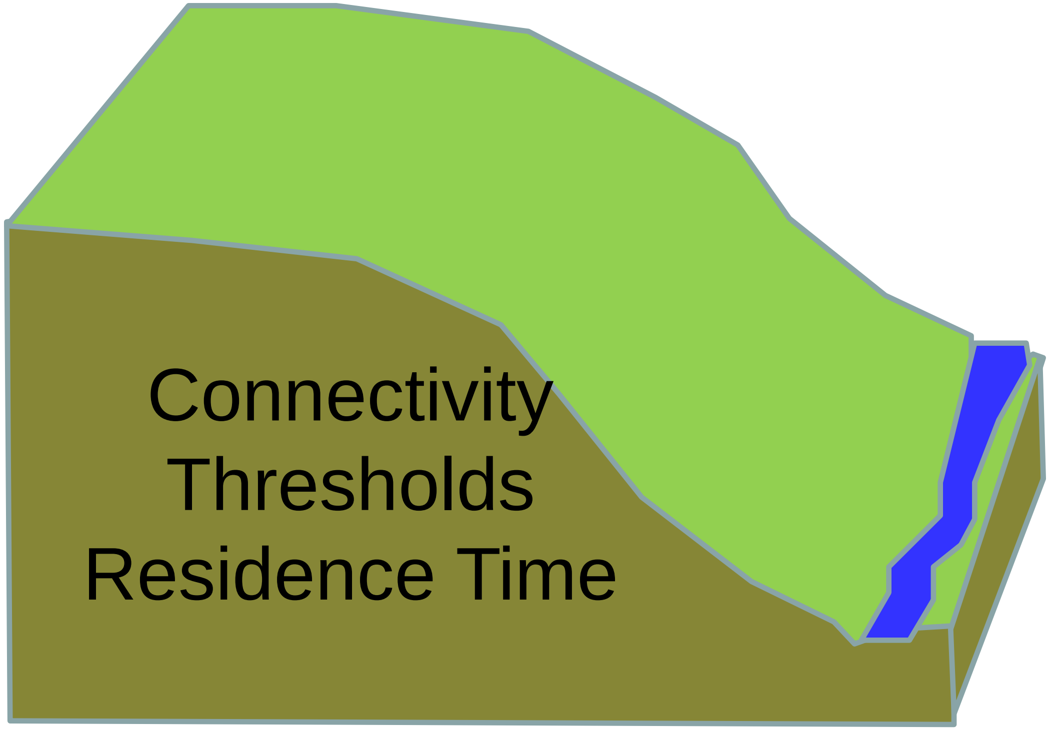
- **Retain** the computationally efficiency and **lumped philosophy** of systems models

- **Observe** how catchments create **physically lumped properties**

- **Replace** mathematical lumping approaches with **physically lumped properties**
  - **Use as validation targets**
  - **Build into new model structures**



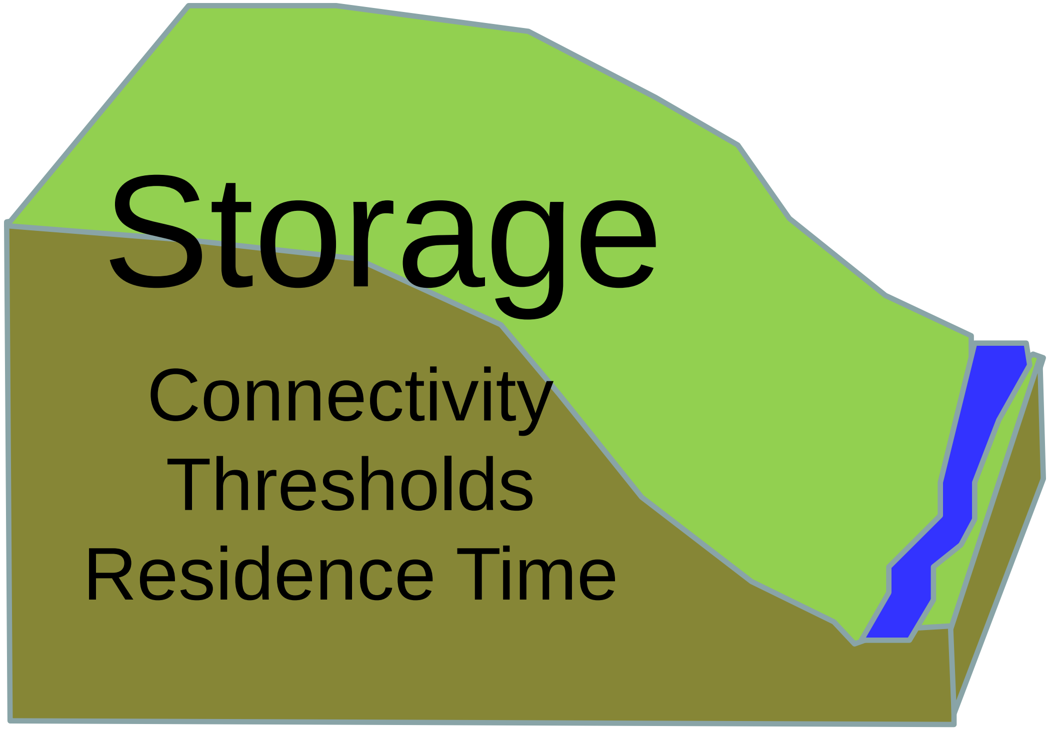
What do we do with this awareness?



Connectivity
Thresholds
Residence Time

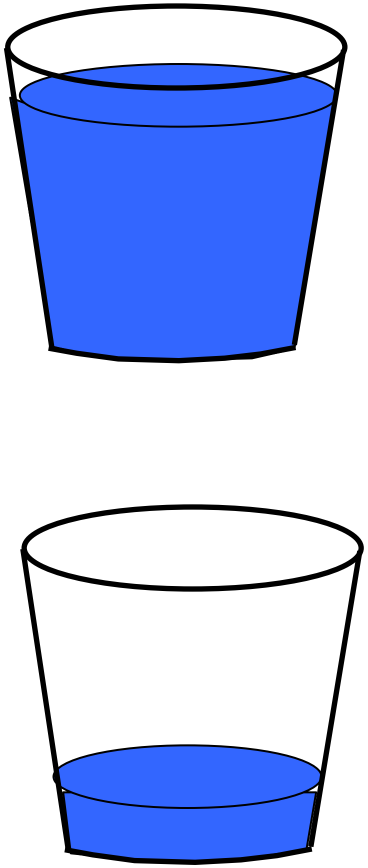
Lump the lumps
It’s about Storage

P-ET-Q =dS/dt

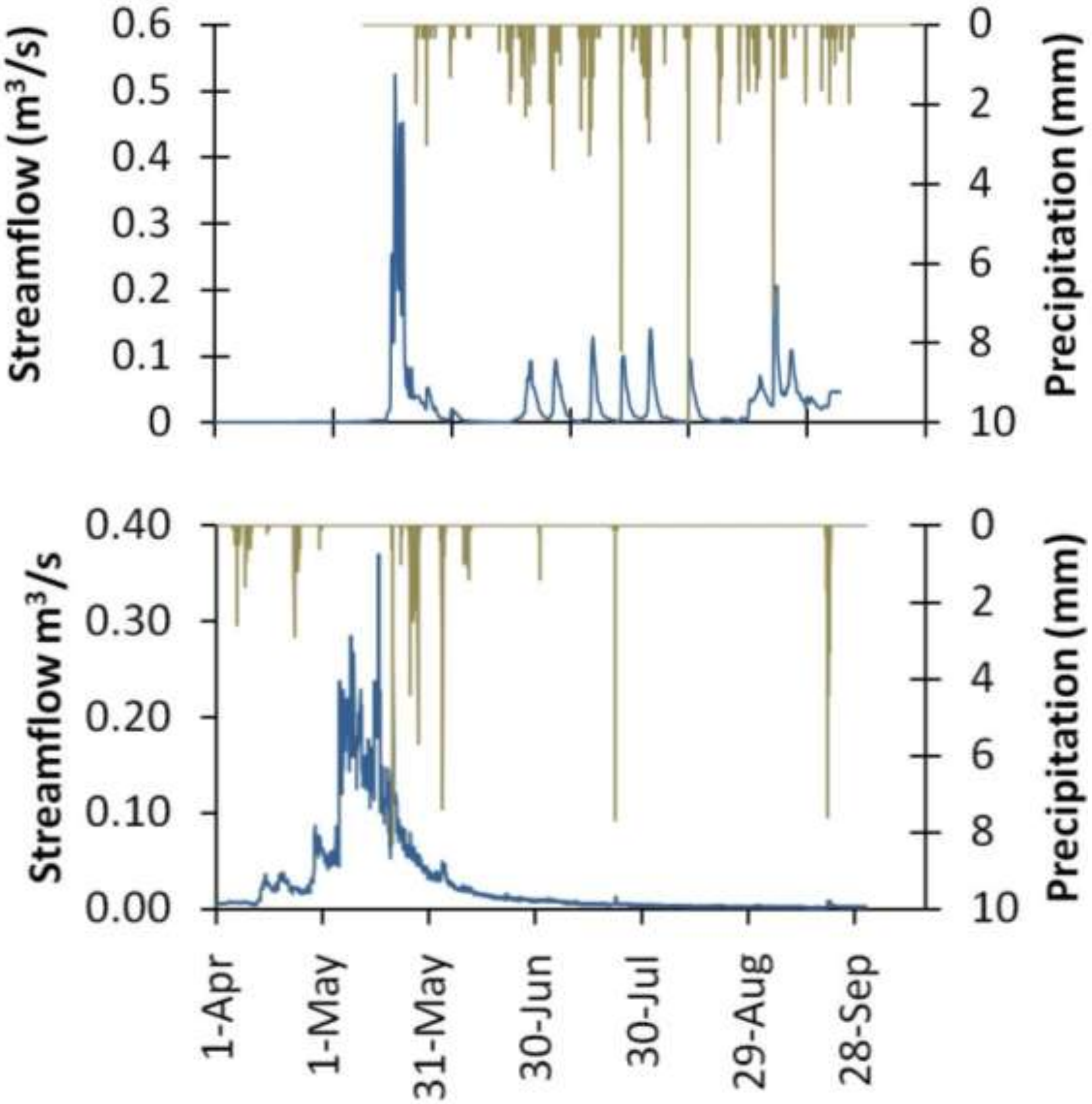


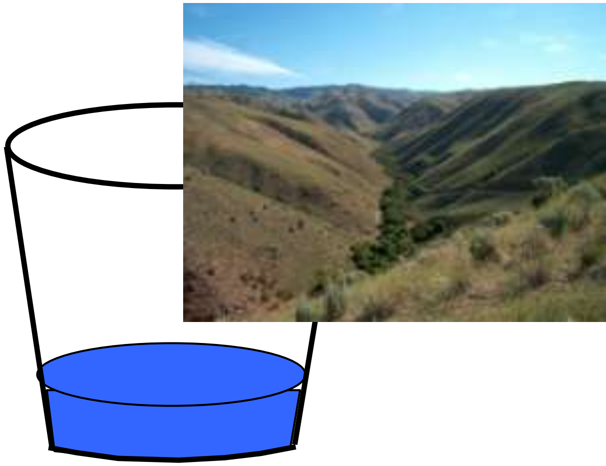
Storage

Connectivity
Thresholds
Residence Time

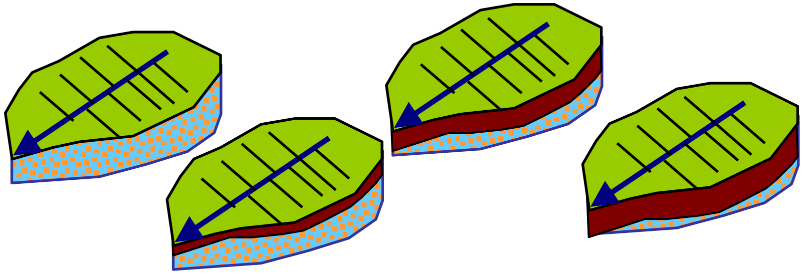


A Tale of Two Catchments

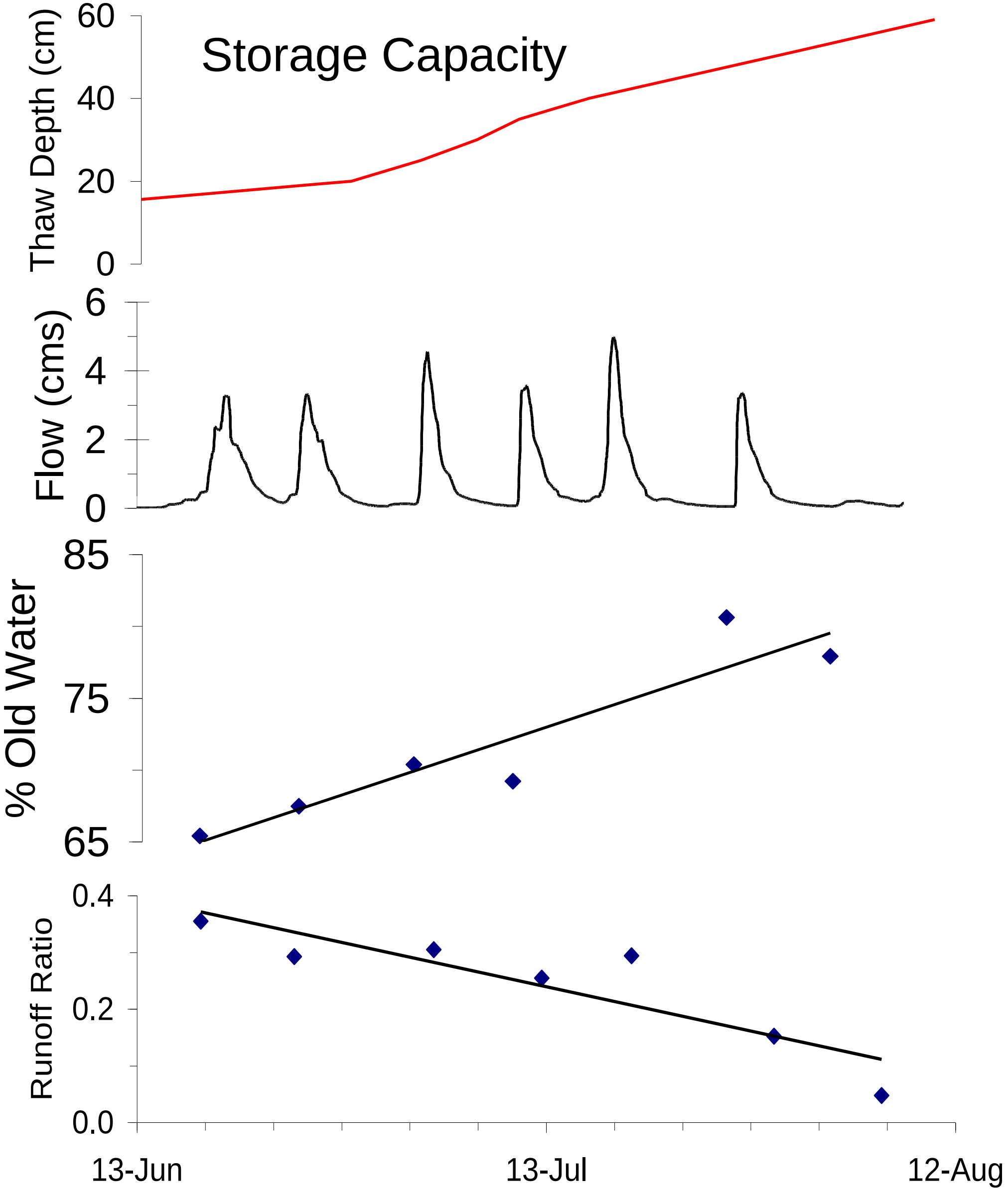




A Natural Storage Experiment



Andrew W. Balser
Toolik Field Station GIS



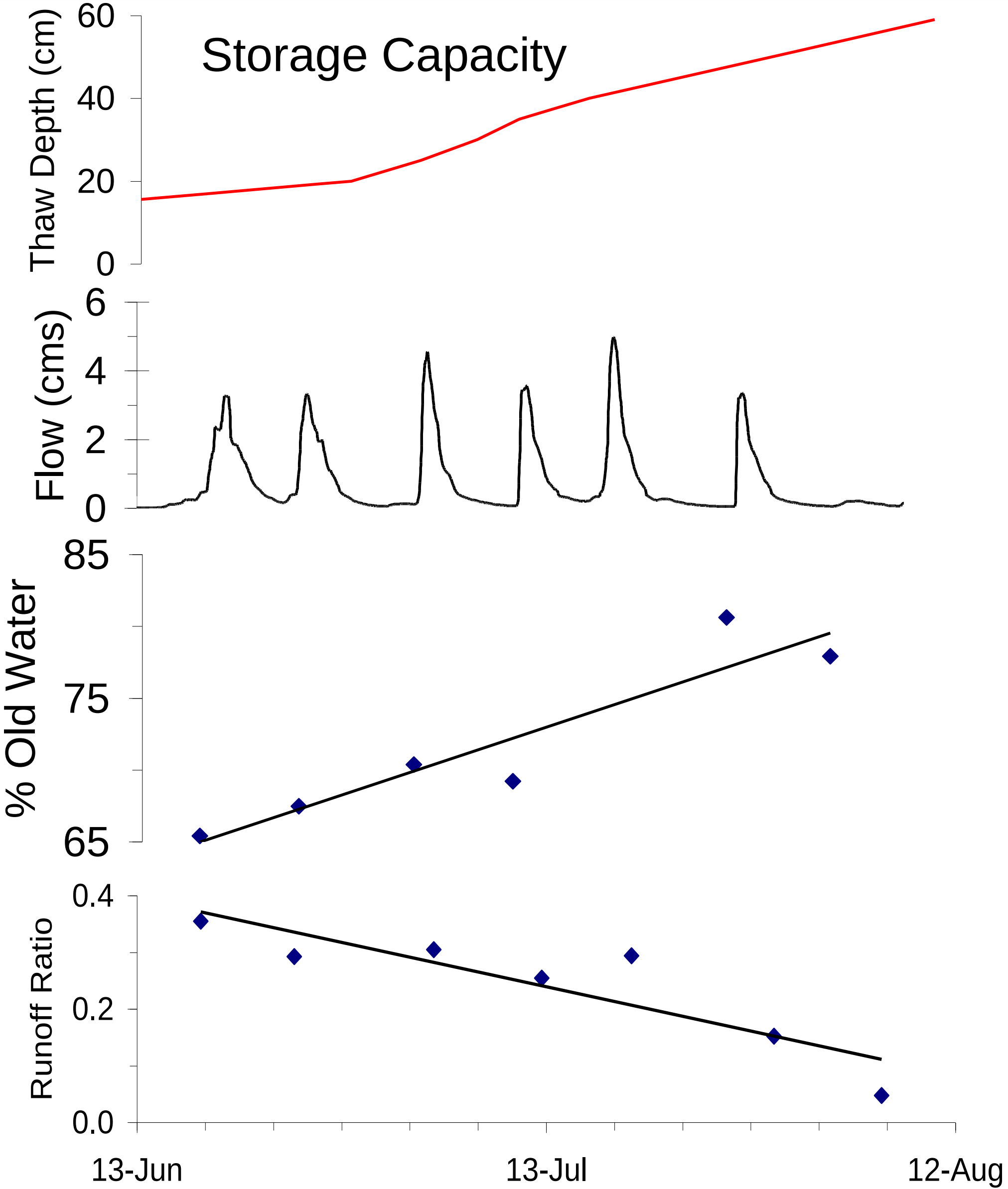
The Case for Storage

P-ET-Q =dS/dt

- The mechanisms by which catchments **STORE** water ultimately characterize the hydrologic **SYSTEM**

- Storage regulates fluxes (ET, Recharge, Streamflow)

- Storage is responsible for emergent behavior such as connectivity, thresholds, and residence time

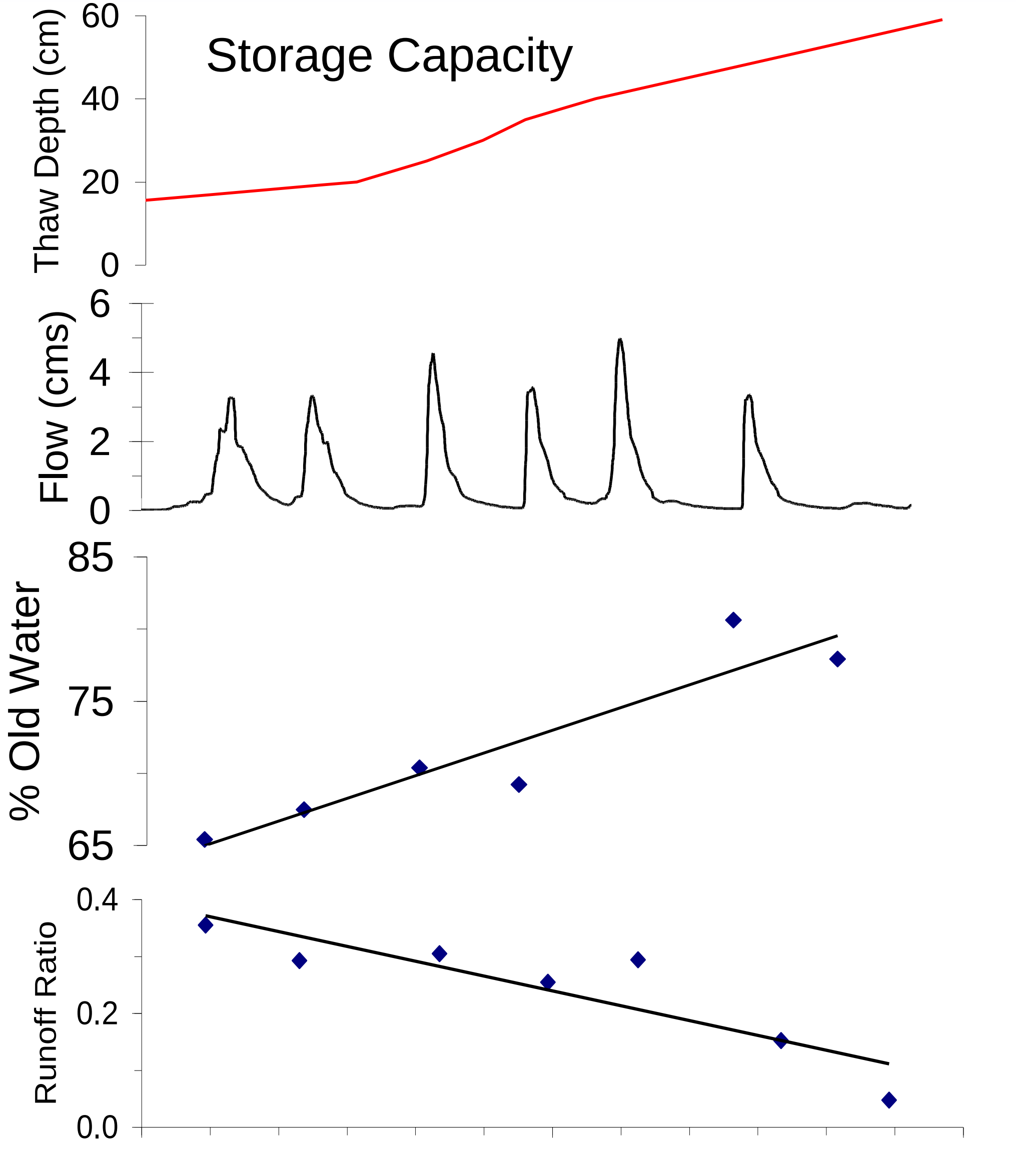


A Natural Storage Experiment

P-ET-Q =dS/dt

- We should focus on **Runoff Prevention** mechanisms in addition to runoff generation mechanisms

- We should concern ourselves with how catchments **Retain Water** in addition to how they release water



The Storage Problem

- Storage is not commonly measured

- Storage is often estimated as the residual of a water balance

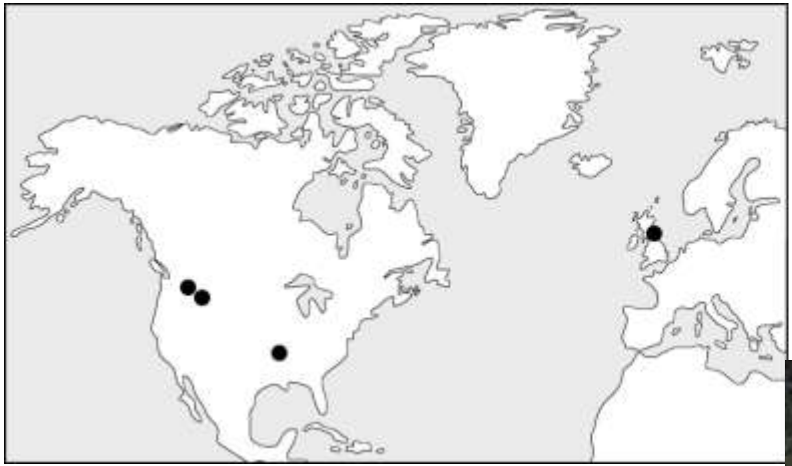
- Storage is treated as a secondary model calibration target

CUAHSI Catchment Comparison Exercise

Dry Creek, Idaho, USA
Snowy, semi-arid,
ephemeral

Girnock, Scotland, Rain, humid

Panola, Georgia, USA
Rain, humid, perennial

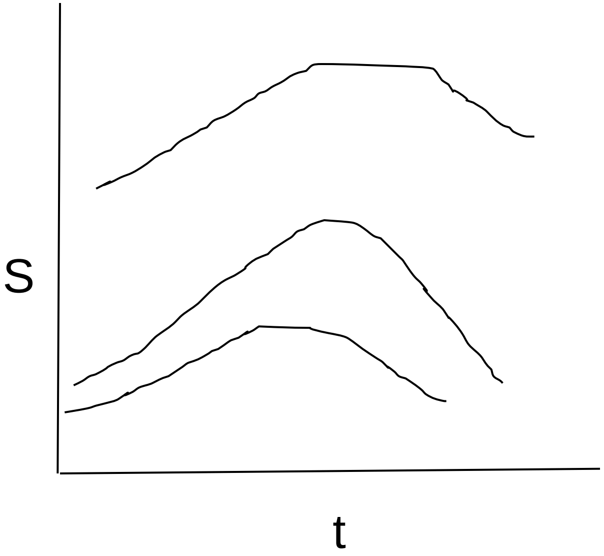


Reynolds Creek, Idaho, USA
Snowy, semi-arid, perennial

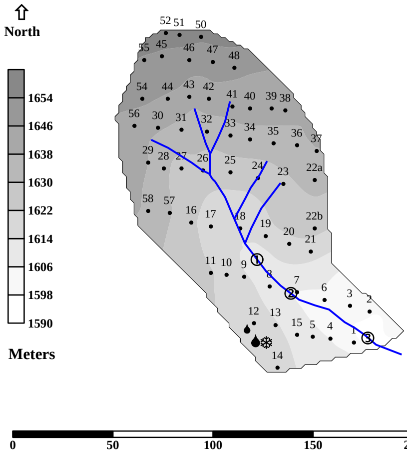
Gårdsjön, Sweden,
Snow, ephemeral

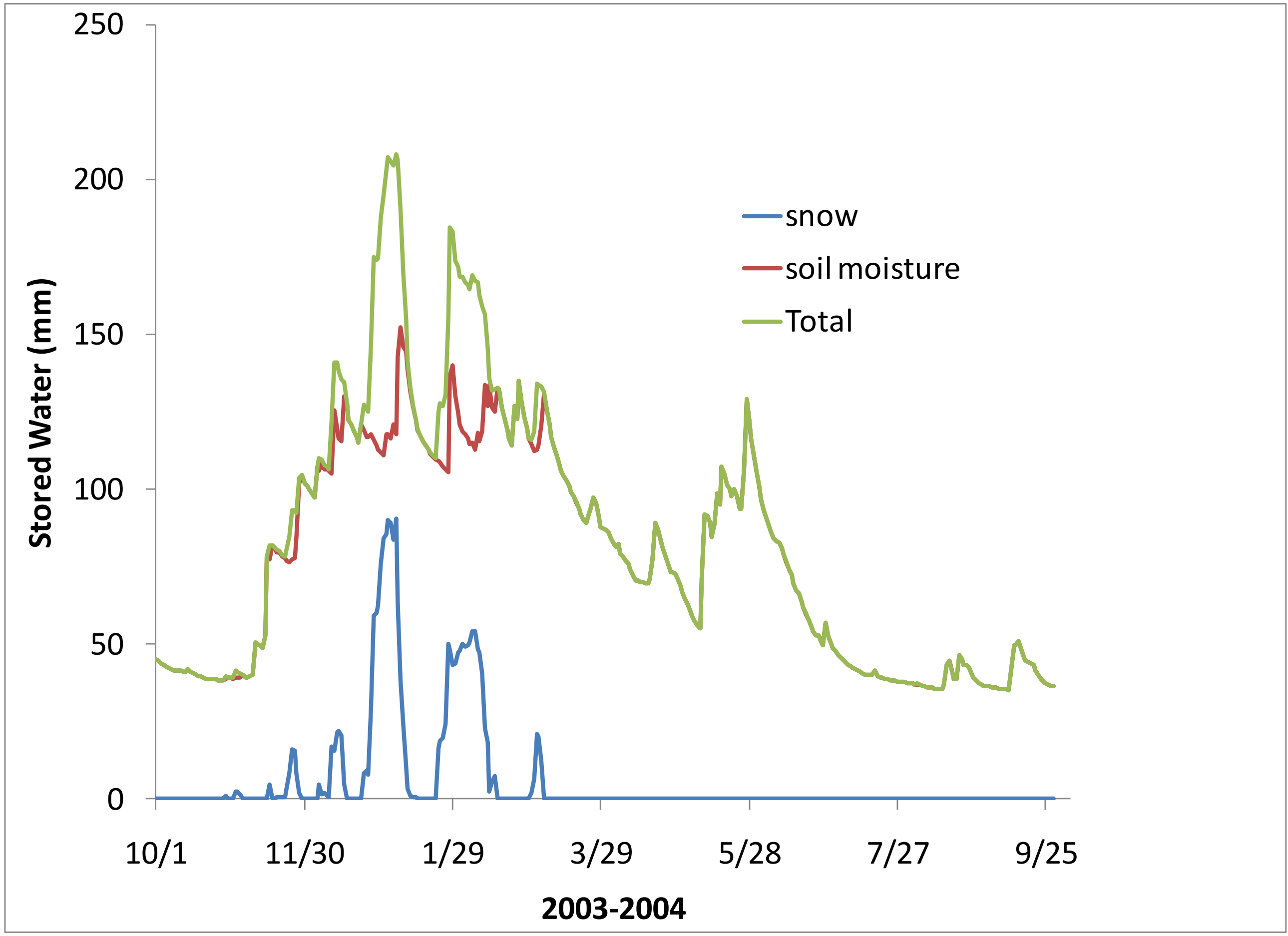
Storage Zones

Snow
Vegetation
Surface
Soils
Bedrock



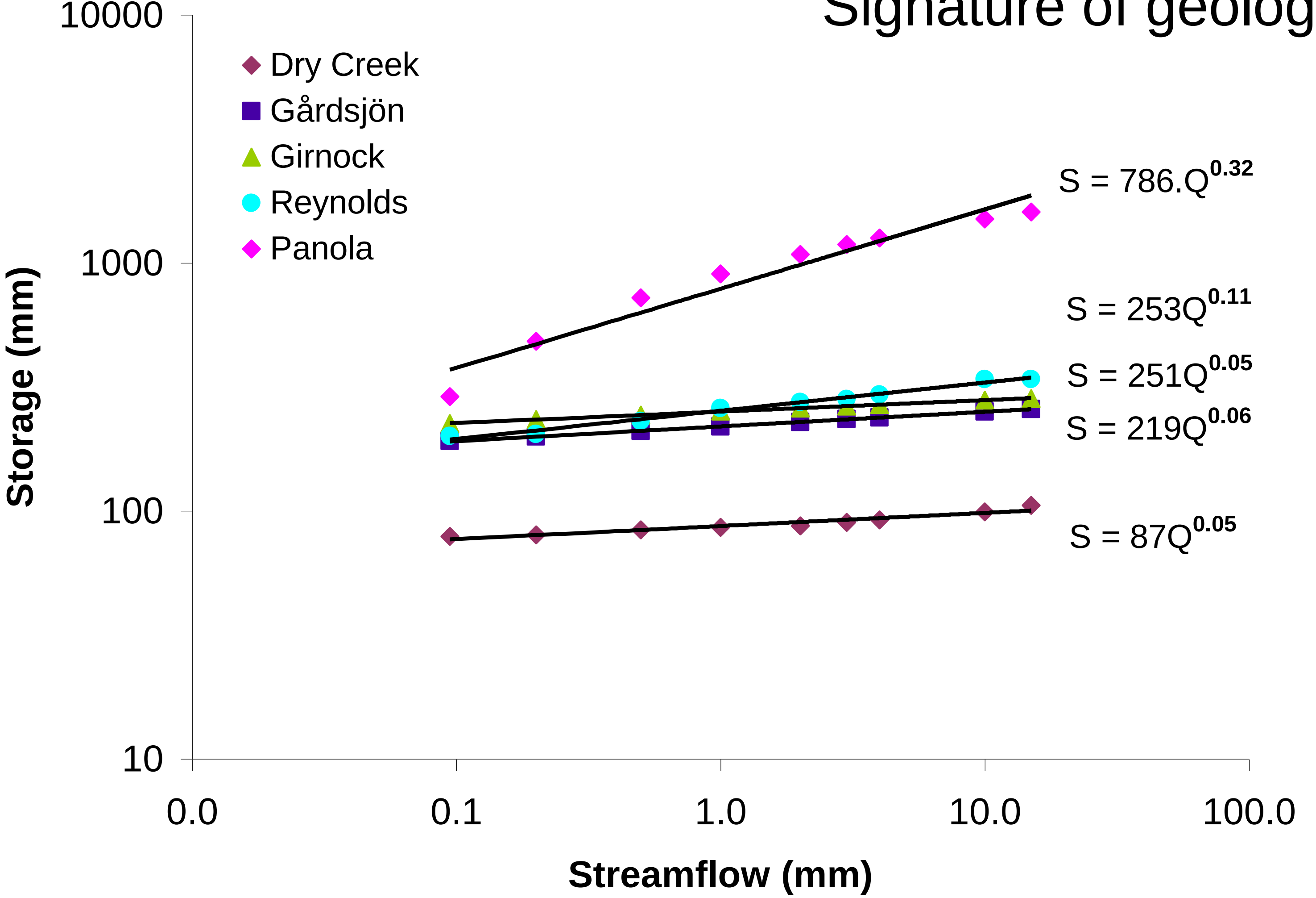
Storage Time Series by Direct Measurement





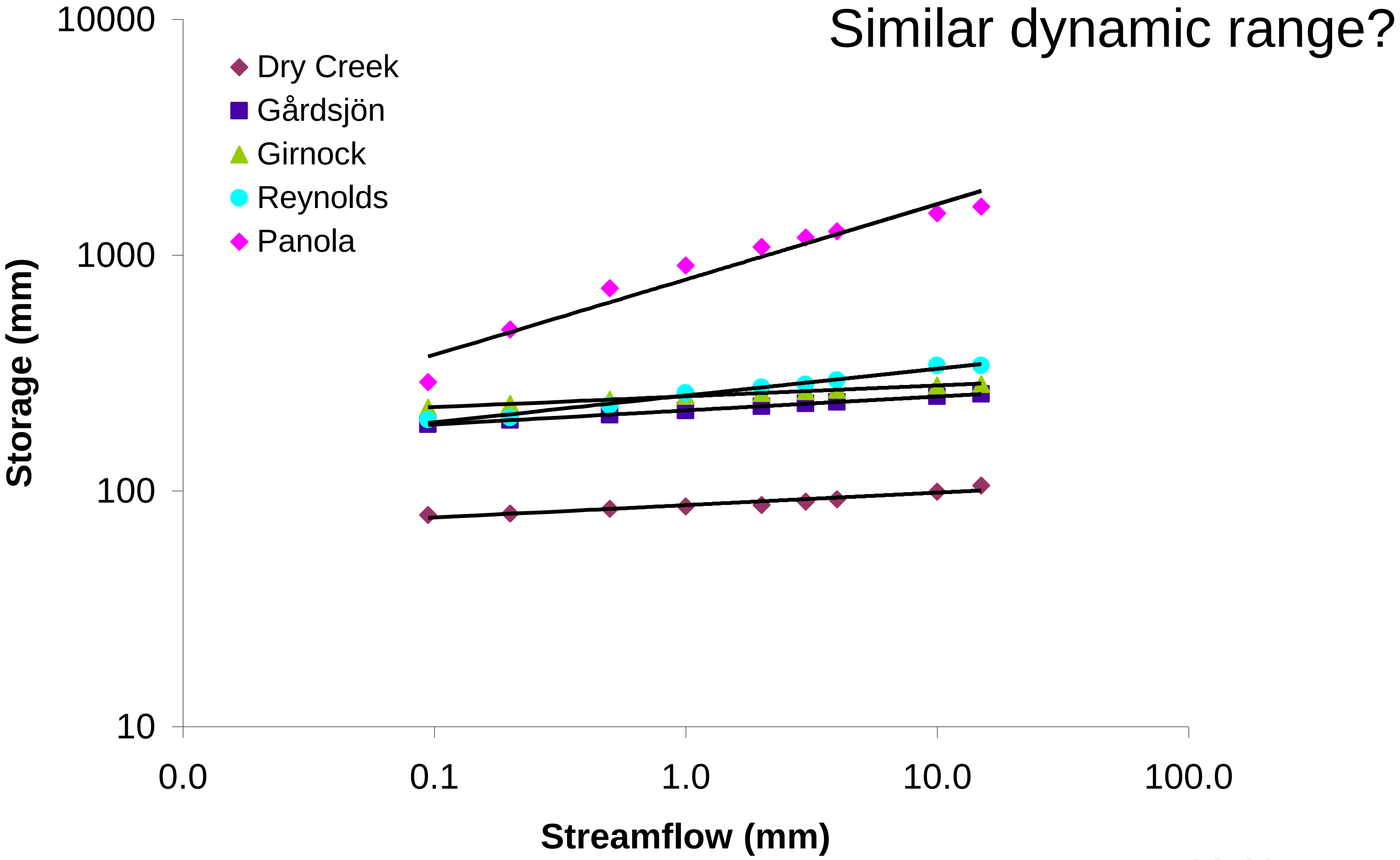
Storage-Discharge

Signature of geology?



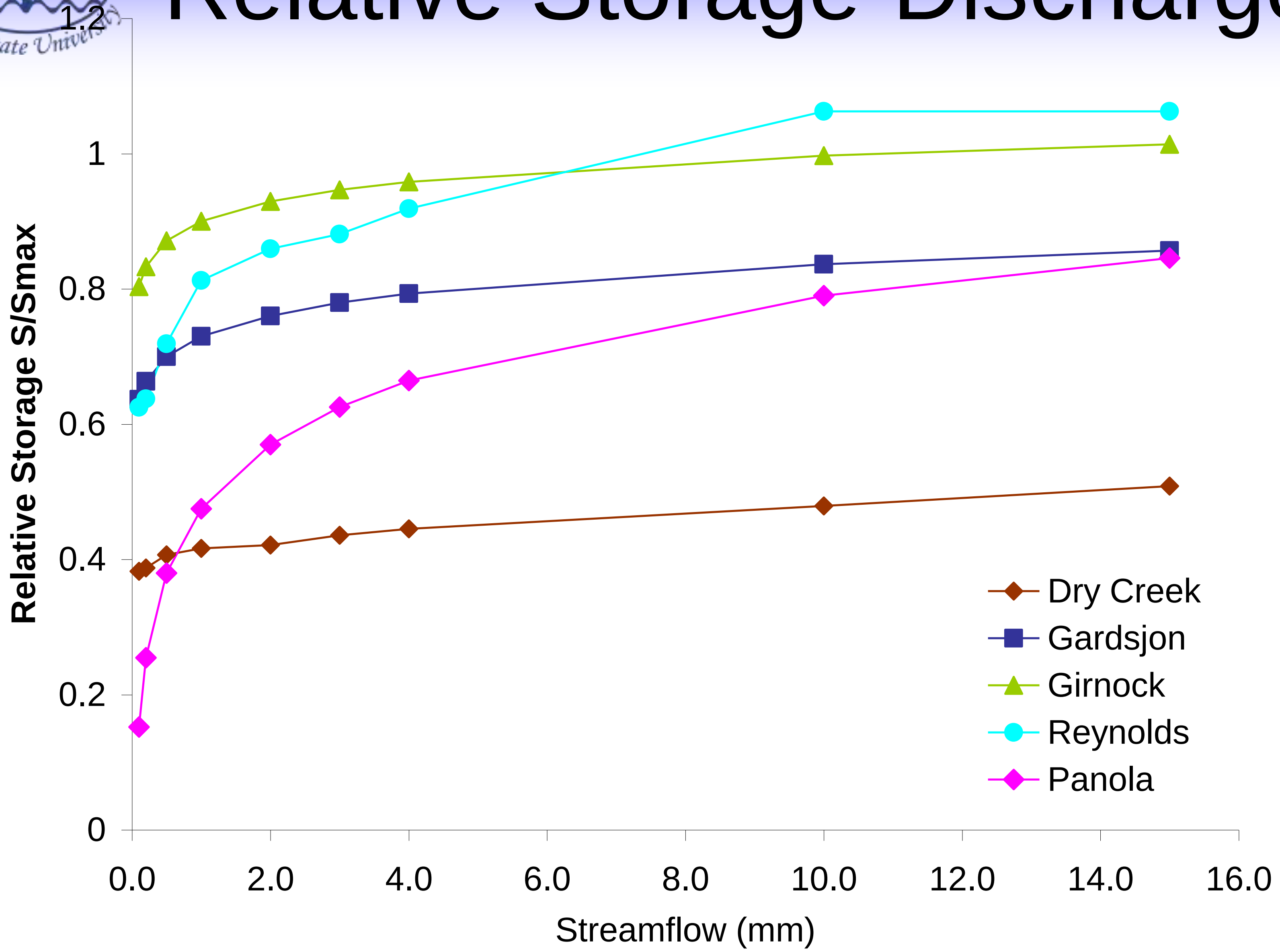
McNamara et al., 2011

Storage-Discharge



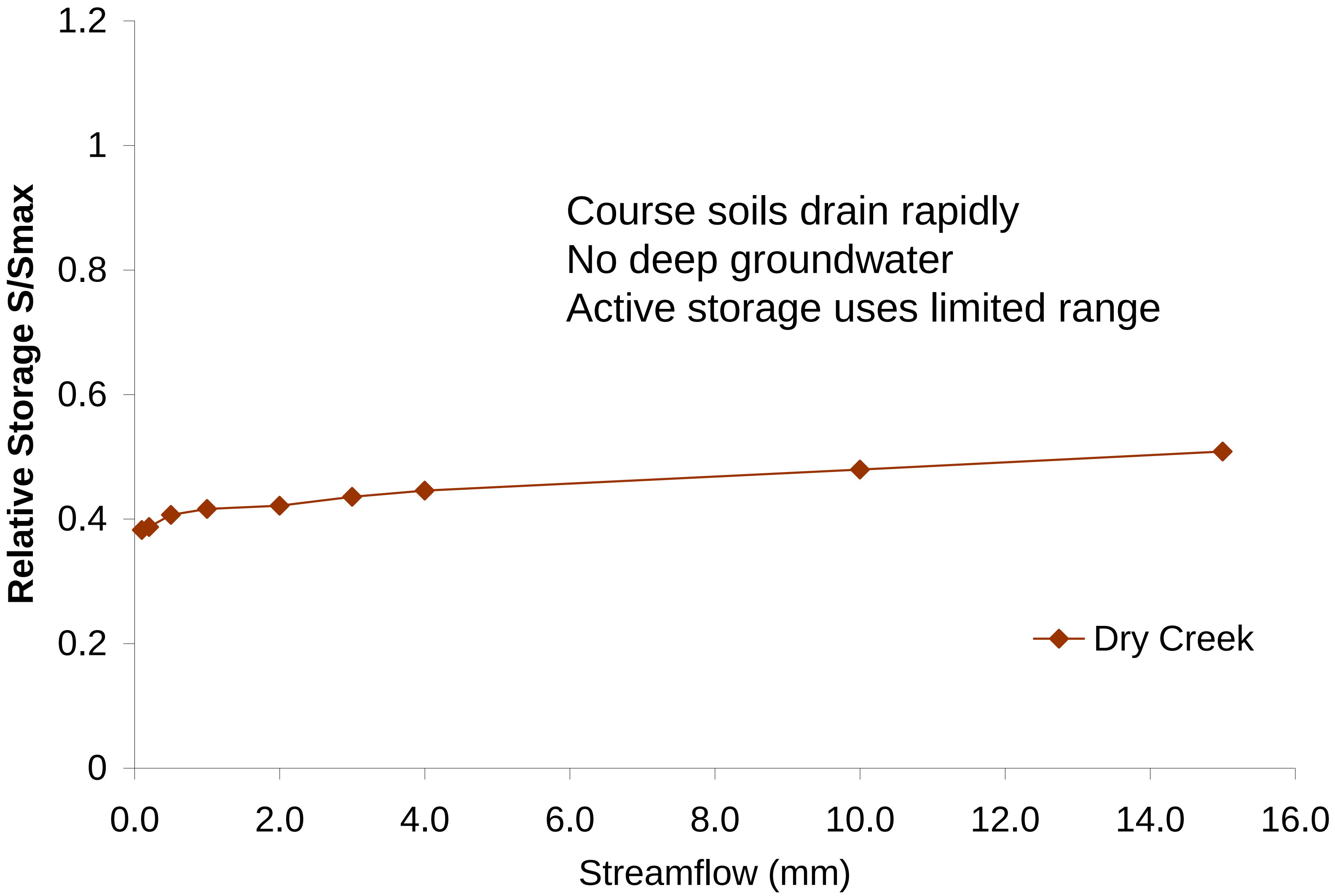
McNamara et al., 2011

Relative Storage-Discharge



McNamara et al., 2011

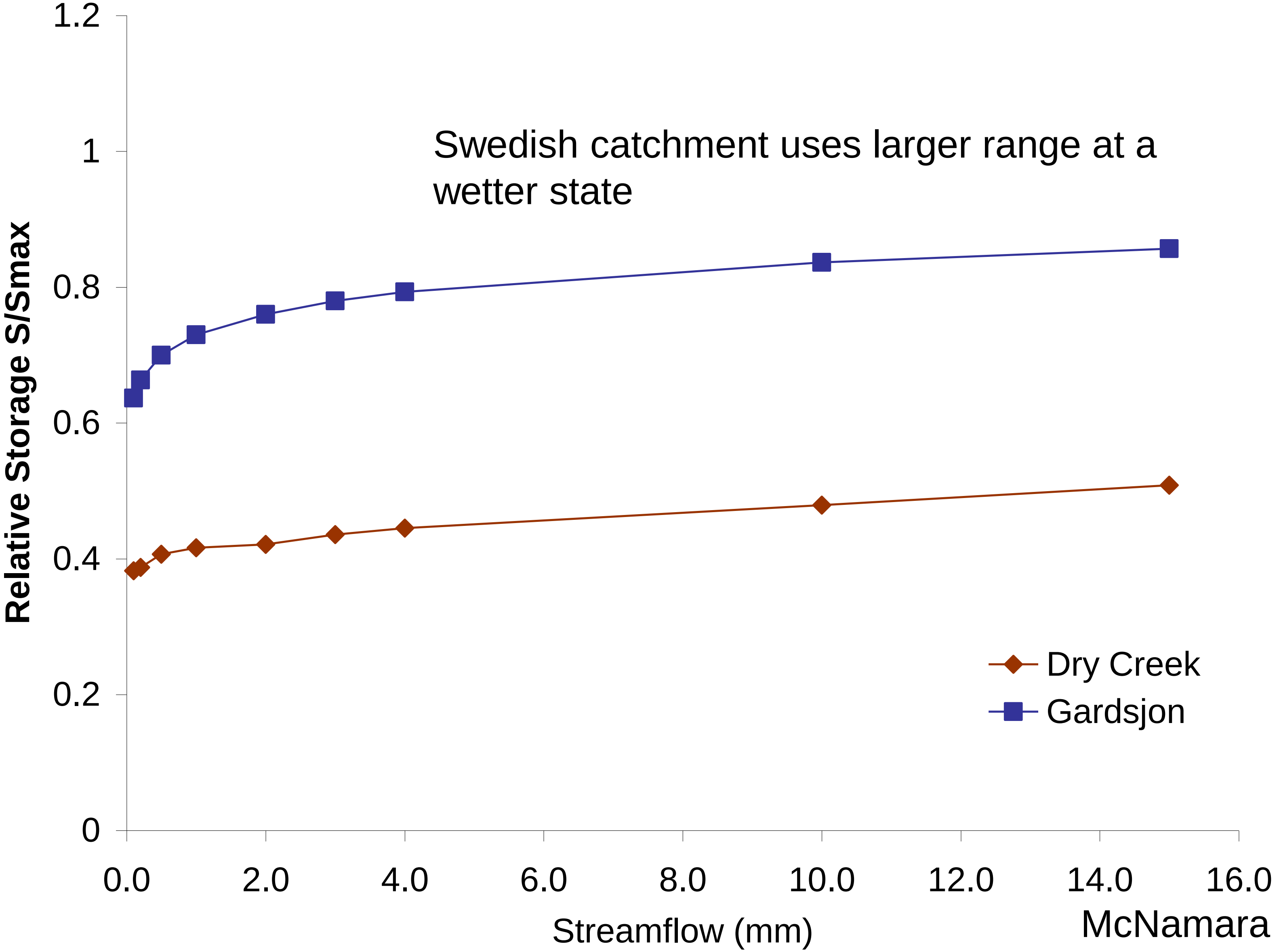
Relative Storage-Discharge



Course soils drain rapidly
No deep groundwater
Active storage uses limited range

McNamara et al., 2011

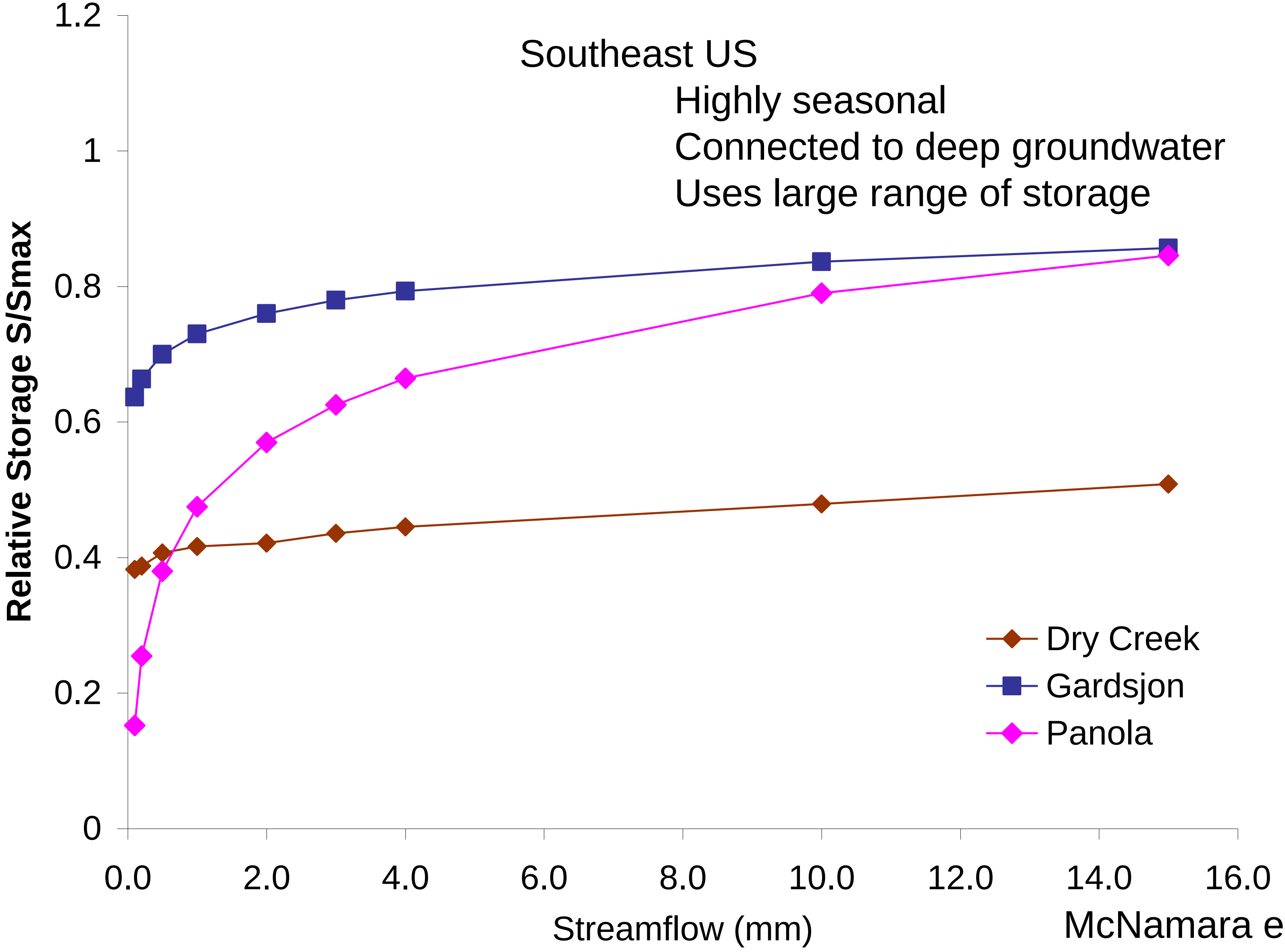
Relative Storage-Discharge



Swedish catchment uses larger range at a wetter state

McNamara et al., 2011

Relative Storage-Discharge

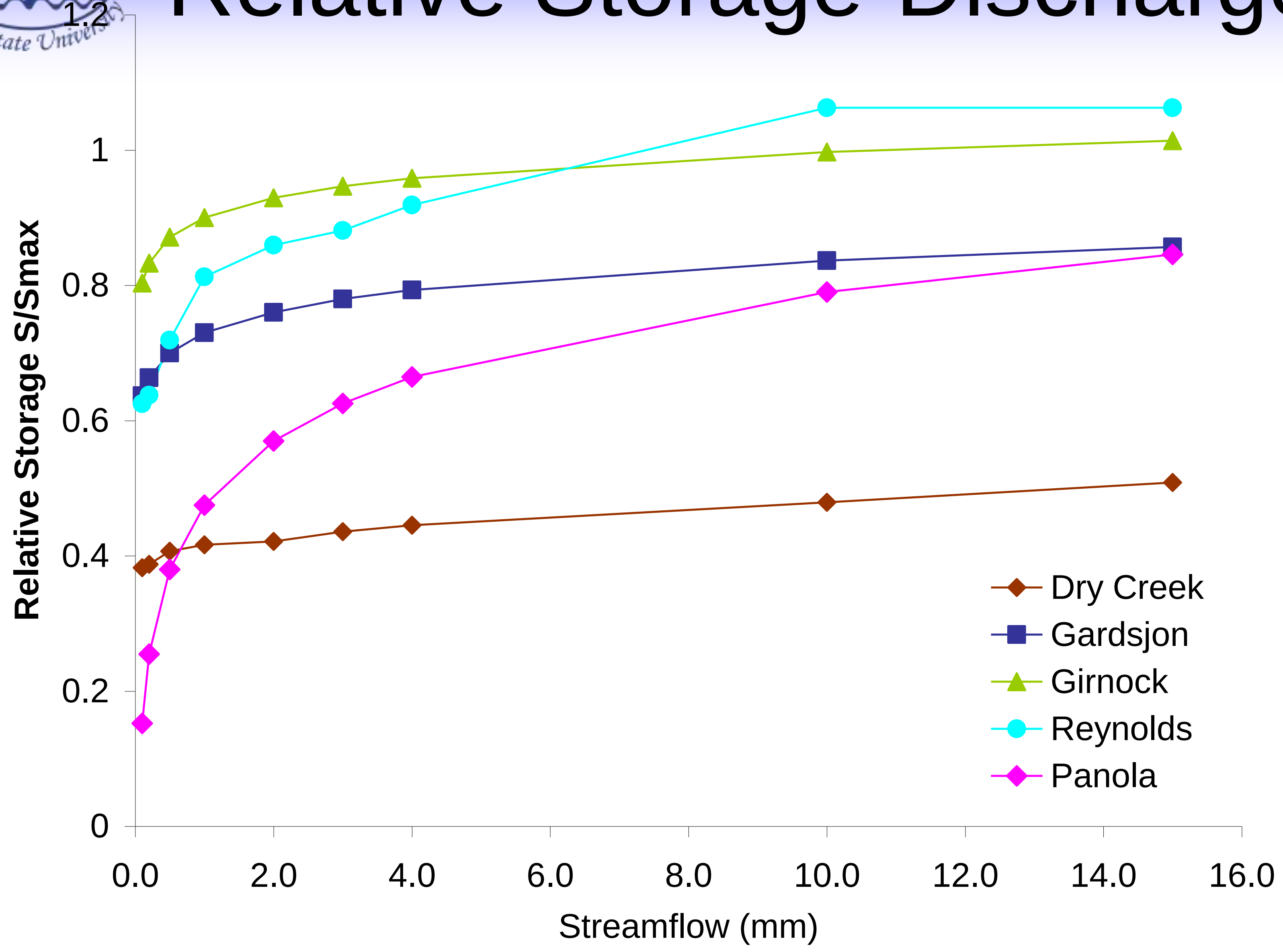


Southeast US

- Highly seasonal
- Connected to deep groundwater
- Uses large range of storage

McNamara et al., 2011

Relative Storage-Discharge

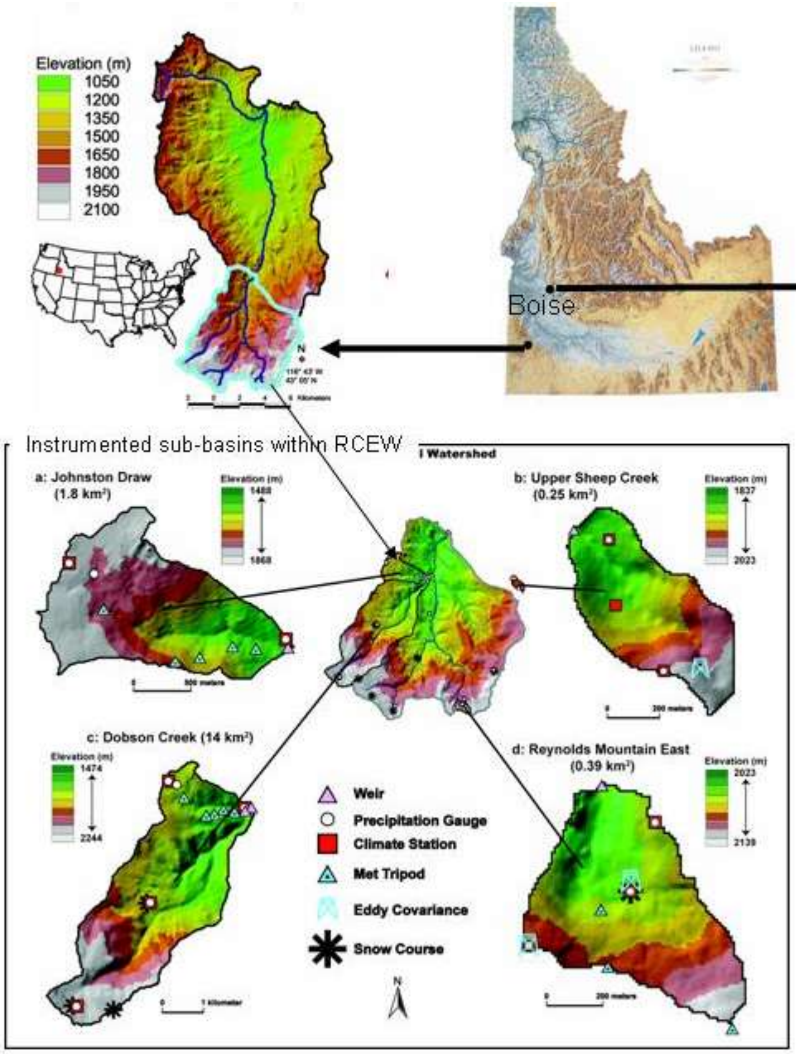


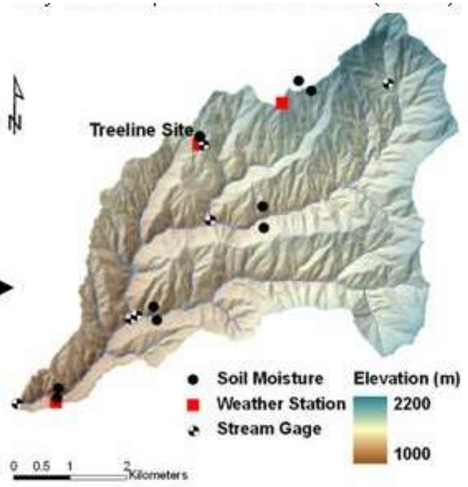
McNamara et al., 2011

Improved storage characterization will lead to improved prediction

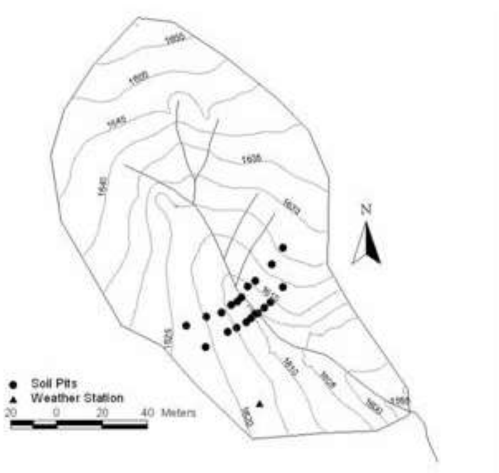
Reynolds Creek

Dry Creek

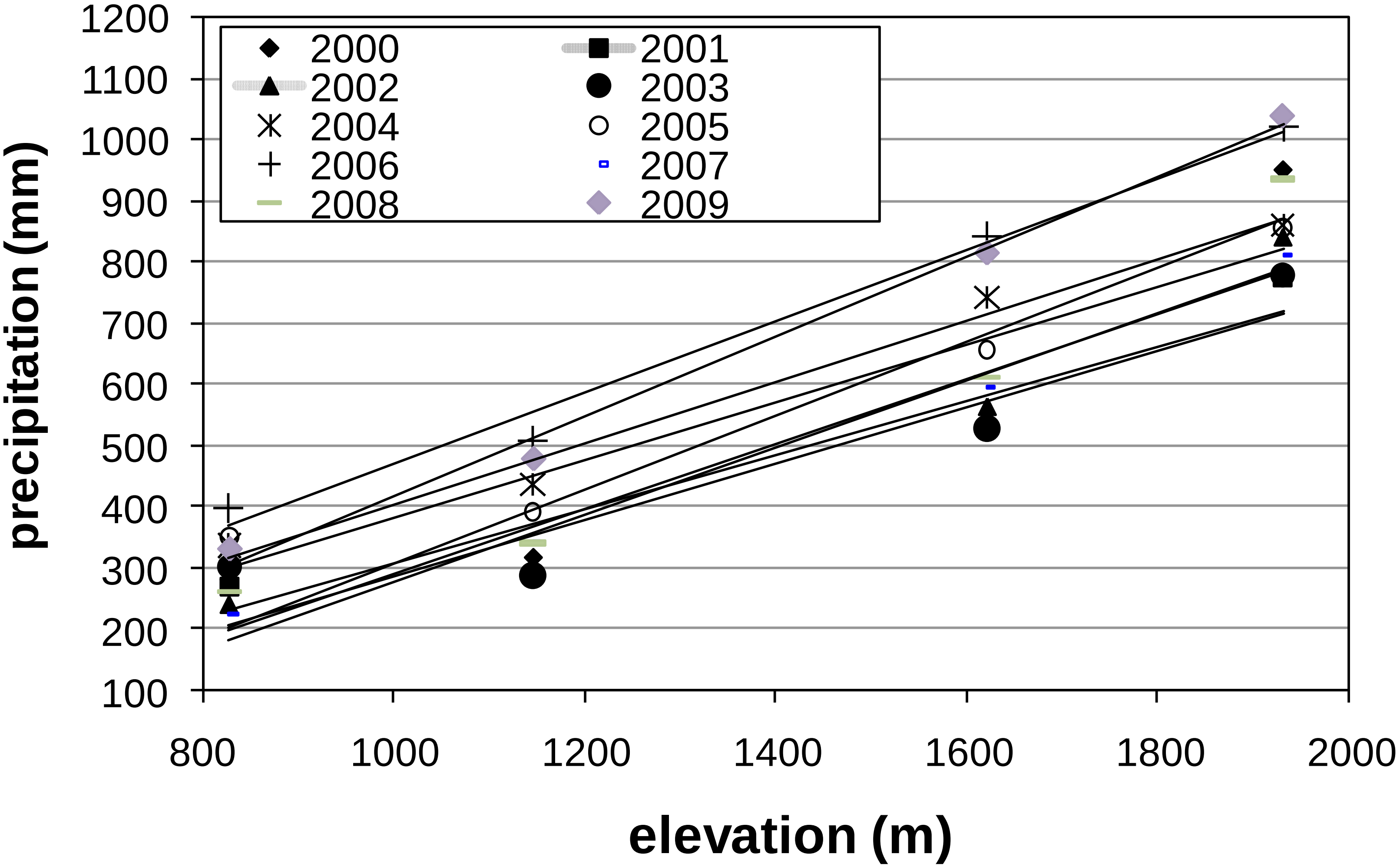


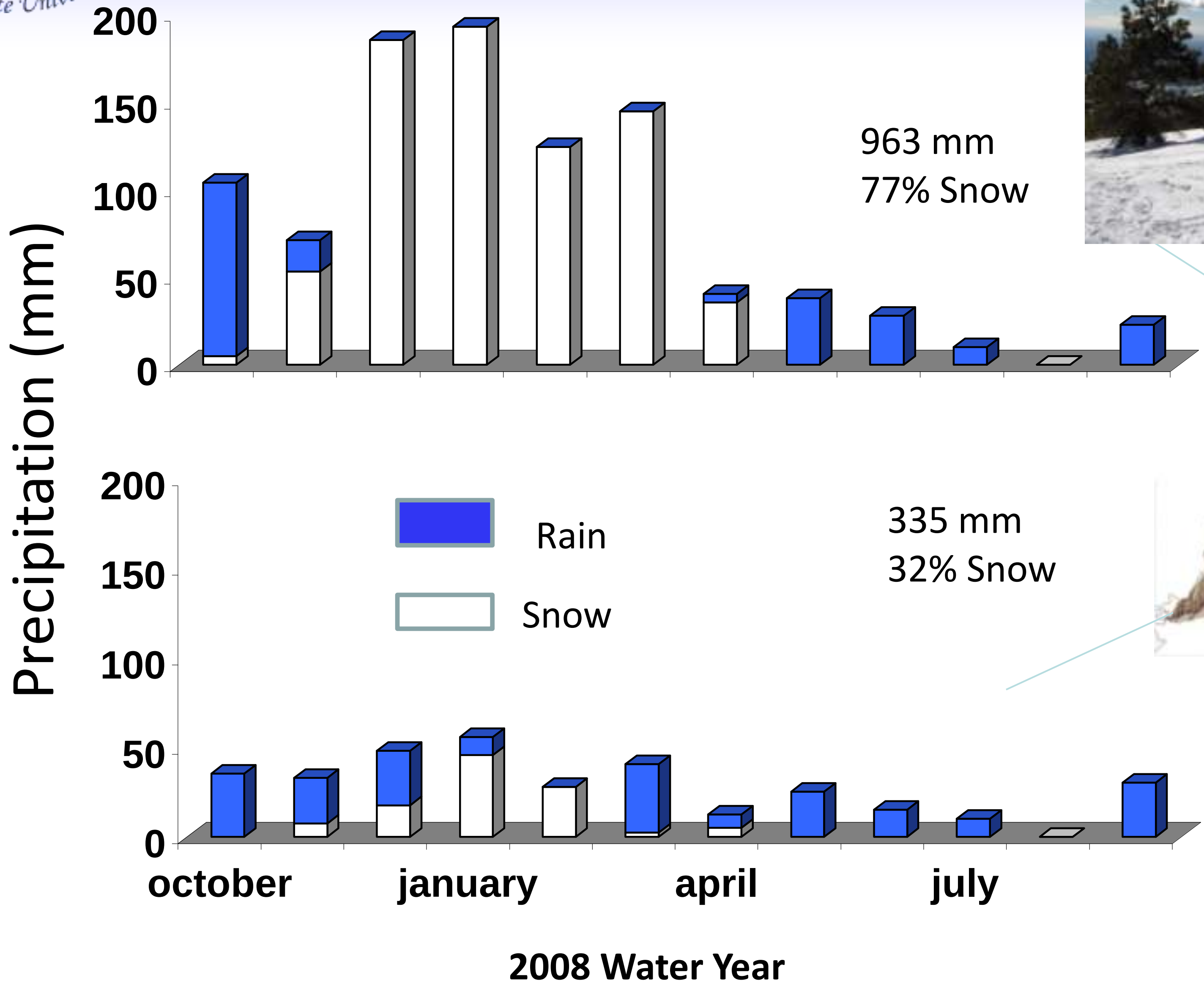


Treeline Catchment within DCEW



Precipitation

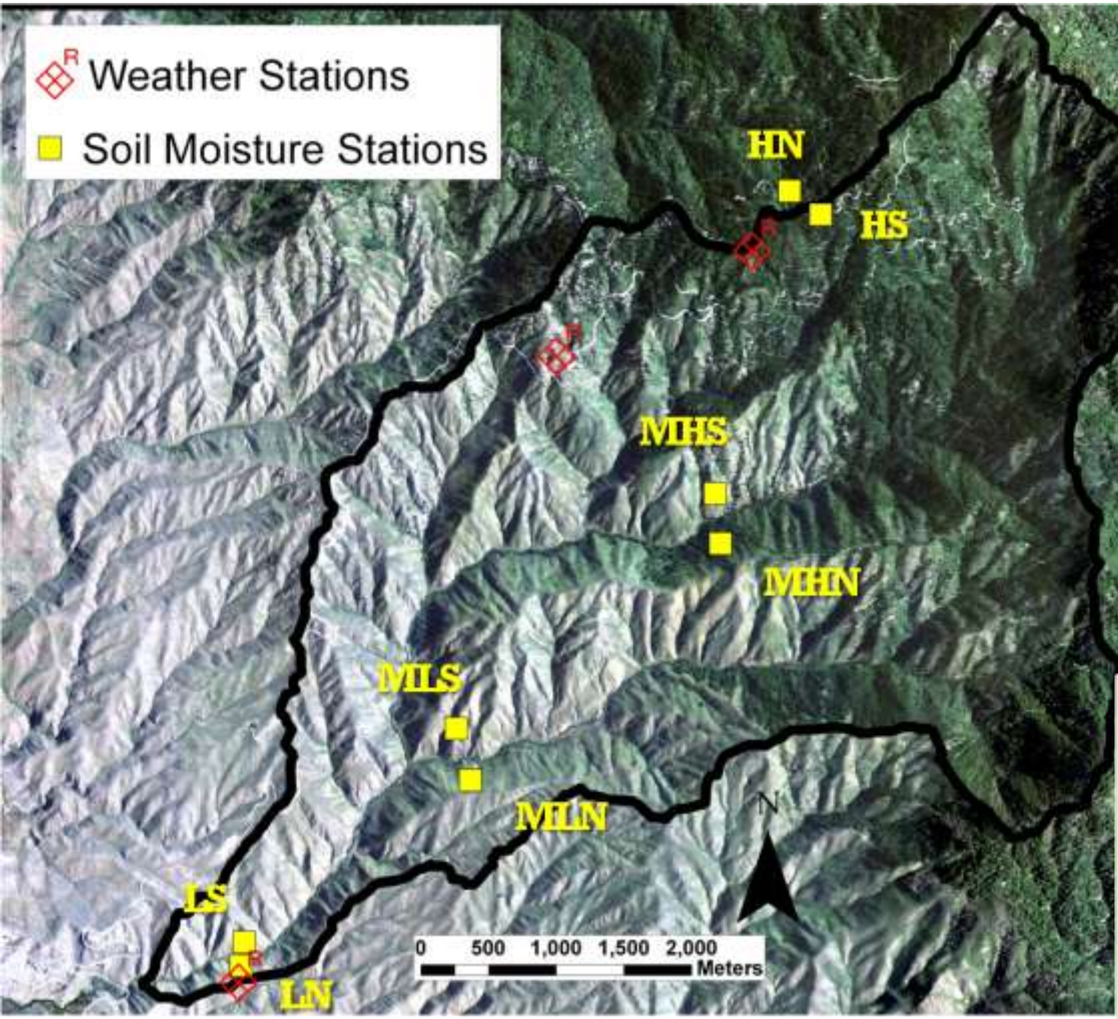


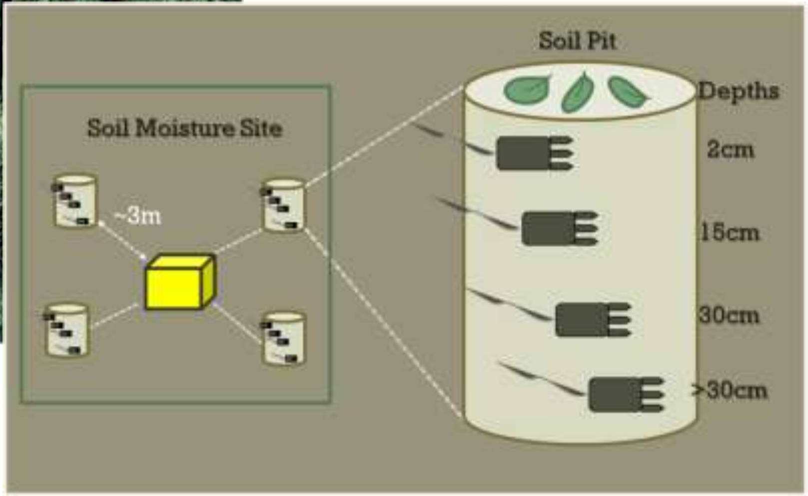


963 mm
77% Snow

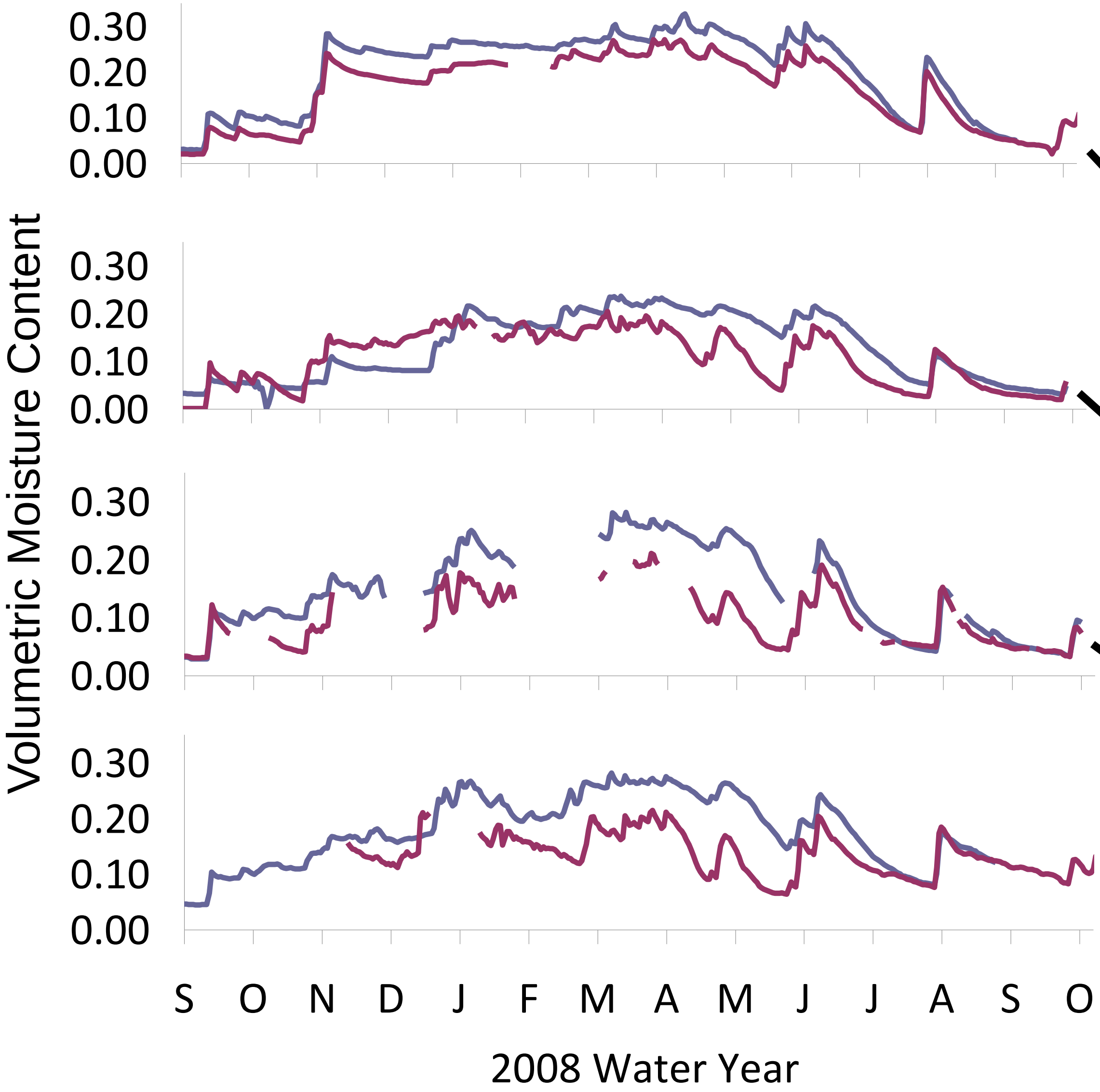
335 mm
32% Snow

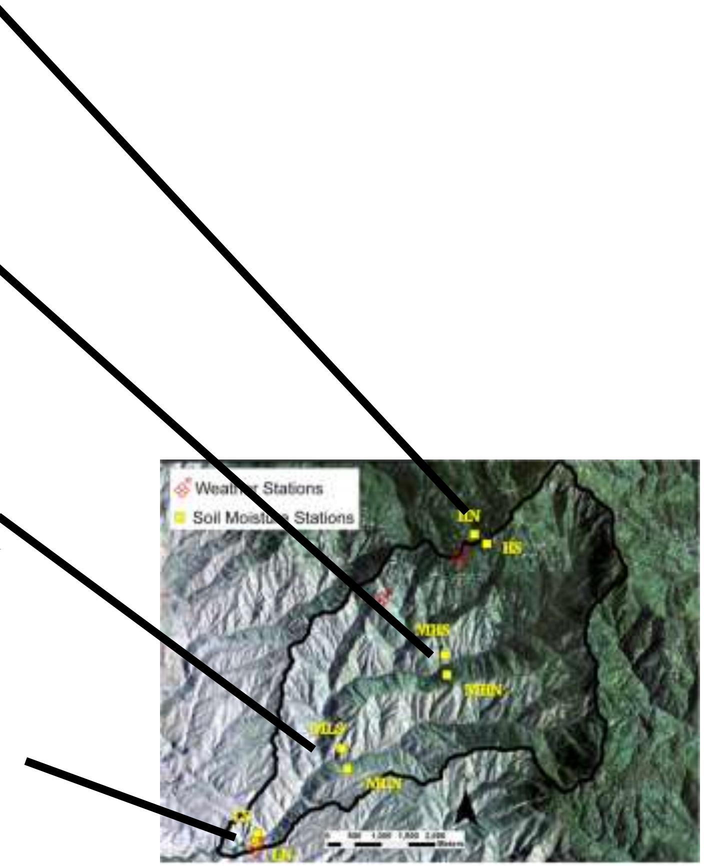
Distributed Soil Moisture Measurements - Aspect





Moisture and Aspect



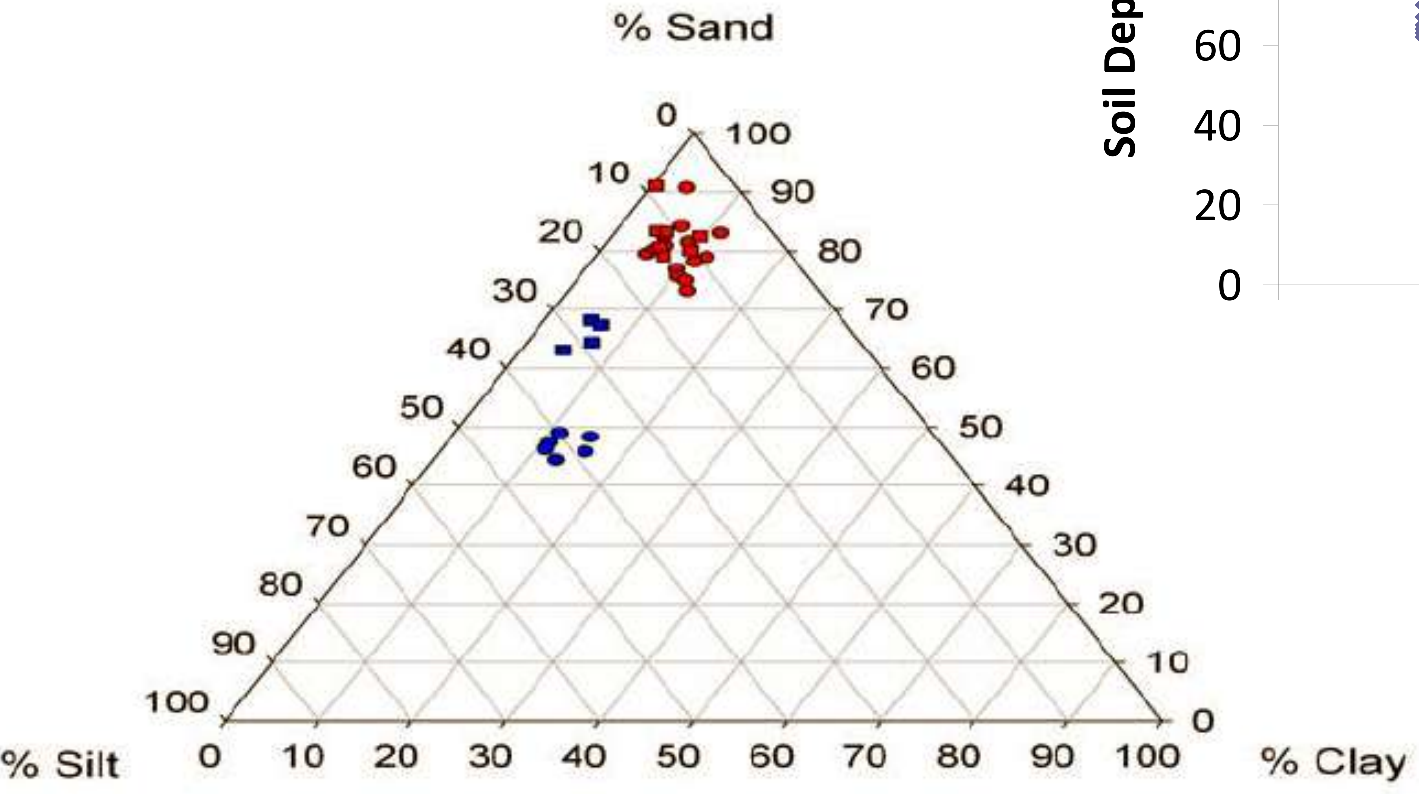


Smith et al., in review

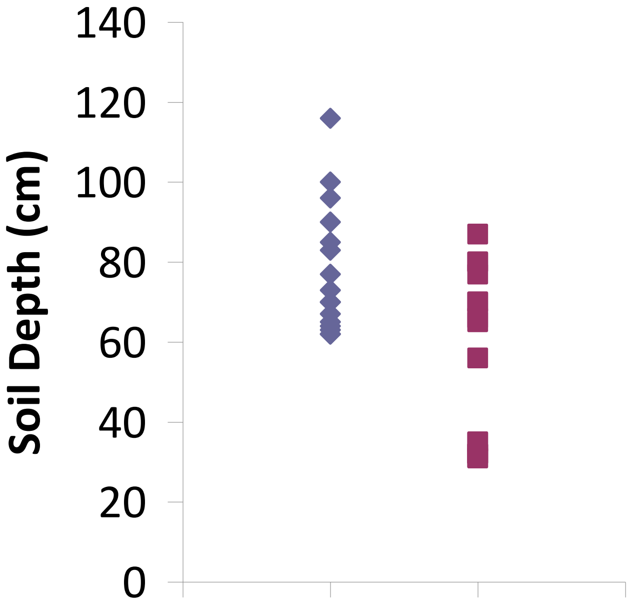
Soils properties vary with aspect

North aspect 🟦

South aspect 🟥

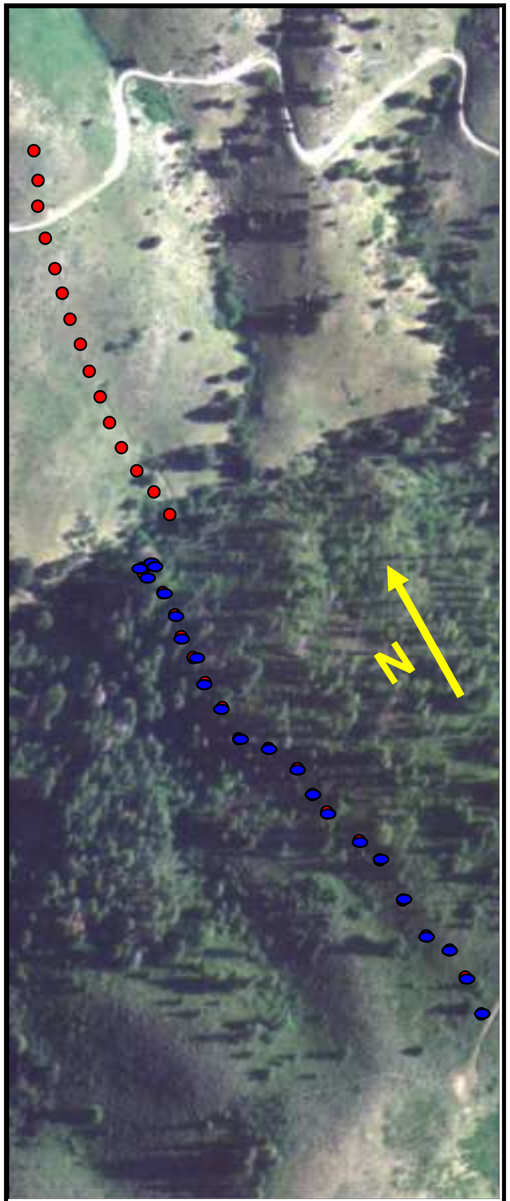


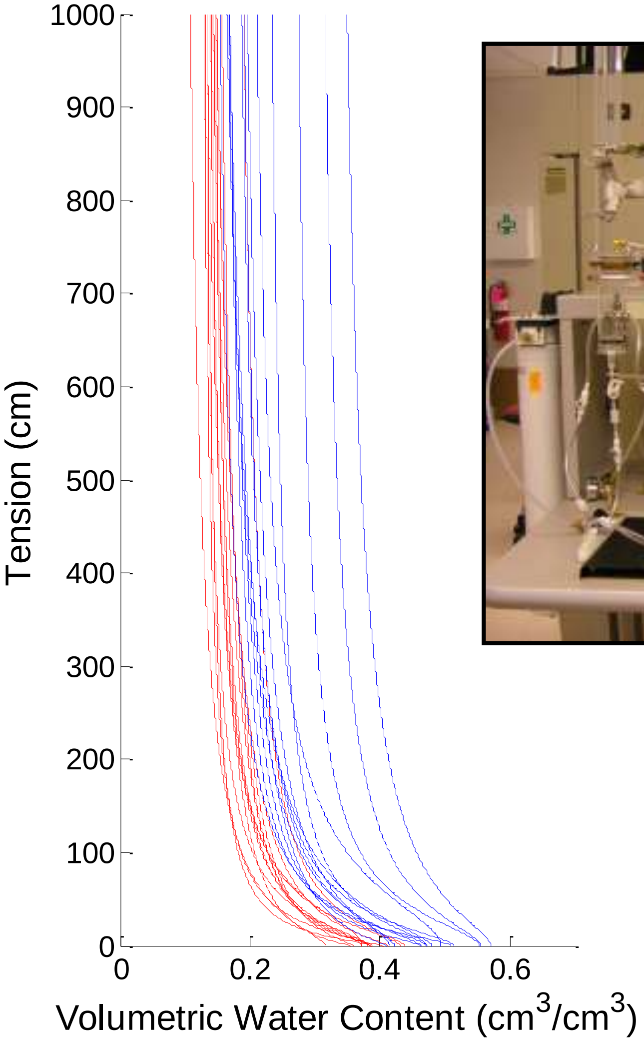
Smith, T., in progress, MS Thesis

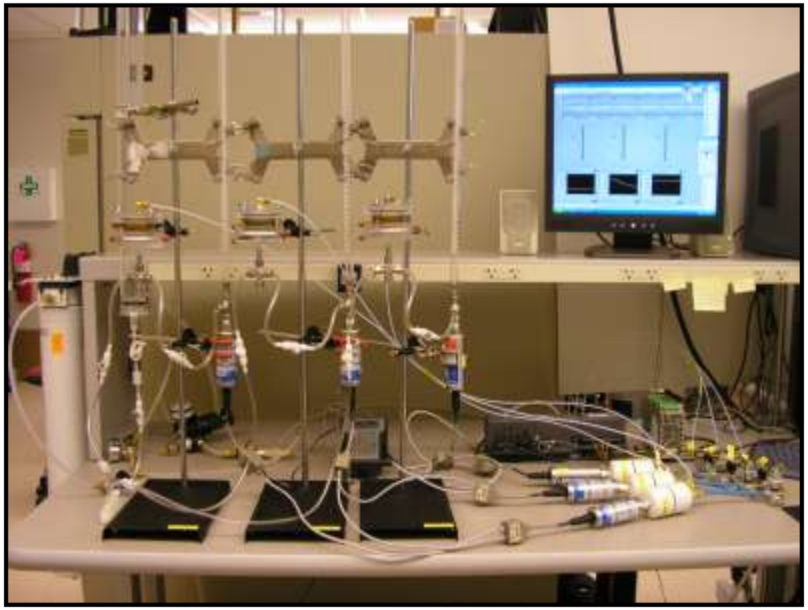


Smith et al., in review

North facing aspects retain more water than south facing aspects



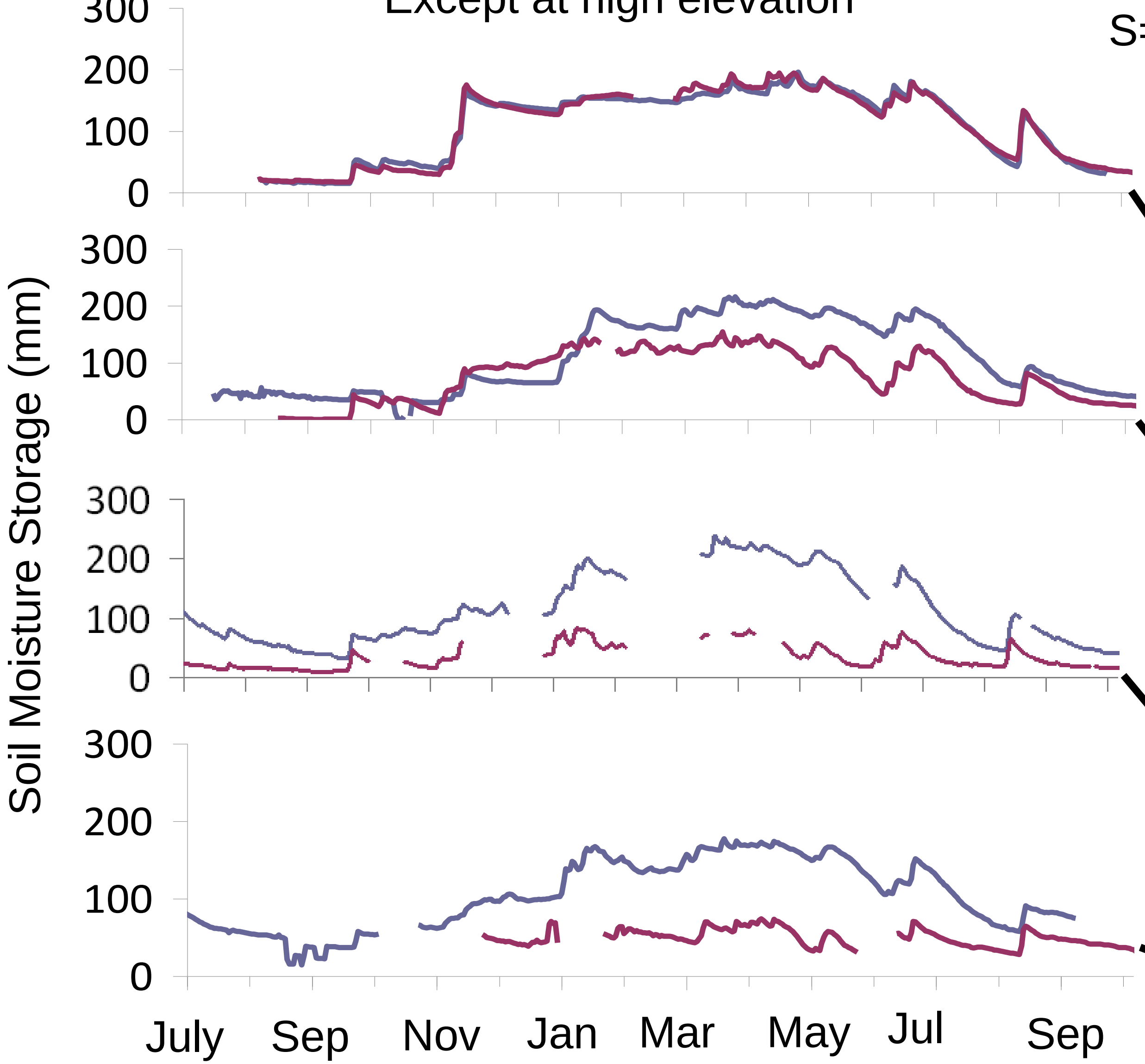




Geroy et al., in review

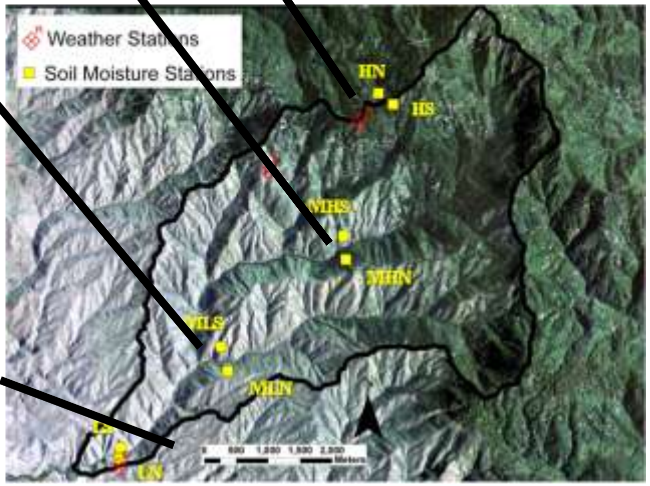
More Storage on North aspects

Except at high elevation



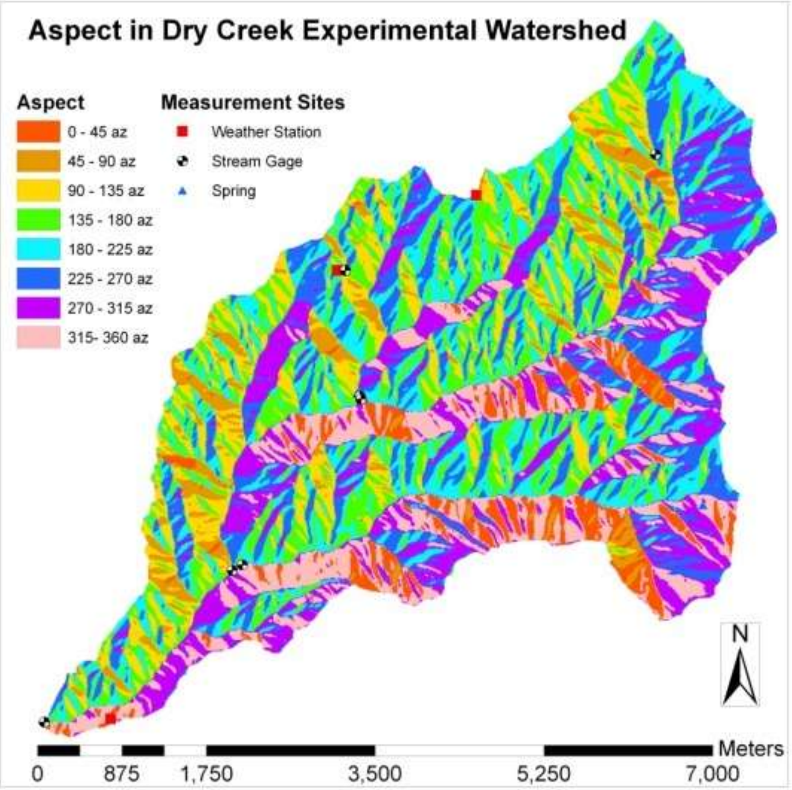
S=(soil depth)(moisture content)

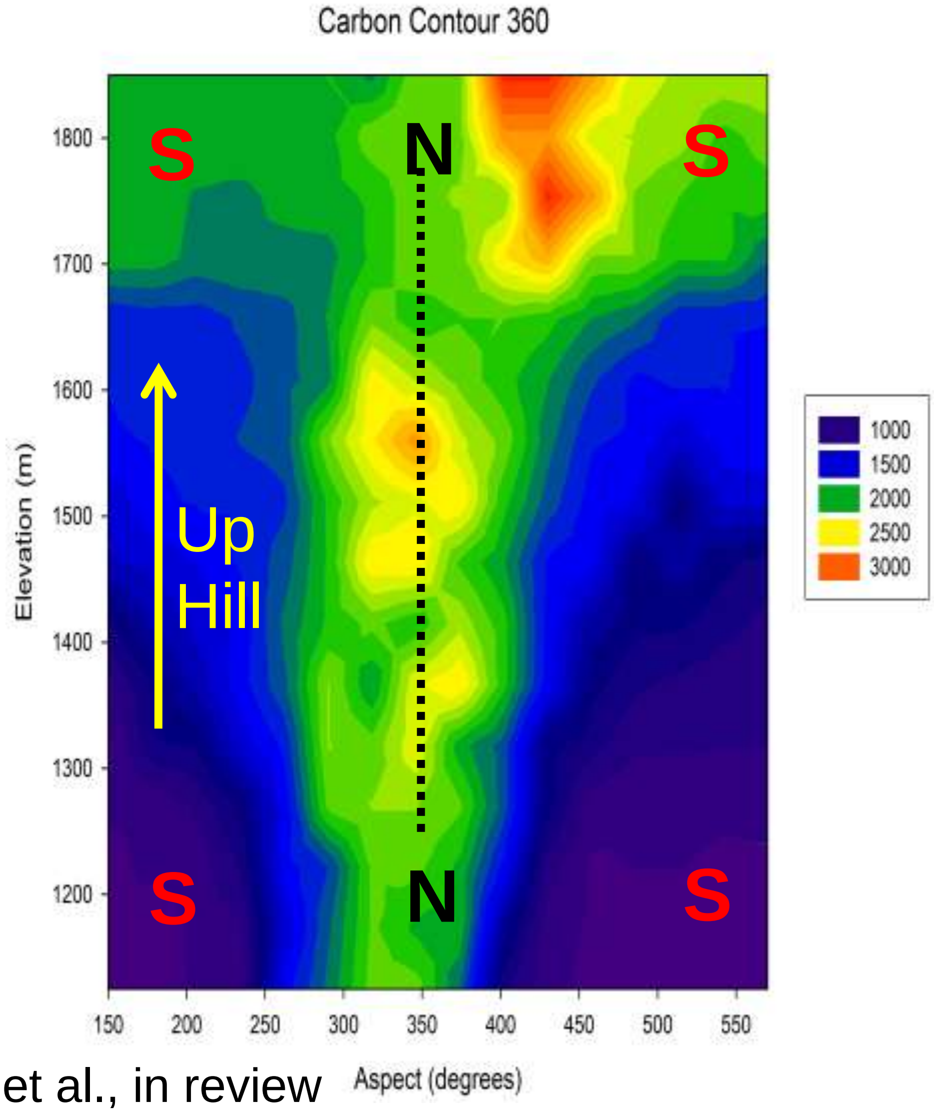
- -Higher moisture content
- -Higher moisture retention
- -Deeper soils
- -Finer grained soils
- -Lower insolation



Aspect-Insolation-Soil Carbon

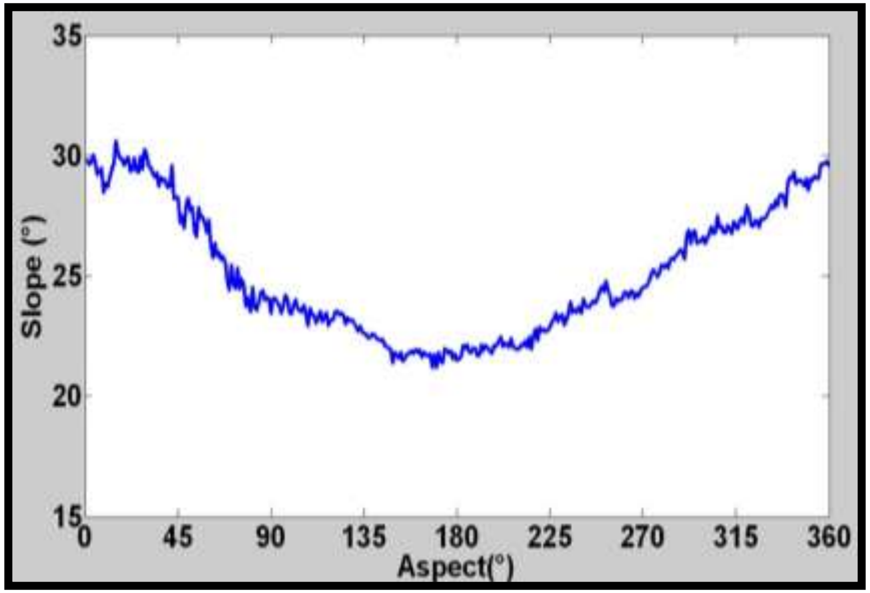
- Soil organic carbon content increases with aspect and elevation

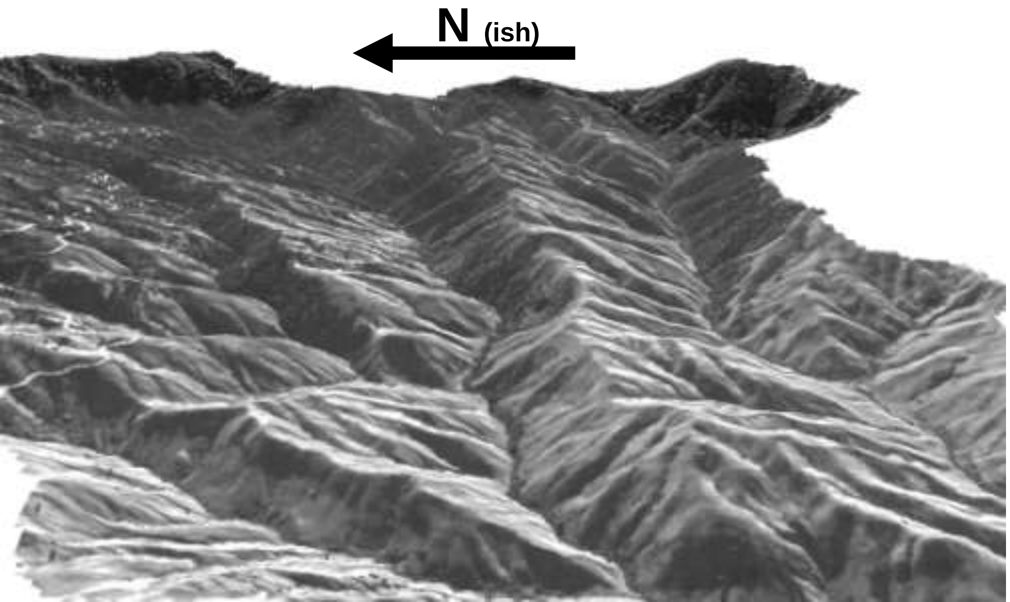




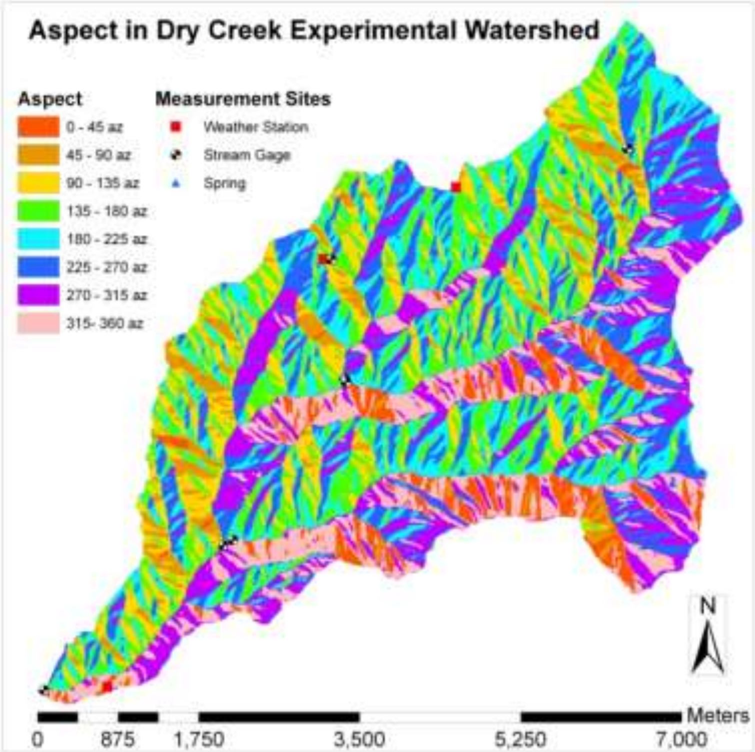
Kunkel et al., in review

Geomorphology and Aspect





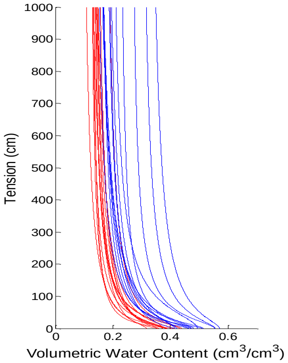
North facing slopes are steeper and shorter

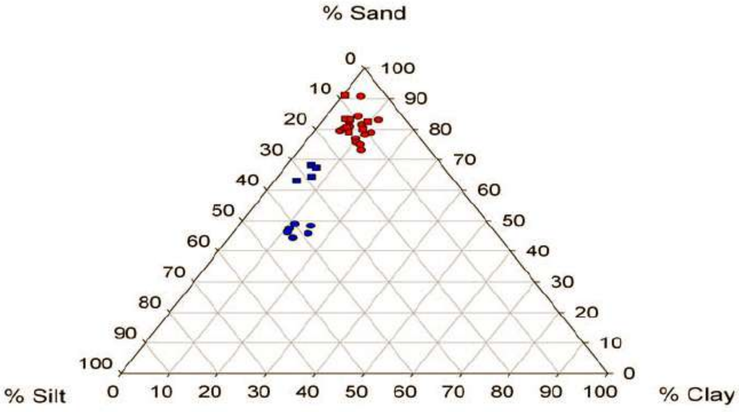


Poulos et al., in review

Storage Capacity

- Rooted in the co-evolution of landscape form and hydrologic processes



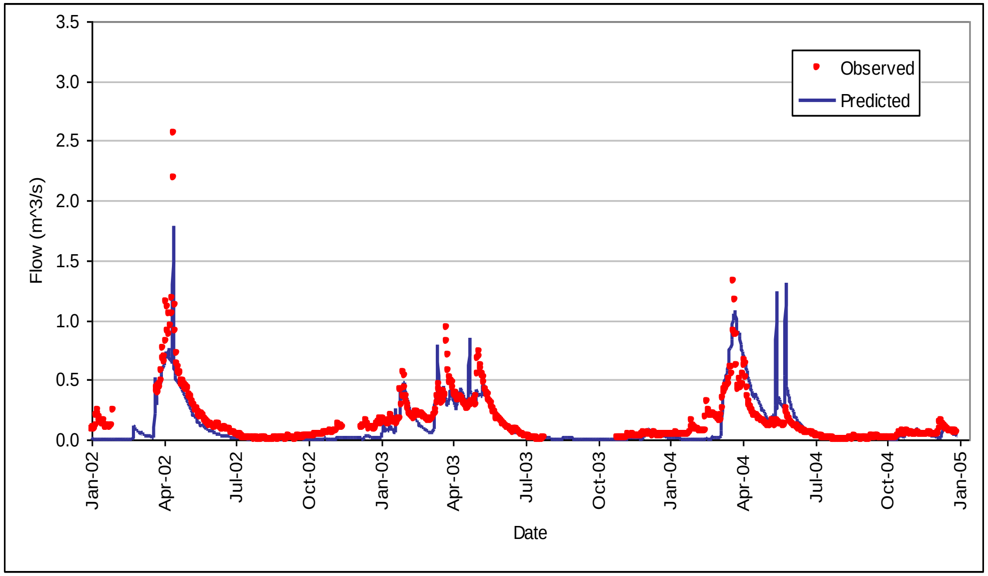


- Responsible for catchment-scale emergent behavior – Physical Lumped Properties
  - Connectivity, Thresholds, Residence time

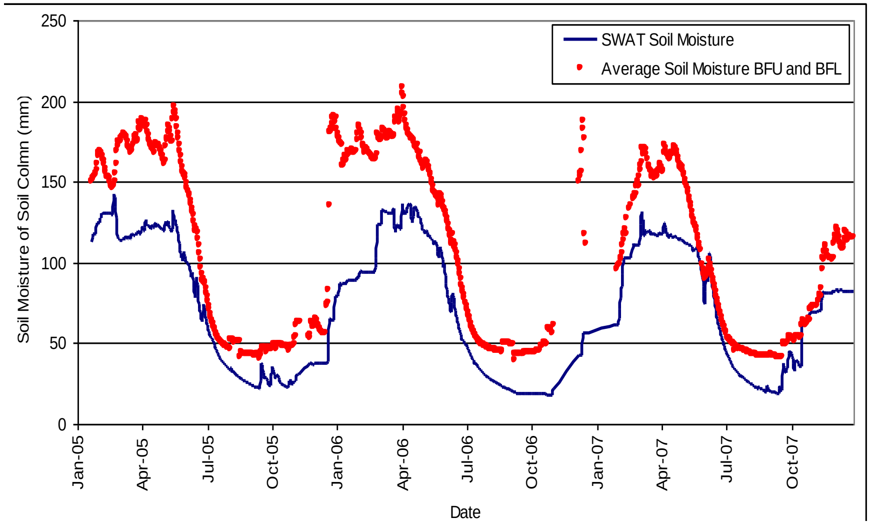
Our Modeling Experience

- Soil Water Assessment Tool (SWAT)

Hydrograph “Right”

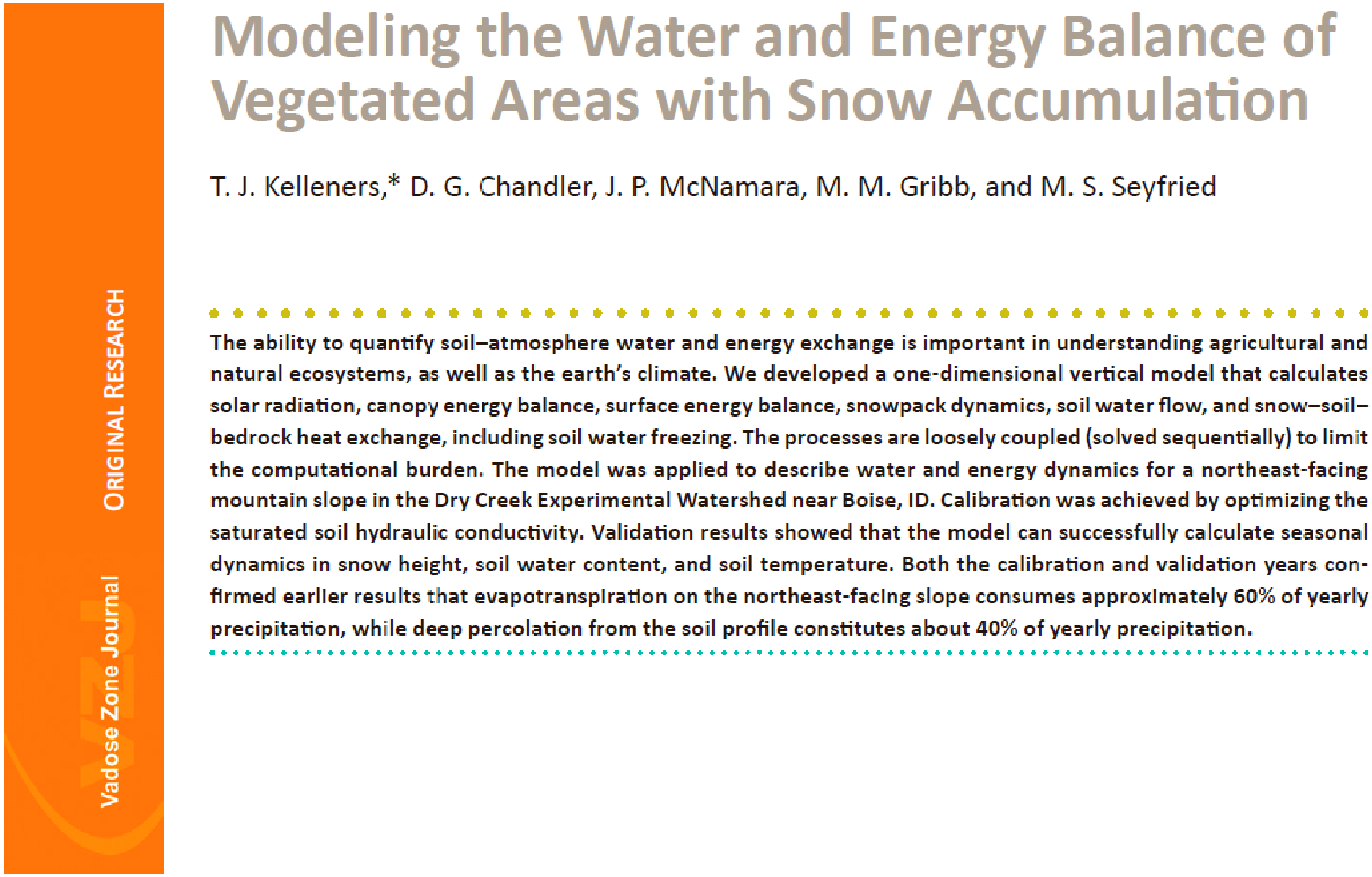


Storage Wrong



Stratton et al., 2009

VERY Physically-Based 1D



ORIGINAL RESEARCH

Vadose Zone Journal

Modeling the Water and Energy Balance of Vegetated Areas with Snow Accumulation

T. J. Kelleners,* D. G. Chandler, J. P. McNamara, M. M. Gribb, and M. S. Seyfried

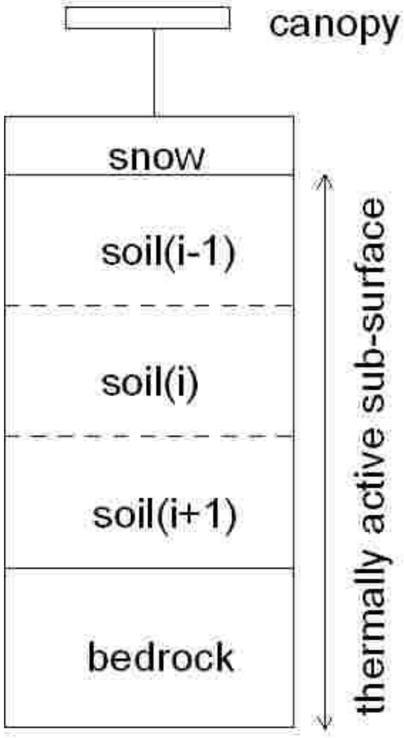
The ability to quantify soil–atmosphere water and energy exchange is important in understanding agricultural and natural ecosystems, as well as the earth's climate. We developed a one-dimensional vertical model that calculates solar radiation, canopy energy balance, surface energy balance, snowpack dynamics, soil water flow, and snow–soil–bedrock heat exchange, including soil water freezing. The processes are loosely coupled (solved sequentially) to limit the computational burden. The model was applied to describe water and energy dynamics for a northeast-facing mountain slope in the Dry Creek Experimental Watershed near Boise, ID. Calibration was achieved by optimizing the saturated soil hydraulic conductivity. Validation results showed that the model can successfully calculate seasonal dynamics in snow height, soil water content, and soil temperature. Both the calibration and validation years confirmed earlier results that evapotranspiration on the northeast-facing slope consumes approximately 60% of yearly precipitation, while deep percolation from the soil profile constitutes about 40% of yearly precipitation.

Kelleners et al., 2010

VERY Physically-Based 1D

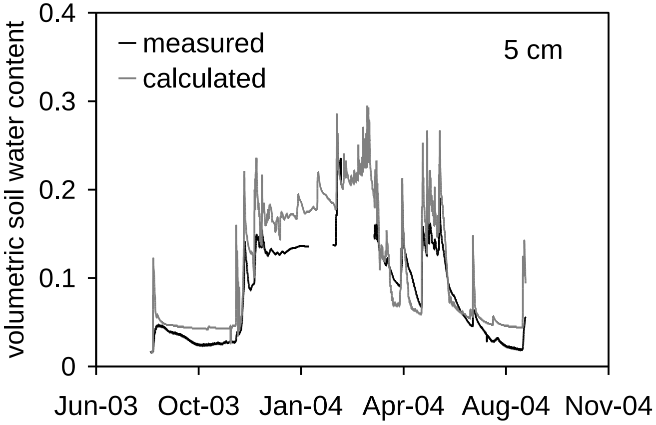
- Simulates Snow accumulation, melt, infiltration, and Bedrock infiltration with “NO” shortcuts
  - Over **70 equations** just for 1 dimension
    - NOT PRACTICAL
    - Allows us to determine the relative importance of physical controls

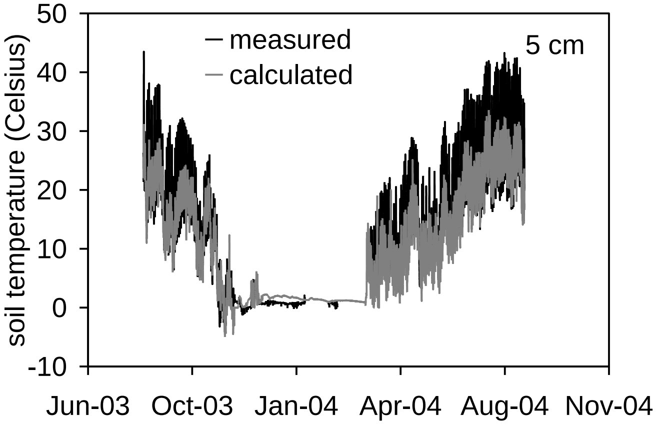
- Wavelength-dependent solar radiation
- Iterative canopy energy balance => T_{leaf}
- Iterative surface energy balance => $T_{surface}$
- Snow water flow
- Soil water flow
- Snow-soil-bedrock heat transport
- Snow-soil water phase change

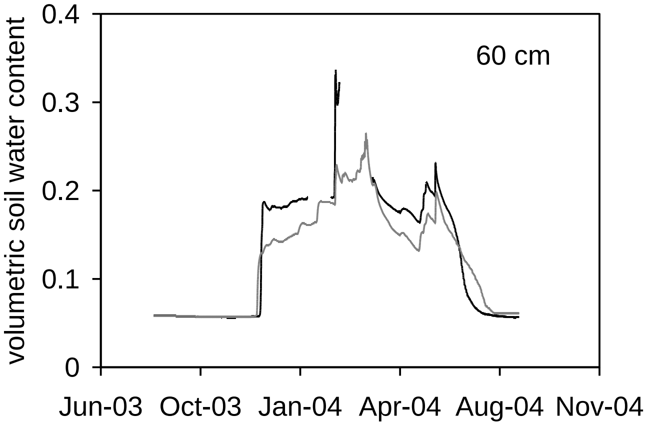


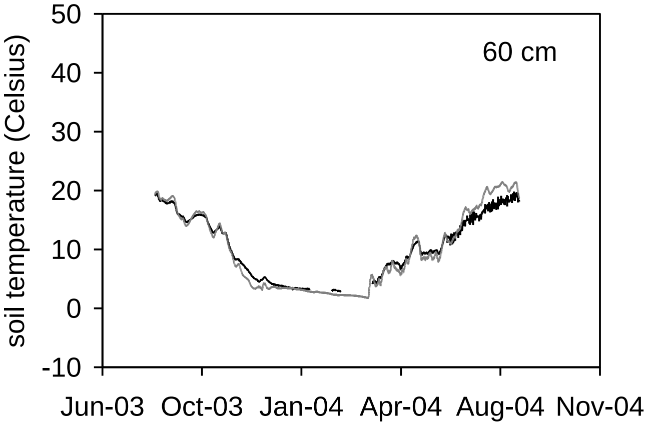
Kelleners et al., 2010

VERY Physically-Based 1D





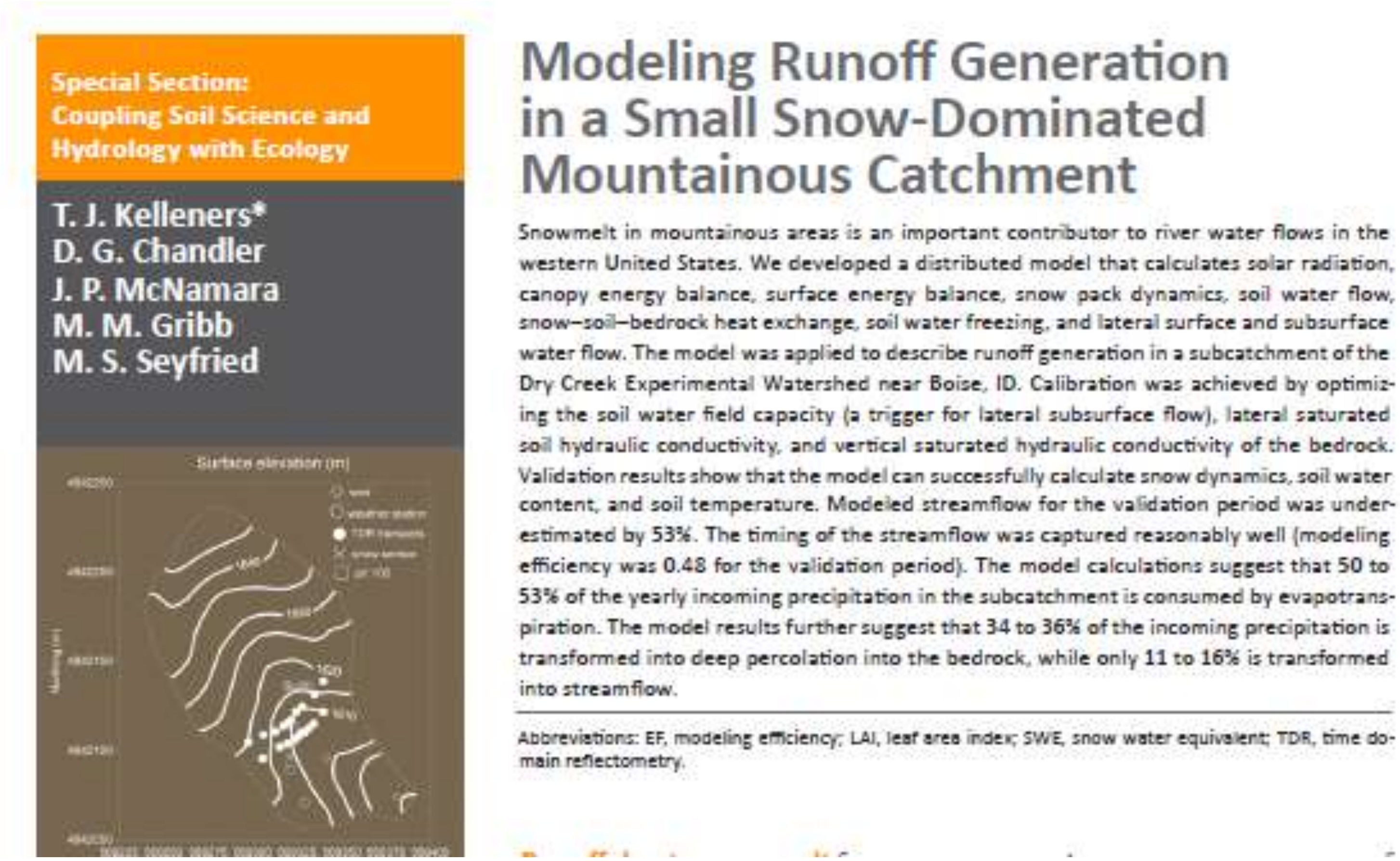




Root Mean Square Error: 20-38 %
Modeling Efficiency: 0.65-0.86

Root Mean Square Error: 11-28 %
Modeling Efficiency: 0.88-0.95

Very Physically Based – 3D



Special Section: Coupling Soil Science and Hydrology with Ecology

T. J. Kelleners*
D. G. Chandler
J. P. McNamara
M. M. Gribb
M. S. Seyfried

Modeling Runoff Generation in a Small Snow-Dominated Mountainous Catchment

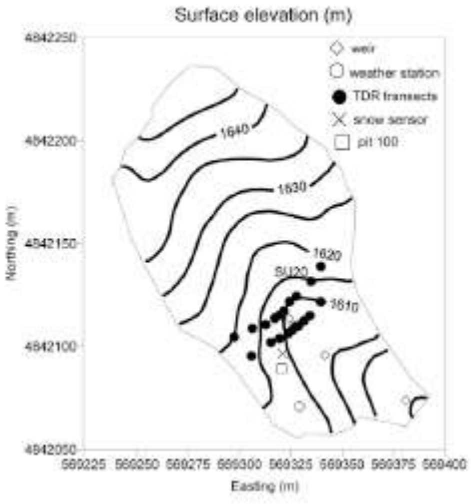
Snowmelt in mountainous areas is an important contributor to river water flows in the western United States. We developed a distributed model that calculates solar radiation, canopy energy balance, surface energy balance, snow pack dynamics, soil water flow, snow–soil–bedrock heat exchange, soil water freezing, and lateral surface and subsurface water flow. The model was applied to describe runoff generation in a subcatchment of the Dry Creek Experimental Watershed near Boise, ID. Calibration was achieved by optimizing the soil water field capacity (a trigger for lateral subsurface flow), lateral saturated soil hydraulic conductivity, and vertical saturated hydraulic conductivity of the bedrock. Validation results show that the model can successfully calculate snow dynamics, soil water content, and soil temperature. Modeled streamflow for the validation period was underestimated by 53%. The timing of the streamflow was captured reasonably well (modeling efficiency was 0.48 for the validation period). The model calculations suggest that 50 to 53% of the yearly incoming precipitation in the subcatchment is consumed by evapotranspiration. The model results further suggest that 34 to 36% of the incoming precipitation is transformed into deep percolation into the bedrock, while only 11 to 16% is transformed into streamflow.

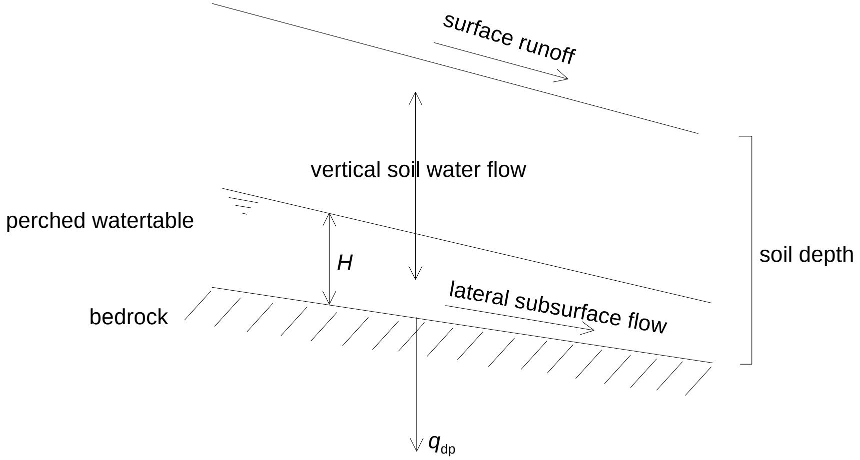
Abbreviations: EF, modeling efficiency; LAI, leaf area index; SWE, snow water equivalent; TDR, time domain reflectometry.

Kelleners et al., 2010

Very Physically Based – 3D

- Catchment is divided into 141 grid cells (10×10 m)





surface runoff

vertical soil water flow

perched watertable

soil depth

H

lateral subsurface flow

bedrock

q_{dp}

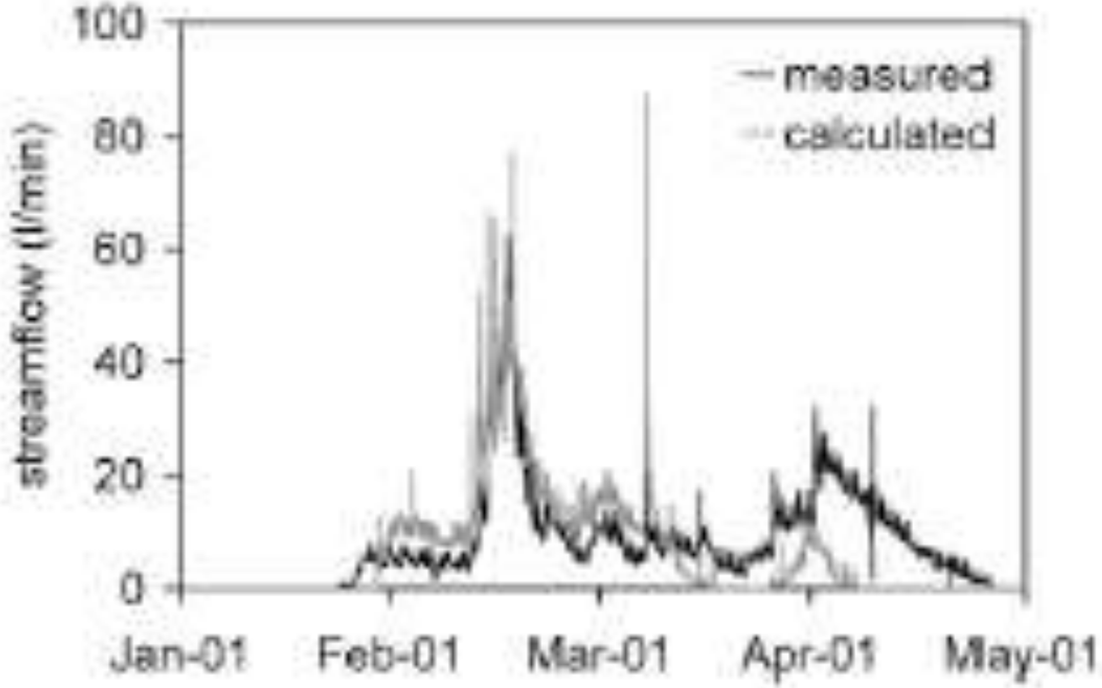
$$\phi = \nu_j \sum \left(Q^{*}_{streami} - Q_{streami} \right)^2 + \nu_j \sum \left(\theta^{*}_{i*} - \theta_i \right)^2$$

$$q_{dp} = \left\{ k_{sr} \frac{H + D}{D} \quad \right\}$$

Kelleners et al., 2010

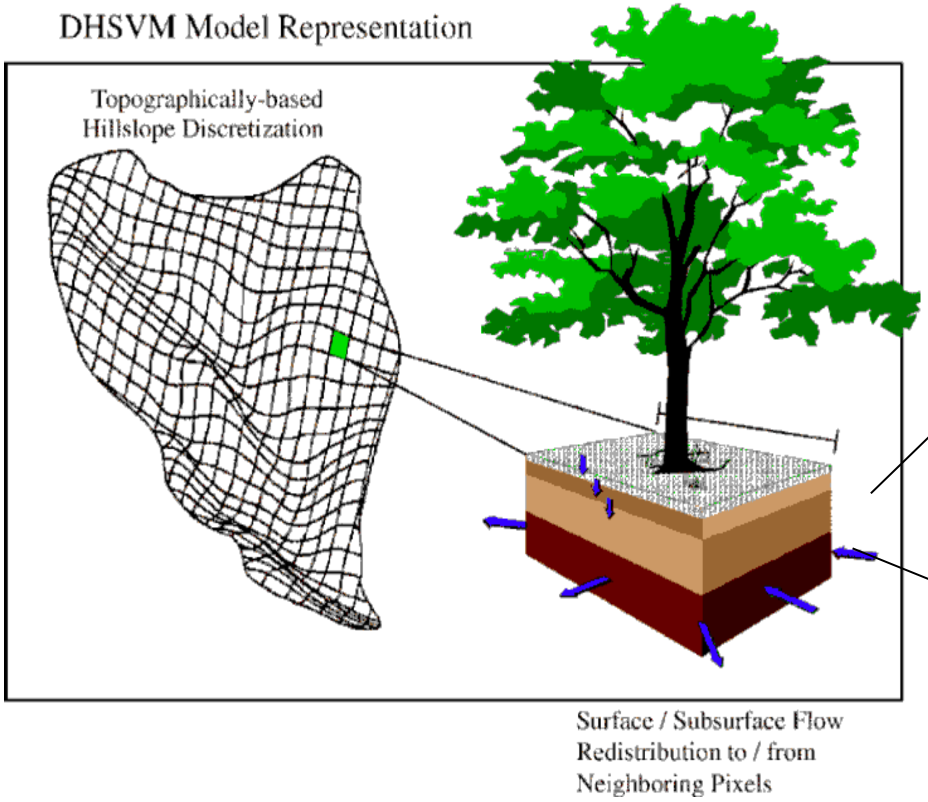
Very Physically Based – 3D

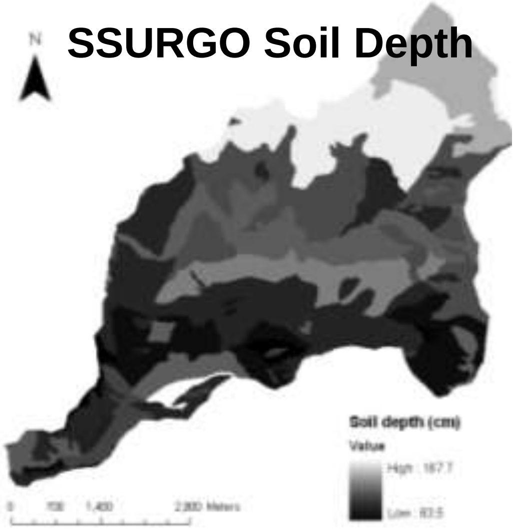
- Decent simulation of soil moisture, unsatisfactory simulation of streamflow
  - Wrong for the right reasons

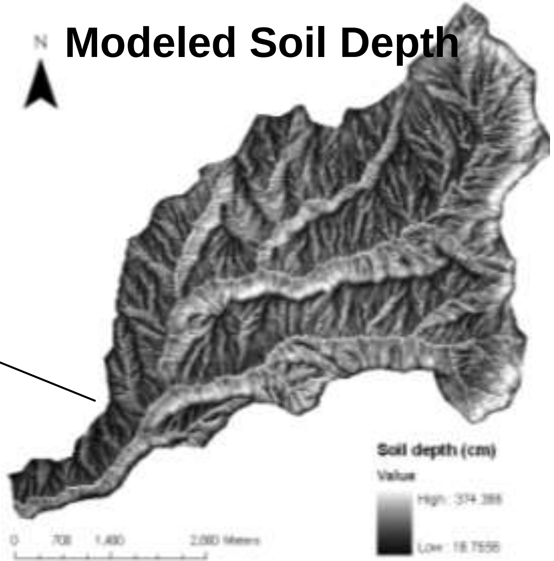


Distributed Hydrology Soil Vegetation Model (DHSVM)

Evaluate the impact of “improved” soil depth information on streamflow and soil moisture simulations



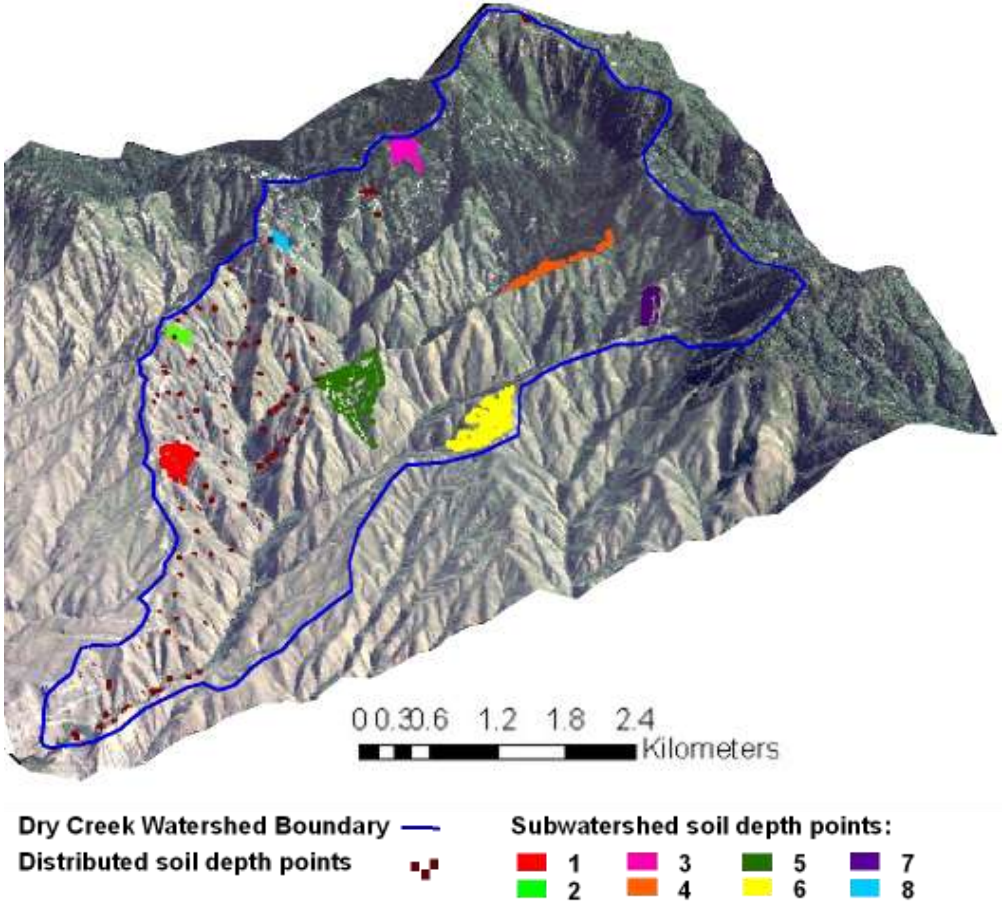




Soil Depth: Field Data

Soil depth measurement
- 2.2 m rod
- 1.27 cm diameter
- Pounded to refusal
- 2 or 3 repeats

819 points (calibration)
- 8 subwatersheds
- 130 random points (testing)
- During Spring when soil was moist



Fence Post Pounder

Copper Coated Steel Rod

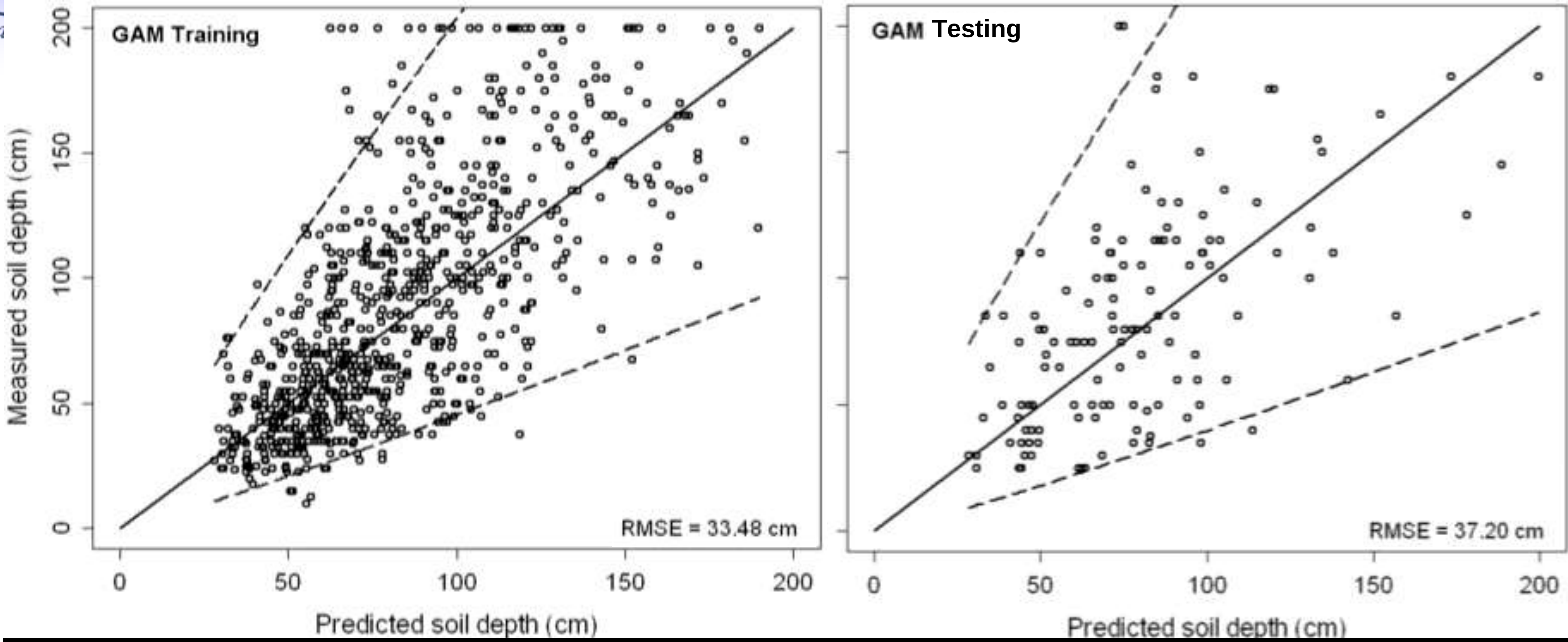
Predictor Variables

Symbol	**Description**
sca	Specific catchment area from the D∞ method. This is contributing area divided by the grid cell size
modcurv	Curvature modeled based on field observed curvature.
ang	The D∞ flow direction: the direction of the steepest outwards slope reported as the angle in radians counter-clockwise from east
avr	Average D∞ vertical rise to ridge
lspv	Longest vertical slope position
lvs	Longest D∞ vertical drop to stream
slpg	Magnitude of topographic slope computed using finite differences on a 3x3 grid cell window
sd8a	Slope averaged over a 100 m path traced downslope along D8 flow directions
elv	Elevation above sea level
plncurv	Plan curvature: the curvature of the surface perpendicular to the direction of the maximum slope
pc1	First principal component from ERDAS IMAGINE

○ **Newly derived variables**

□ **Land cover variable**

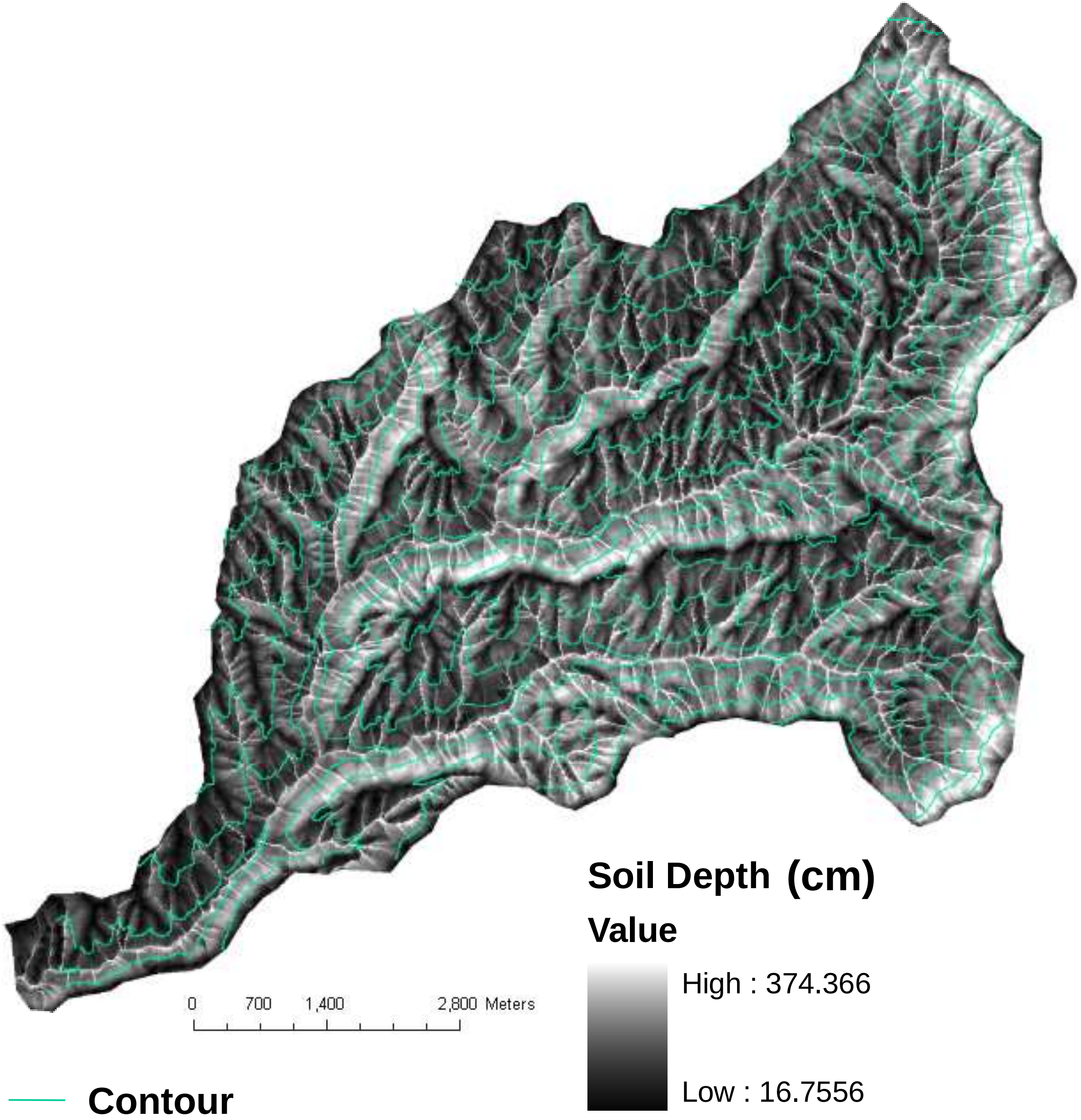
Measured vs Modeled Soil Depth



- - - - - - 95% Confidence interval ——— 1:1

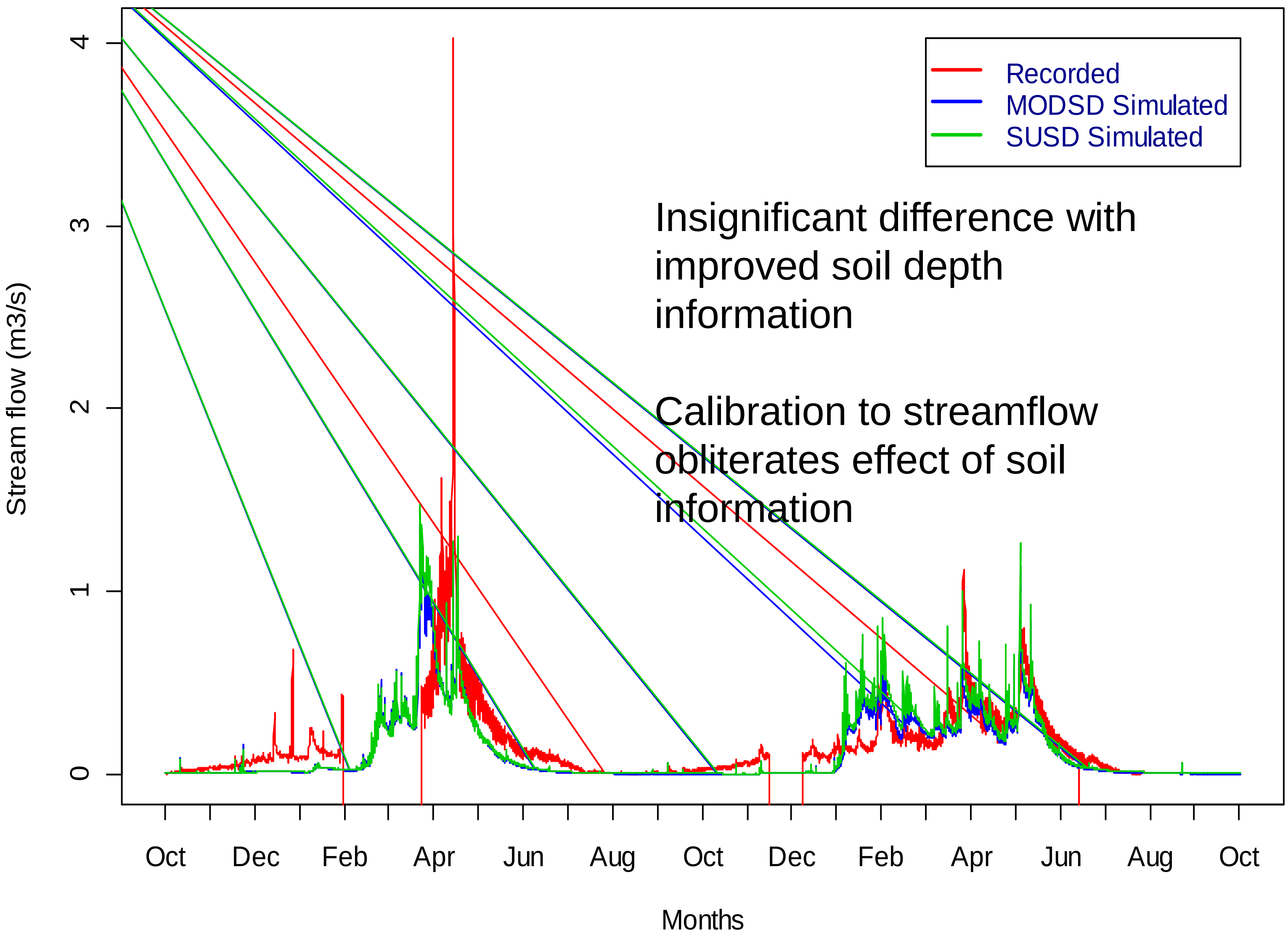
Tesfa et al., 2009

Predicted Soil Depth Map



DHSVM

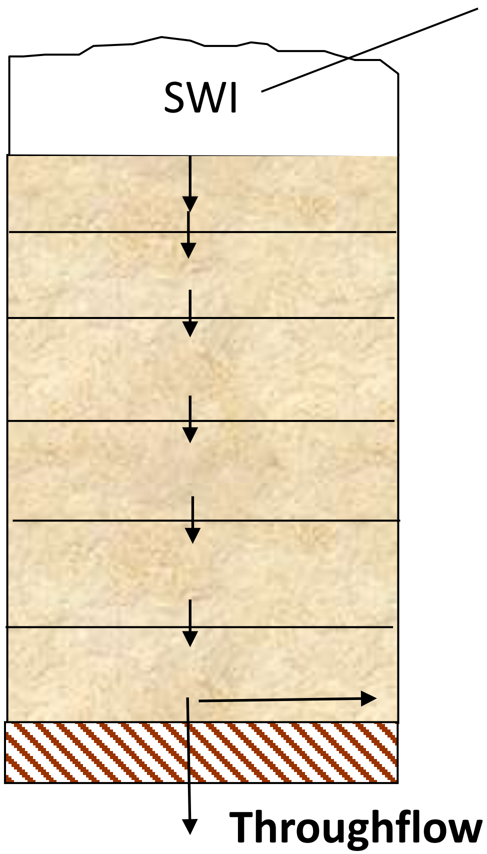
Recorded and Simulated stream flow (2002-2003)



Insignificant difference with improved soil depth information

Calibration to streamflow obliterates effect of soil information

Soil Capacitance Model (Reynolds Creek)



Snow Water Input (ISNOBAL)

Get the inputs right (accumulation, STORAGE,and ablation of snow)

Get the 1D soil water storage right

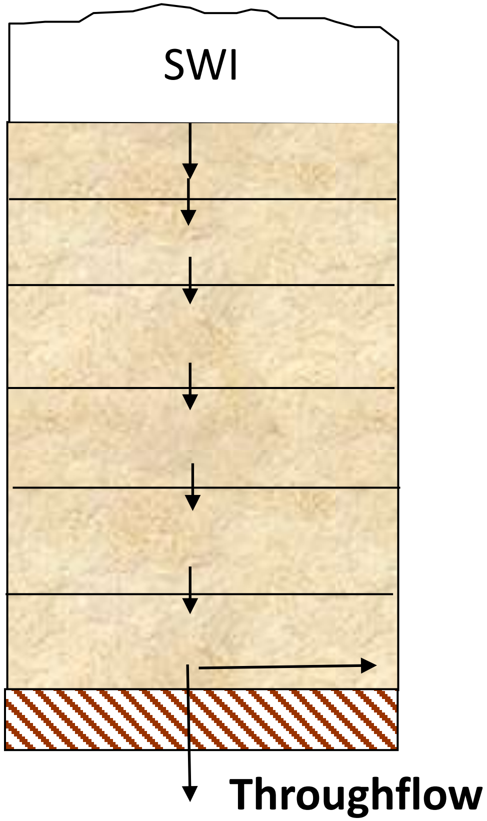
Ignore all lateral movement

No calibration to streamflow

See what happens

Seyfried et al., 2009, Hydrological Processes

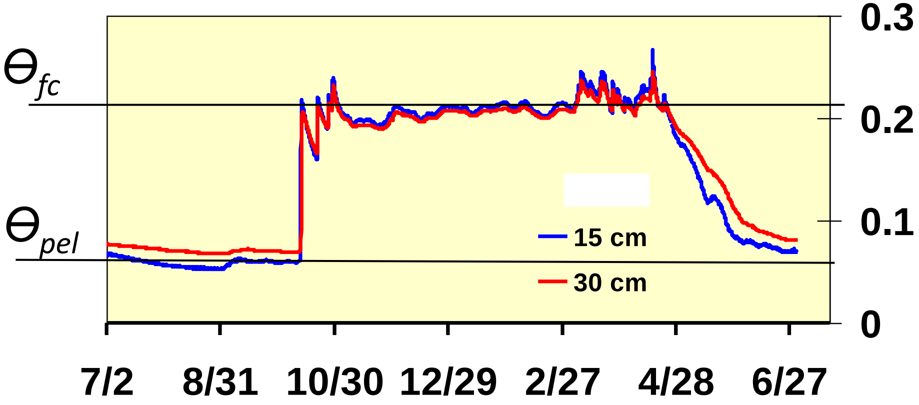
Soil Capacitance Model (Reynolds Creek)



- Throughflow occurs when soil column water holding capacity is exceeded

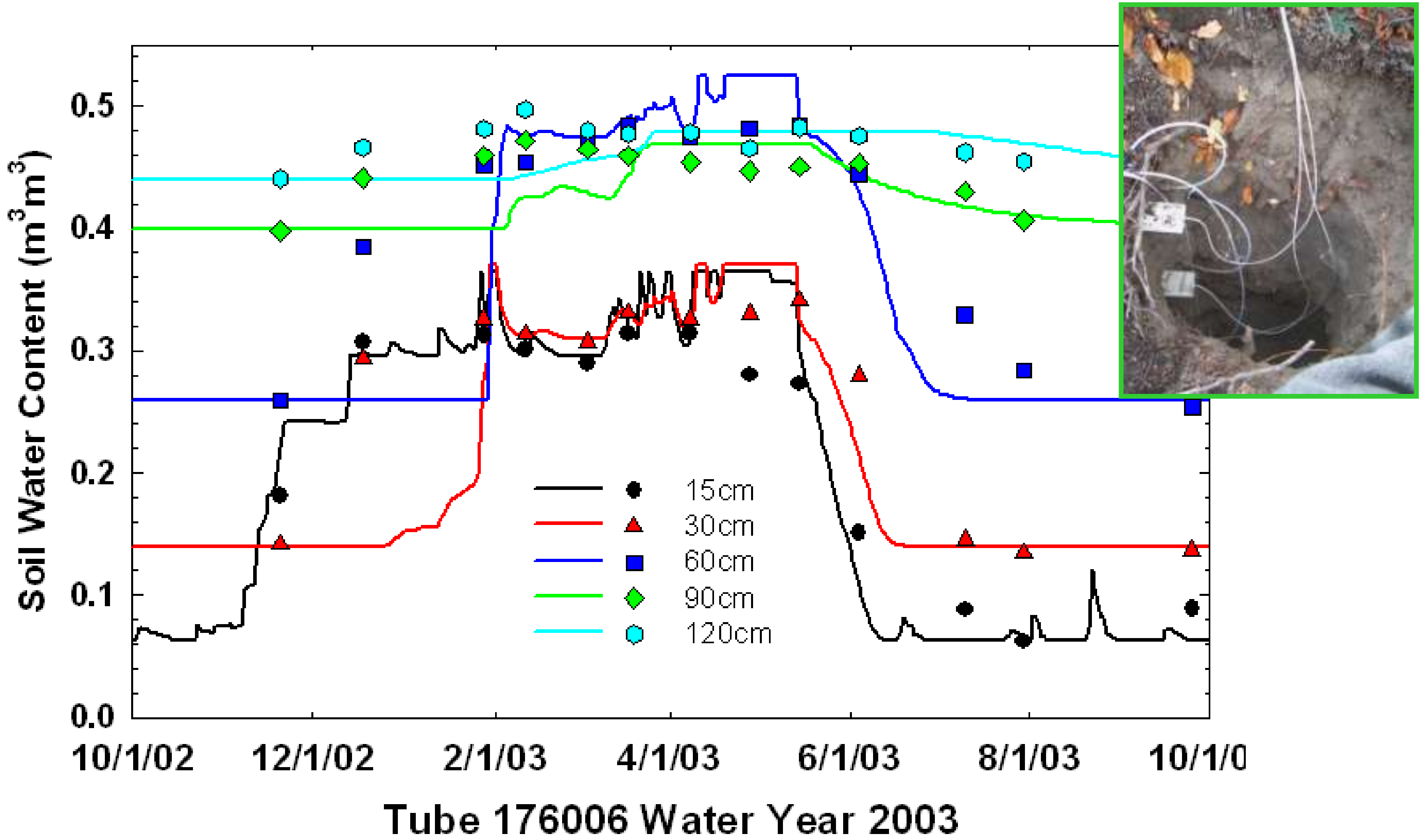
- Soil water storage parameterized by field capacity, plant extraction limit, soil depth

$$S = \sum_{i=1}^{i=numlayer} \theta_i T_i \qquad S_{FC} = \sum_{i=1}^{i=numlayer} \theta_{fc_i} T_i$$

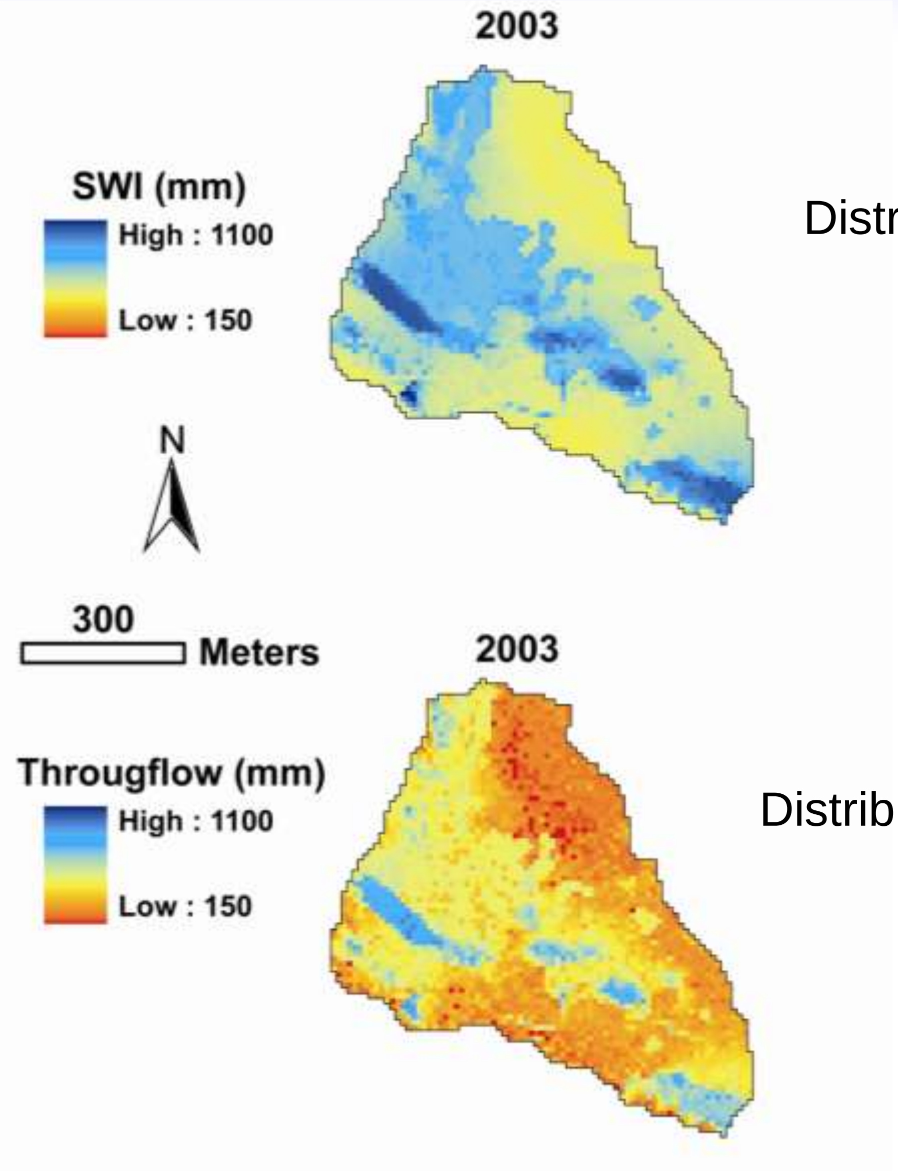


Seyfried et al., 2009, Hydrological Processes

Good 1D Performance



Distributed Model



Distributed energy balance forcing

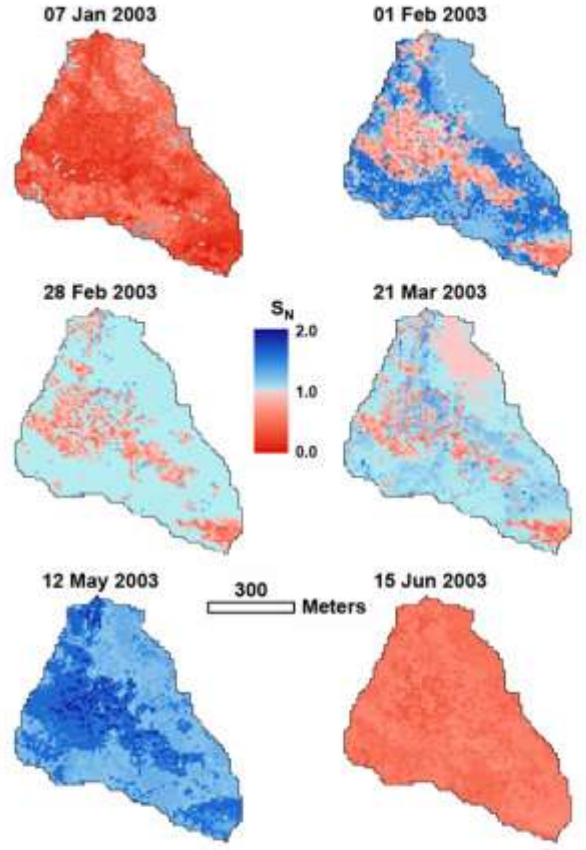
Distributed soil properties by similarity classes

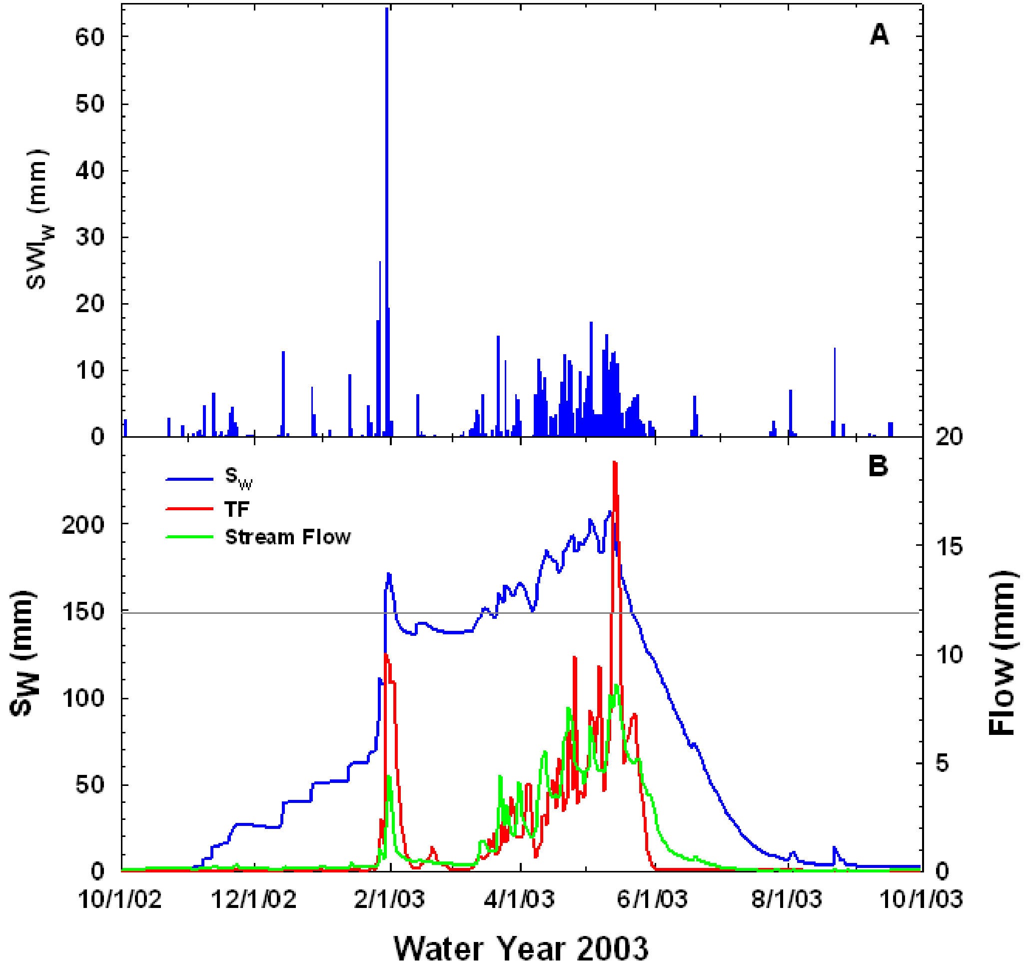
No lateral flow simulated

Simulated storage excess agrees with streamflow

Connectivity Index

$$S_N = \frac{S - S_{PEL}}{S_{FC} - S_{PEL}}$$





How do we Apply Process Understanding to Improve Prediction?

- **Revisit the lumped philosophy** of systems models

- **Recognize** catchments create **physically lumped properties**

- **Replace** mathematical lumping approaches with **physically lumped properties**
  - **Use as validation targets**
  - **Build into new model structures**

- **The mechanisms by which catchments STORE water characterize the catchment system**

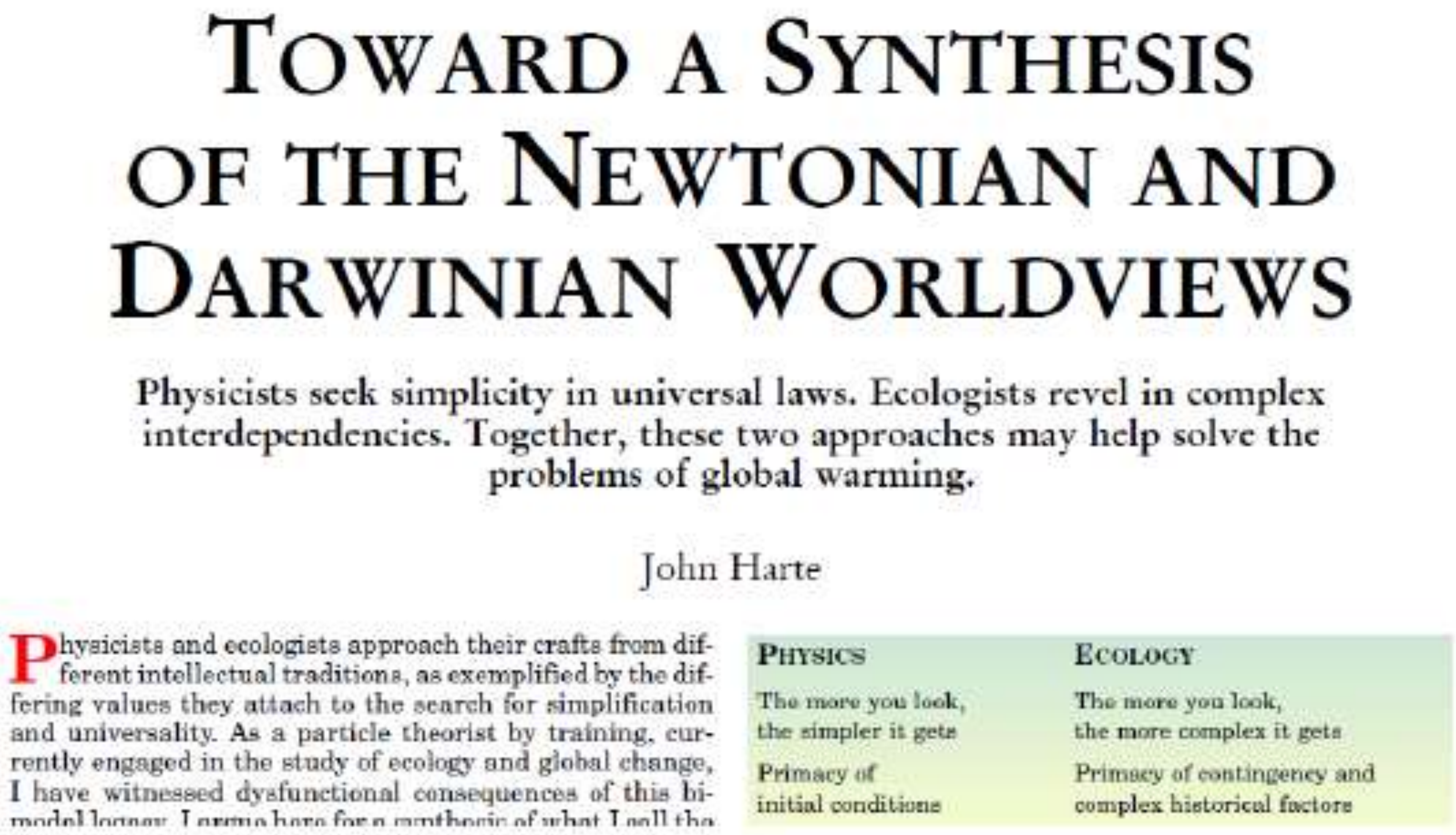
- We should concern ourselves with how catchments **Retain Water** in addition to how they release water
  - **Get storage right, and everything else will work out**

How do we Apply Process Understanding to Improve Prediction?

- …ecohydrology should synthesize Newtonian and Darwinian approaches to science…combining Newtonian principles of simplification, ideal systems, and predictive understanding (often, but not solely embraced by hydrologists) with Darwinian principles of complexity, contingency, and interdependence (often, but not solely embraced by ecologists)…offers the potential for profound and more rapid advances in our understanding of environmental process…

Brent Newmann

Striving towards a synthesis



TOWARD A SYNTHESIS OF THE NEWTONIAN AND DARWINIAN WORLDVIEWS

Physicists seek simplicity in universal laws. Ecologists revel in complex interdependencies. Together, these two approaches may help solve the problems of global warming.

John Harte

Physicists and ecologists approach their crafts from different intellectual traditions, as exemplified by the differing values they attach to the search for simplification and universality. As a particle theorist by training, currently engaged in the study of ecology and global change, I have witnessed dysfunctional consequences of this bimodal legacy. I argue here for a synthesis of what I call the

PHYSICS	ECOLOGY
The more you look, the simpler it gets	The more you look, the more complex it gets
Primacy of initial conditions	Primacy of contingency and complex historical factors

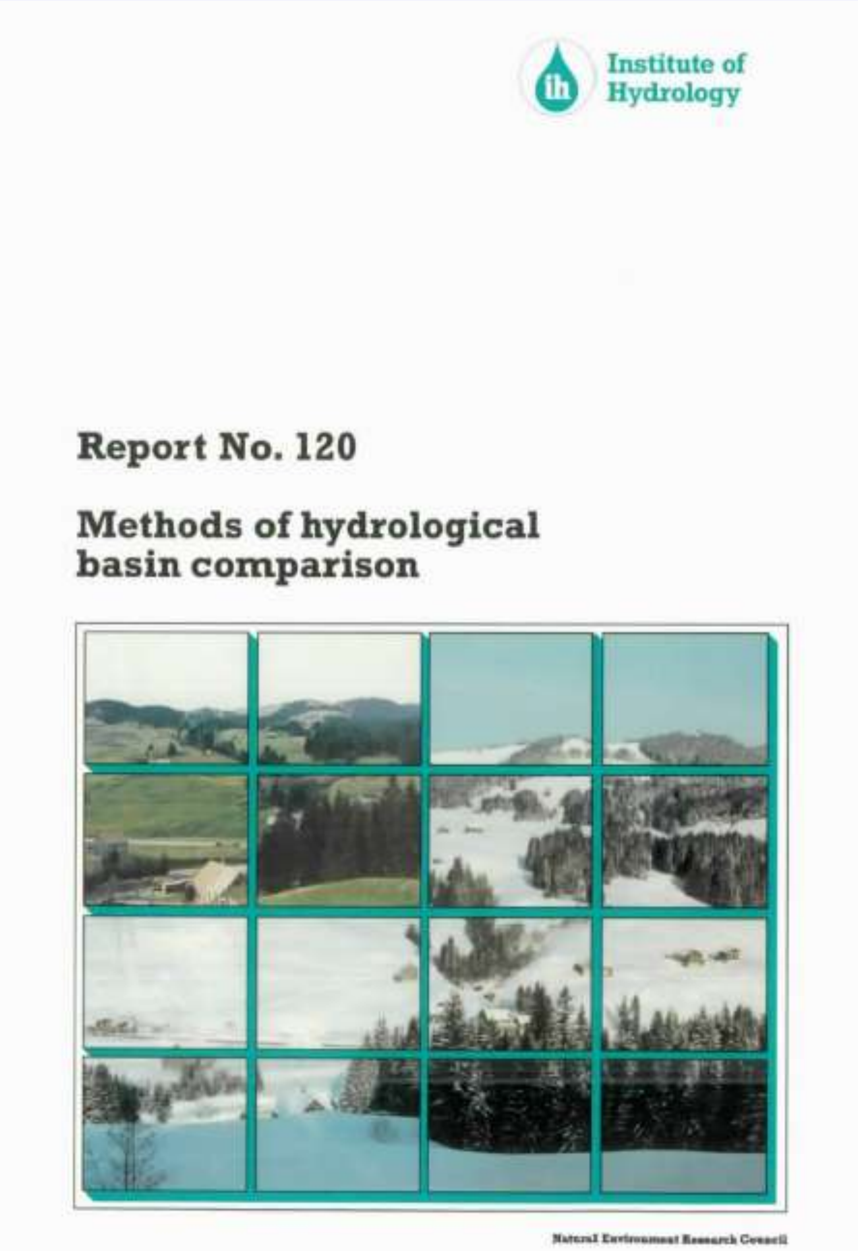
However…

- …ecohydrology should synthesize Newtonian and Darwinian approaches to science…combining Newtonian principles of simplification, ideal systems, and predictive understanding (often, but not solely embraced by hydrologists) with Darwinian principles of complexity, contingency, and interdependence (often, but not solely embraced by ecologists)…offers the potential for profound and more rapid advances in our understanding of environmental process…

Brent Newmann

How do we compare catchments?

- M. Robinson (1992)
  - 20 papers from western and central Europe
  - Key Conclusion: Intercomparison is difficult



Institute of Hydrology

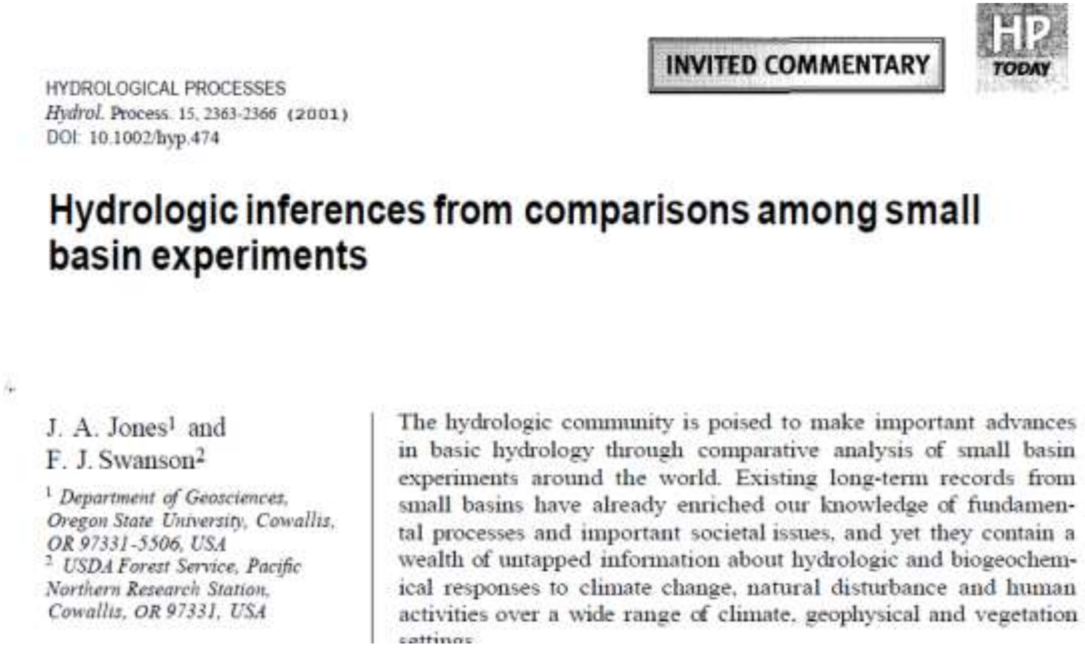
Report No. 120

Methods of hydrological basin comparison

Natural Environment Research Council

How do we compare basins?

- Jones and Swanson (2001)
  - A basin's streamflow may be predicted by characterizing basin **storage capacities** in vegetation, soil, and snow…



HYDROLOGICAL PROCESSES
Hydrol. Process. 15, 2363-2366 (2001)
DOI: 10.1002/hyp.474

INVITED COMMENTARY

Hydrologic inferences from comparisons among small basin experiments

J. A. Jones[1] and
F. J. Swanson[2]

[1] *Department of Geosciences, Oregon State University, Cowallis, OR 97331-5506, USA*
[2] *USDA Forest Service, Pacific Northern Research Station, Cowallis, OR 97331, USA*

The hydrologic community is poised to make important advances in basic hydrology through comparative analysis of small basin experiments around the world. Existing long-term records from small basins have already enriched our knowledge of fundamental processes and important societal issues, and yet they contain a wealth of untapped information about hydrologic and biogeochemical responses to climate change, natural disturbance and human activities over a wide range of climate, geophysical and vegetation settings

How do we compare basins?

- McDonnell and Woods (2004)
  - Governing principles are known
    - **Heterogeneity** rules the day
  - Possible classification metrics include
    - Response time of **dominant storage**

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Journal of Hydrology 299 (2004) 2–3

Journal of Hydrology

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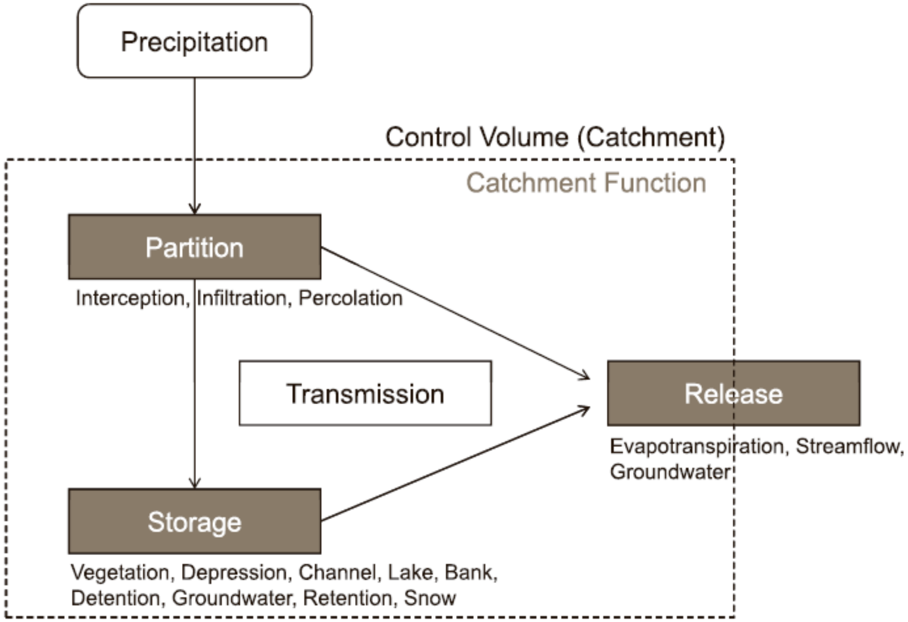
Editorial

On the need for catchment classification

How do we compare basins?

- Wagener et al. (2007)
- **Classification** is a rigorous scientific inquiry into the causes of similarities and relationships between catchments.



Geography Compass 1/4 (2007): 901–931, 10.1111/j.1749-8198.2007.00039.x

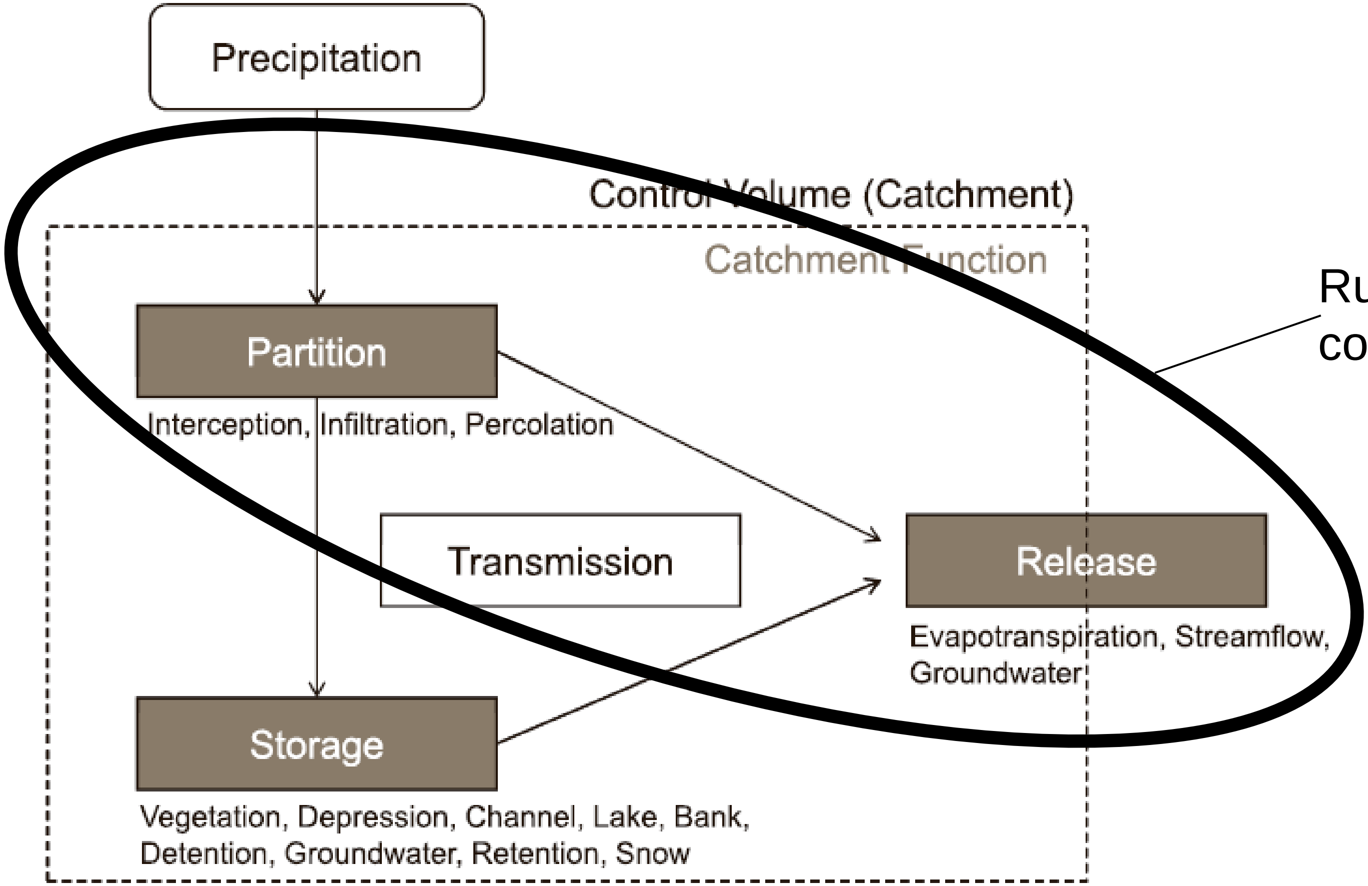
Catchment Classification and Hydrologic Similarity

Thorsten Wagener,[1]* Murugesu Sivapalan,[2] Peter Troch,[3] and Ross Woods[4]

[1] *Department of Civil and Environmental Engineering, Pennsylvania State University*
[2] *Departments of Geography, and Civil and Environmental Engineering, University of Illinois, Urbana-Champaign*
[3] *Department of Hydrology and Water Resources, University of Arizona*
[4] *National Institute of Water and Atmospheric Research, New Zealand*

How do we compare basins?

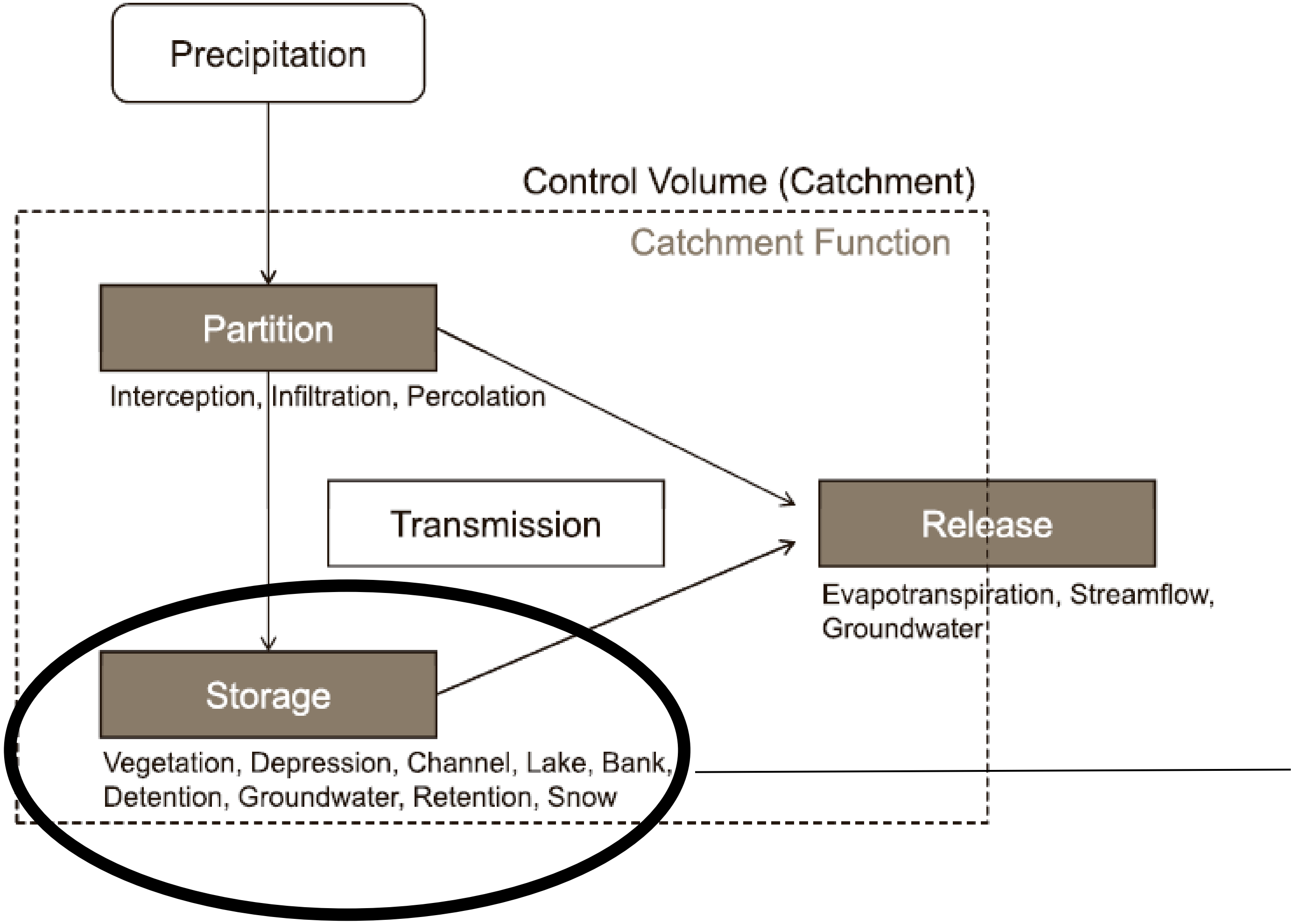
- Wagener et al. (2007)



Runoff generation commonly studied

How do we compare basins?

- Wagener et al. (2007)



Precipitation

Control Volume (Catchment)

Catchment Function

Partition

Interception, Infiltration, Percolation

Transmission

Release

Evapotranspiration, Streamflow, Groundwater

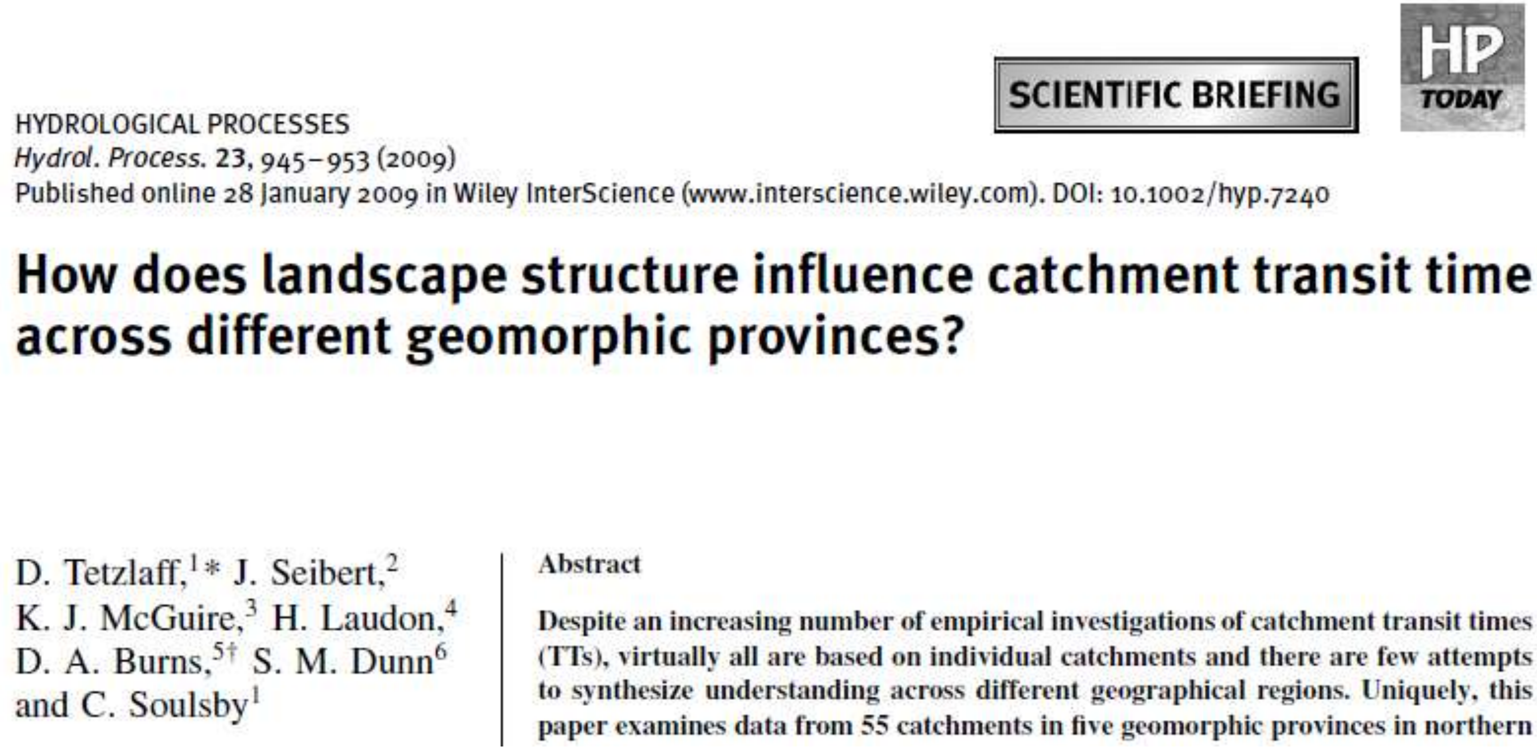
Storage

Vegetation, Depression, Channel, Lake, Bank, Detention, Groundwater, Retention, Snow

Storage uncommonly studied

How do we compare basins?

- Landscape structure moderates transit times



HYDROLOGICAL PROCESSES
Hydrol. Process. **23**, 945–953 (2009)

How does landscape structure influence catchment transit time across different geomorphic provinces?

D. Tetzlaff,[1]* J. Seibert,[2]
K. J. McGuire,[3] H. Laudon,[4]
D. A. Burns,[5†] S. M. Dunn[6]
and C. Soulsby[1]

Abstract

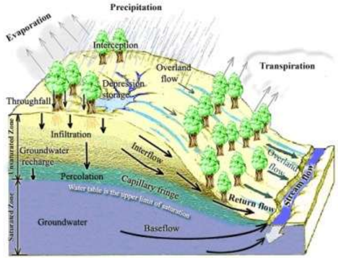
Despite an increasing number of empirical investigations of catchment transit times (TTs), virtually all are based on individual catchments and there are few attempts to synthesize understanding across different geographical regions. Uniquely, this paper examines data from 55 catchments in five geomorphic provinces in northern

How to Apply Process Information to Improve Prediction

- **Recognize** that the existence of true physically-based models is a **myth**

- **Identify** physically lumped properties

- **Build** conceptual models based on the ways catchments lump properties, not mathematical
  - Systems approaches using “essential” parameters



How to Apply Process Information to Improve Prediction?

- **Recognize** that the existence of true physically-based models is a **myth**

- **Identify** hydrologically relevant processes or properties for hydrogeographic regions
  - Classification

- **Build** models that target **relevant** hydrologic processes or properties
  - Systems approaches using “essential” parameters